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Thermal Energy Harvesting WSNs Node for Temperature Monitoring in IIoT

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ABSTRACT As the backbone of industrial Internet of Things (IIoT), wireless sensor networks (WSNs) are generally powered by batteries with limited energy, which constrain the continuous operations of WSNs and IIoT. Energy harvesting is a promising solution for this problem. Industrial plants have many hot pipelines or walls, and the temperature is one of the critical parameters to be monitored in industrial processes. This paper developed a novel thermal energy harvesting WSN node for temperature monitoring in IIoT. The feasibility of the presented self-powered WSN node is experimentally verified for a range of different sleep periods of the device. These results demonstrate that the designed boost circuit has an energy conversion rate of about 27%, and the proposed thermal energy harvester is able to indefinitely power a commercial WSN node when the sleep period of the device exceeds 16 s, which represents a duty cycle of 5.4%.

INDEX TERMS Wireless sensor networks, energy harvesting, thermoelectric generator, Internet of Things, temperature monitoring.

I. INTRODUCTION

Industrial Internet of Things (IIoT) is the deployment of Internet of Things (IoT) in industrial settings, and IIoT will play a vital role in transforming and updating traditional industries, and the enabling of smart manufacturing [1]. Over the last few years, a variety of IIoT architectures and applications have been developed and reported by different researchers [2]–[5]. As the backbone of IIoT, wireless sensor networks (WSNs) collect information from various physical objects and devices and then transmit the information to the Internet to link the virtual world and the real world [6], [7]. Generally, WSN nodes are powered by batteries with limited energy, which constrains the continuous operations of WSNs and IIoT. Although high capacity batteries, low power design [8], and on-sensor-node data processing [9] will prolong WSN node lifetime, the key issue is that the node energy from batteries is limited. Harvesting energy from the surrounding environment of the WSN node provides a promising solution for allowing indefinite operational lifetime.

Energy harvesting approaches using various energy sources, such as light [10], wind [11], thermal energy [12], and radio frequency (RF) signal [13], have been developed and presented in recent years. The selection of a suitable energy harvesting method needs to consider the setting of the WSNs application and the available energy. This project is focused on thermal energy harvesting in WSN node for temperature monitoring in IIoT because industrial plants have many hot pipelines or walls, even when there is insufficient light, wind, or RF signal power for energy harvesting, and because the temperature is one of the critical parameters to be monitored in industrial processes.

We have previously published the results of some initial experiments in using thermal energy harvesting [14]. This paper extends that preliminary work, and gives more detailed descriptions on the related background, a broader background on thermal energy harvesting principles, descriptions of equivalent electronics circuits, an analysis of thermoelectric collector temperature distribution, and extended experimental validation and result analysis.

Recently, thermal energy harvesting technology for self-powered WSN nodes has been investigated by several researchers. In [15], a small thermoelectric generator using a flameless catalytic burner as the heat source is developed and tested to power autonomous sensors in remote environmental sites. The results show that with a matched load resistance and 10°C temperature difference across the TEG, the generator is able to supply an output voltage larger than 200mV and an output power around 10mW for at least 6 hours, which is able to cyclically supply a LED used to represent low power sensors [15].

A commercial thermal energy generator, GM-200-127-14-16 from European Thermodynamics, is employed to harvest thermal energy produced by a solar thermal collector in [16]. The results from experiments demonstrate that one TEG module is able to generate 4.7mW power for WSN nodes at 3.75×10^4 lux illumination in full daylight, however, the proposed energy harvester has not been demonstrated to actually power an industrial sensor node [16].

The design in [17] proposed a novel heat storage thermoelectric harvesting device using 23g water in a 60mm*30mm*30mm custom-made aluminum alloy heat storage as the phase-change material (PCM). The TEG on the proposed device is able to scavenge the heat energy stored in the PCM or produced during the phase change process of the PCM when the device undergoes significant temperature variation over time, like aircraft flights. The experimental results show that 105J energy, namely 22mW for 80 minutes, is produced from an environmental temperature sweep from +20°C to −21°C, and then to +25°C.

Besides using a TEG to collect the thermal energy produced by additional devices, such as flameless catalytic burner [15], solar thermal collector [16], or heat storage with PCM [17], some research activities explored harvesting waste thermal energy by putting the TEG directly on the available hot surfaces of industrial devices.

A self-powered WSN node for data center monitoring is described in [18]. The presented energy harvester consists of three stacked TEGs placed on the top of the target host CPU in a data center. The prototype is developed and evaluated using a TI eZ430-RF2500 microprocessor board, in which the proprietary simple communication protocol is embedded. The testing results indicate that the proposed WSN node is able to complete the parameter monitoring and self-powering tasks simultaneously.

The simulation, implementation, and testing of an energy harvester based on the thermoelectric generator for wireless sensors in a boiler environment are introduced in [19]. The results show that the proposed harvester is able to produce about 114mW power, when the temperature of the top of the harvester, which is inserted in the oven, is 500°C and the temperature difference across the TEG is 34°C.

The work in [20] explores the possibility of an autonomous wireless temperature sensing node powered by a commercial TEG (Kryotherm TMG 127-1.0-2.5). However, this work does not use a commercial industrial temperature sensor. Instead, a simple low power conditioning circuit and radio transmitter are interfaced with a temperature sensor. This radio periodically sends the measurement information to a base station. This solution sacrifices the convenience and reliability of a commercial sensor node to achieve low power operation.

A self-powered thermal energy harvesting wireless sensor node for temperature measurement with a small, compact, and mechanically rigid structure is reported in [12]. However, this system is based on a custom TEG, and a custom sensor node, and so it does not demonstrate that commercial sensors can be successfully powered by a TEG.

In summary, some of the above-mentioned applications use simulation or model analysis of the proposed thermal energy harvester [17], [18]; some examples measure the output power of the harvester to show its capability for powering the WSN node [15], [16], [19]; some papers use a LED as a load [15] or a simple low power conditioning circuit and RF transmitter [20], while some systems use a custom designed TEG and sensor node [12], rather than a standard commercial WSN node, as the load of the thermal harvester to prove the self-powered possibility of the presented approach.

In this paper, a complete system is built to explore whether a commercial TEG without additional heat energy collector or storage can power a commercial WSN node with a useful duty cycle for temperature monitoring in IIoT.

The remainder of this paper is organized as follows. Thermal energy harvesting principle is introduced in Section II. Section III describes the system architecture and implementation methodology, while Section IV discusses the experimental results. Finally, Section V presents the overall conclusions.

II. THERMAL ENERGY HARVESTING PRINCIPLES

A commercial TEG is generally an array of series-connected semiconductor thermocouples clamped between two electrically insulating and heat conducting ceramic plates, as shown in Fig. 1. Due to the Seebeck effect, when there is a temperature difference across a TEG, each thermocouple composed of *p*-type and *n*-type semiconductor material will generate electric energy and the series output of all the thermocouples in a TEG will deliver power at the level of microwatts/K. The open circuit voltage of a TEG (V_G) is proportional to the temperature difference across the TEG, and can be calculated by [20]:

$$V_G = N\alpha_{pn}\Delta T_{TEG} \tag{1}$$

where N is the number of semiconductor thermocouples, α_{pn} is the Seebeck coefficient of the thermocouple, and ΔT_{TEG} is the temperature difference across the thermocouples in a TEG. α_{pn} and ΔT_{TEG} are defined as below:

$$\alpha_{pn} = \alpha_p - \alpha_n \tag{2}$$

$$\Delta T_{TEG} = \frac{K}{K + 2K_{in}}\Delta T = \beta \Delta T \tag{3}$$

where α_p and α_n are the Seebeck coefficient of p-type and n-type semiconductor, respectively; ΔT is the external temperature difference between the two ceramic plates, K is the

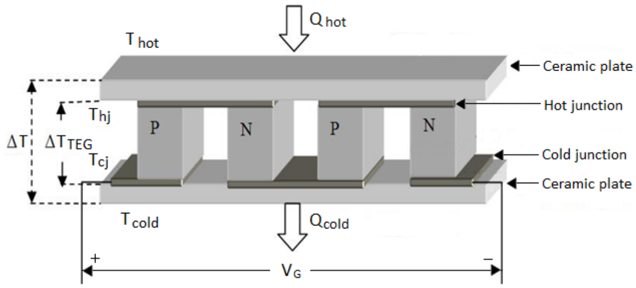


FIGURE 1. Structure of TEG elements.

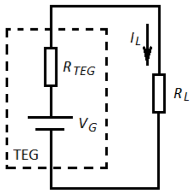


FIGURE 2. Equivalent circuit of a TEG with a load.

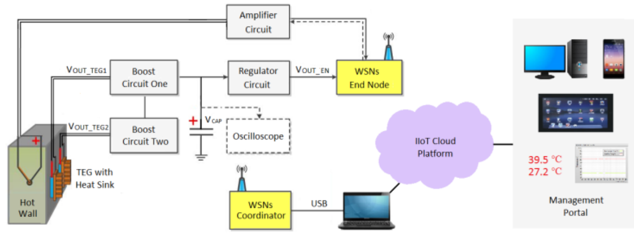


FIGURE 3. Schematic diagram of the thermal energy harvesting WSN node for temperature monitoring in IIoT.

thermal conductivity of the ceramic plate, while K_{in} is the internal thermal conductivity of the thermocouples.

The equivalent circuit of a TEG connected with a load R_L is shown in Fig. 2. The output power P_L delivered by a TEG to the load R_L is given by:

$$P_L = I_L^2 R_L = \left(\frac{N\alpha_{pn}\Delta T_{TEG}}{R_{TEG}+R_L}\right)^2 R_L = N^2\alpha_{pn}^2\beta^2\Delta T^2\frac{R_L}{(R_{TEG}+R_L)^2} \quad (4)$$

where R_{TEG} is the internal resistance of the TEG. When load resistance R_L is equal to R_{TEG}, the maximum power P_{Lmax} is transferred from TEG to R_L, namely the corresponding energy conversion circuits and WSN node powered by the TEG. The maximum power P_{Lmax} is:

$$P_{Lmax} = \frac{N^2\alpha_{pn}^2\beta^2\Delta T^2}{4R_{TEG}} \quad (5)$$

III. SYSTEM ARCHITECTURE AND IMPLEMENTATION

The schematic diagram of the proposed thermal energy harvesting WSN node for temperature monitoring in IIoT is shown in Fig. 3. The TEG-powered WSN node consists of a TEG with the heatsink, boost circuit, regulator circuit, supercapacitor, amplifier circuit, the control circuit for the amplifier, and a commercial WSN node.

Instead of one single TEG mode, this research installed two commercial TEG modules, TGM287-1.0-1.3 from Kryotherm, on the imitated industrial hot wall to convert waste heat energy into electric energy because our previous work in [21] shows that ΔT, the external temperature difference across a TEG, will stabilize around ten degrees, although the hot side temperature of the TEG is about one hundred degree, and when ΔT is below 15°C, due to the basic energy consumption of the conversion circuit and the WSN node, the energy produced by one TEG is insufficient to power a commercial WSN node.

In order to simplify the design process, two highly integrated step-up converter and power manager chips, LTC3108 from Linear Technology, connected in series are employed to boost the output voltage of the two TEGs. The turns ratio of the small external step-up transformer for the LTC3108 is 1:20.

The final output voltage of the TEGs is used to charge C7, a 4-farad supercapacitor for harvested energy storage. The leakage current of C7 is 15μA. V_{CAP} is the voltage on the supercapacitor C7. A linear regulator, TPS76801 from TI, is then applied to regulate V_{CAP} to a suitable value for powering a Jennic JN5139, a typical commercial WSN node supporting the ZigBee standard. The equivalent electronic circuit for the above-described energy conversion and storage functions is shown in Fig. 4.

A K-type thermocouple is employed in this system to measure the temperature of an industrial device, i.e. the hot wall in this application, while an MC33202 from ON Semiconductors is used to amplify the thermocouple output signal. The amplified signal is then sampled by a 12-bit A/D converter embedded in the JN5139. To save energy, an LP2985 regulator from Texas Instruments is used to synchronously switch the amplifier mode between sleep and active, according to the status of the JN5139 node. Fig. 5 shows the detailed equivalent electronic circuits for temperature measurement.

Another two K-type thermocouples, a potentiometer, and a USB-TC01, a thermocouple measurement device from National Instruments, are used in the experimental setup to obtain the hot and cold side temperatures and the temperature difference of the TEG.

The higher ΔT is, the more thermal energy will be harvested by the TEG. For a constant temperature at the TEG hot side T_{hot}, a lower temperature at TEG cold side T_{cold} will produce larger ΔT. To obtain lower T_{cold} and larger ΔT, a thermoelectric collector is designed in this system. Fig. 6(a) is the assembly diagram of the thermoelectric collector, (b) is the photo of the TEG, TGM287-1.0-1.3, (c) is the photo of the collector installing on the hot well. After mounting on the hot wall, only the copper heatsink can be seen. From Fig. 6(a) we can see that the collector consists of four 40*40mm thermal conductive silicone pads and two 40*40mm copper plates for heat-transfer from the hot wall to the 40*40mm TEG and

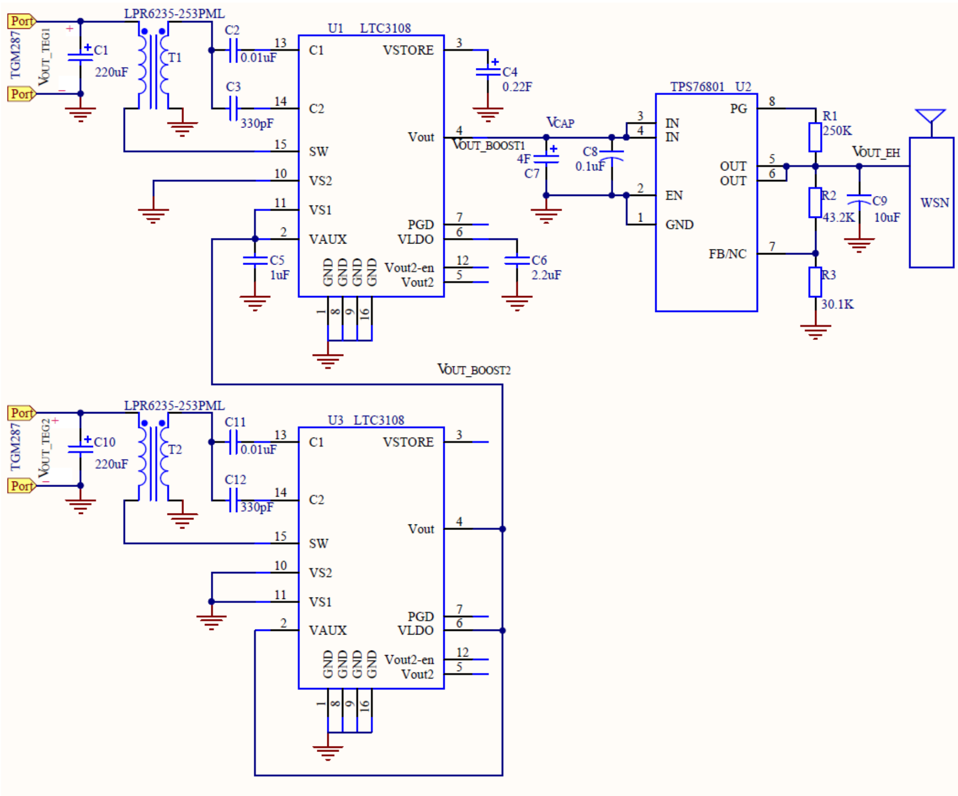


FIGURE 4. Equivalent electronic circuits for energy conversion and storage.

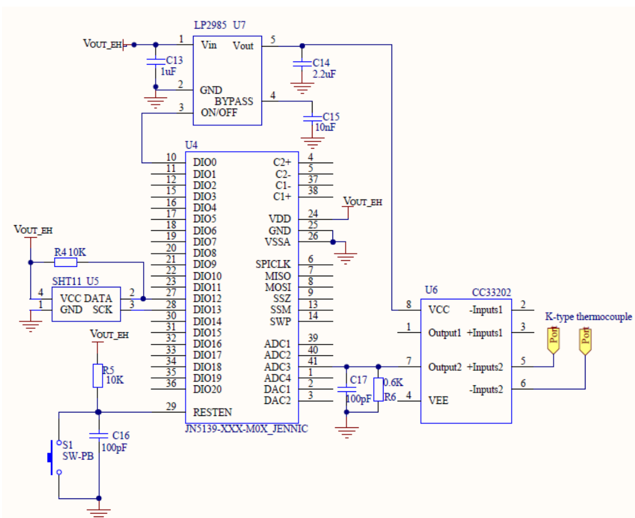


FIGURE 5. Equivalent electronic circuits for temperature measurement.

then to the 88*88*23mm copper heatsink. An aerogel blanket is placed on the hot wall around the TEG to prevent heat-transfer from the hot wall to the cold side of TEG and the copper heatsink to avoid the increase of T_{cold}.

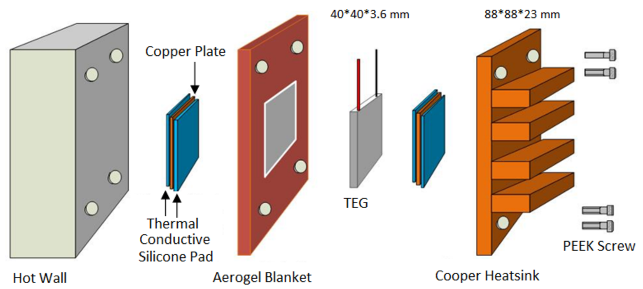
IV. EXPERIMENTS AND DISCUSSION

Whether a thermal energy harvesting WSN node can be indefinitely powered is determined by three main factors: (1) the amount of power that can be harvested by the TEG, which in turn is determined by the temperature differential between the hot and cold sides of the TEG; (2) how efficiently the harvested energy can be converted and regulated to the required operating voltage for the commercial WSN node, and (3) how much energy will be used by the WSN node. When the harvested energy during a period of time is more than the consumed energy of the WSN node and the energy losses in the conversion process, the system can operate indefinitely and autonomously. To validate the proposed thermal energy harvesting WSN node for temperature monitoring in IIoT, a set of experiments were undertaken using the experimental setup as shown in Fig. 7.

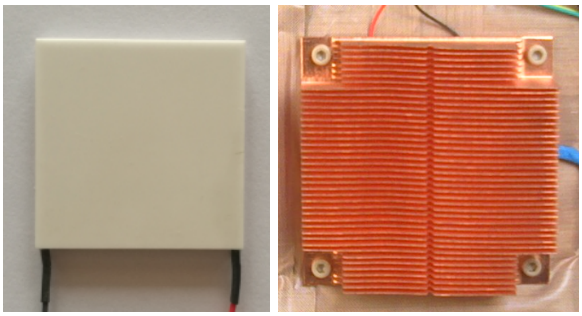
A. THERMOELECTRIC COLLECTOR TEMPERATURE DISTRIBUTION

The harvested energy by the thermoelectric collector depends on the temperature difference across the hot and cold sides of the TEG. The temperature at the hot side of the TEG is almost the same as the hot wall temperature, while the cold side temperature of the TEG is affected by the cold end temperature and efficiency of the heatsink.

In this experiment, the hot and cold side temperatures of the TEG are measured by NI USB-TC01. The results indicate that when the electric heater reaches 110°C, a typical value in an industrial setting, the hot and cold side temperatures



(a)



(b)

FIGURE 6. The thermoelectric collector: (a) assembly diagram, (b) TEG, (c) after installing on the hot wall (only the copper heatsink on the top of the collector can be seen).

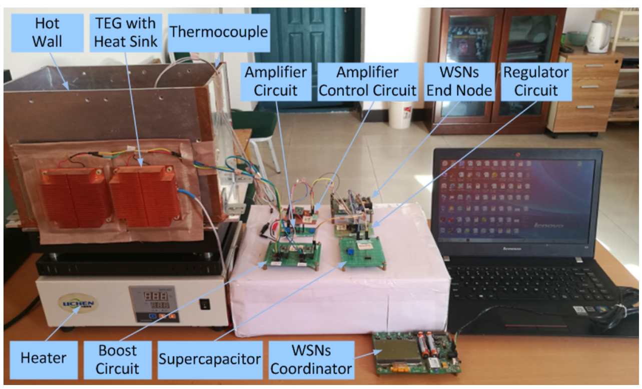
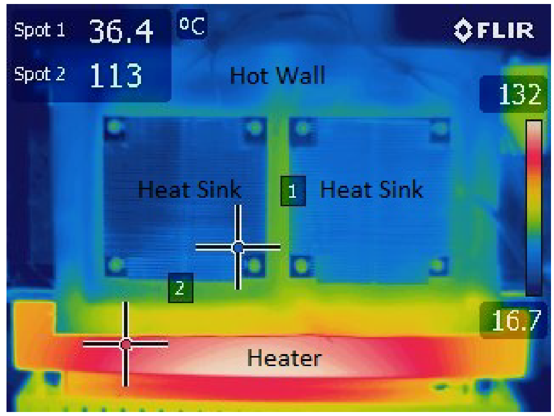
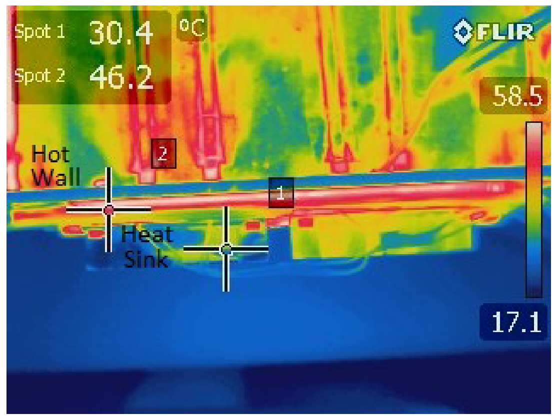


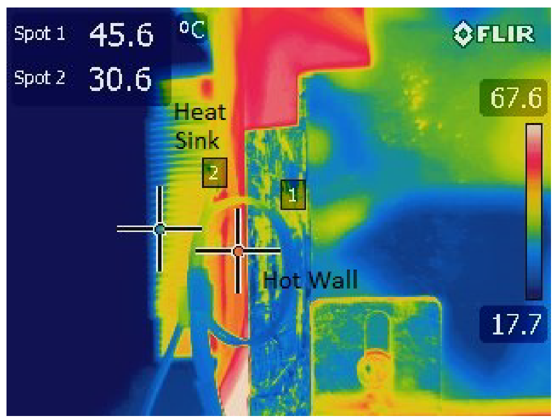
FIGURE 7. View of the experimental setup.



(a)



(b)



(c)

FIGURE 8. Thermovision images of thermoelectric collector, (a) front view, (b) top view, (c) side view.

of the TEG are about 60°C and 46°C, respectively. In order to get a more detailed view of the temperature distribution on the presented thermoelectric collector, a thermal imaging camera, FLIR T420, which has 320×240 infrared resolution and 0.045°C thermal sensitivity, is used to take thermal pictures of the thermoelectric collector. Three typical thermovision images of the designed thermoelectric collector from different views are given in Fig. 8. It can be observed that when the electric heater temperature is 113°C (Spot 2 in Fig. 8(a)), the cold side temperature of the TEG is around 46°C (Spot 2 in Fig. 8(b) and Spot 1 in Fig. 8(c)), while the cold end temperature of the heatsink is about 30°C (Spot 1 in Fig. 8(b) and Spot 2 in Fig. 8(c)). In summary, the temperature difference between the two ends of the heatsink is 16°C, while the temperature difference between the two sides of the TEG is 14°C.

B. FEASIBILITY OF SELF-POWER

Considering the large difference in energy consumption between the active mode and sleep mode of WSN nodes, most WSN applications employ a duty cycled operating mode. In this experiment, various sleep periods of the node are selected and tested to see whether the WSN node can be self-powered under the above-mentioned thermal gradient and

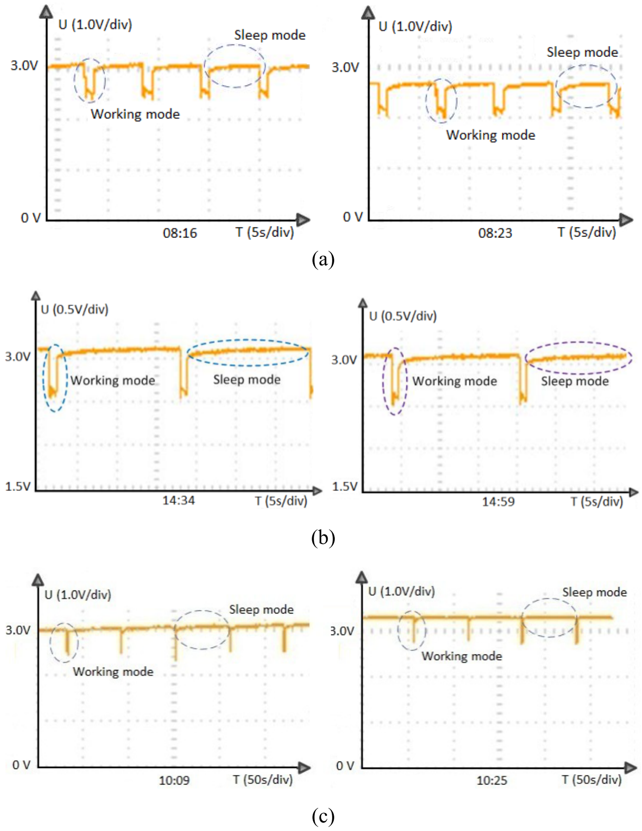


FIGURE 9. **The voltage value of the super-capacitor, V_{CAP}, (a) with 5s sleep period, (b) with 16s sleep period, (c) with 60s sleep period.**

operating environment. The initial voltage value of the super-capacitor (V_{CAP}) is set at 3.0V.

Fig. 9 shows the detailed waveforms of the super-capacitor, V_{CAP}. In Fig. 9(a), the sleep period of the WSN end node and the amplifier circuit is set at 5s, it can be seen that V_{CAP} drops from initial 3.0V to 2.6V (the minimum operating voltage for the regulator) in 7 minutes, from 8:16 to 8:23. In Fig. 9(b), the WSN has a sleep period of 16s. It is clear that the waveform of V_{CAP} at 14:59 is basically identical to the initial waveform at 14:34, namely 25 minutes earlier. In Fig. 9(c), 60s is used as the sleep period, we can observe that V_{CAP} increases to 3.3V (i.e., the maximum voltage of the boost circuit) from an initial 3.0V in 16 minutes (from 10:09 to 10:25).

More experiments for various WSN node sleep periods are conducted. The results are shown in Fig. 10. It is clear that when the WSN sleep periods are 5s and 10s, the generated energy from harvester is less than the energy consumed by the node, the supercapacitor discharges and V_{CAP} slowly decreases to 2.7V in about 20minutes and 45minutes. With sleep periods of 20s and 30s, the harvested energy is more than the consumed energy, the supercapacitor charges, and V_{CAP} increases to 3.3V in about 30 minutes and 75 minutes, respectively. With an asleep period of 16s, the generated energy equals the consumed energy, and V_{CAP} remains constant at 3.0V. So 16s is the minimum period for indefinite operation for the proposed thermal energy harvesting WSN node.

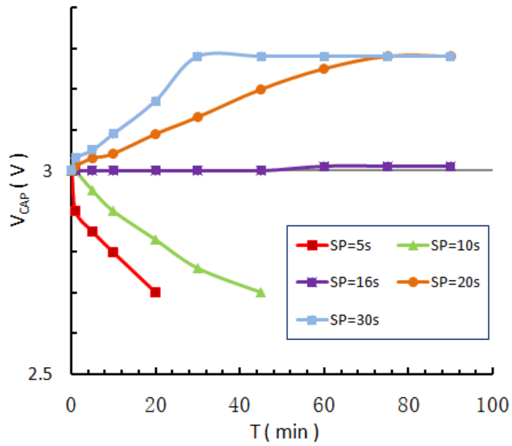


FIGURE 10. **The charging behavior of V_{CAP} under various sleep periods (SPs).**

TABLE 1. **Parameters of energy conversion circuit.**

	$V_{OUT\ TEG}$(mV)	$I_{OUT\ TEG}$(mA)	$P_{OUT\ TEG}$ (mW)
$TEG1_{OP}$	610	56.9	34.7
$TEG2_{OP}$	585	55.9	32.7
TEG1	386	17.06	6.5
TEG2	389	16.9	6.6

TABLE 2. **Parameters of supercapacitor.**

V_{CAP}(V)	I_{CAP}(mA)	$P_{IN\ CAP}$ (mW)
3.28	1.1	3.6

C. ENERGY CONVERSION EFFICIENCY

In this experiment, the parameters of the boost circuit in the energy conversion circuit and the parameters of the super-capacitor are measured and given in Table I and Table II, respectively. Using these parameters, the energy conversion efficiency can be calculated for the boost circuit. The output voltage and current of the two TEGs without load are 610mV, 57mA, and 585mV, 56mA, the unloaded output power of the two TEGs are 34.7mW and 32.7mW. The input voltage and input current for the two boost circuits, namely the output of the TEGs with load, are 386mV and 17mA for TEG1, and 389mV and 17mA for TEG2, and the input power of the boost circuits is 13.1mW (consisting of 6.5mW from TEG1 and 6.6mW from TEG2). The voltage and current of the supercapacitor, V_{CAP} and I_{CAP}, are 3.28V and 1.1mA, and the input power of the supercapacitor, which is the output power of the boost circuits, is 3.6mW. Therefore the energy conversion efficiency of the boost circuits is approximately 27%.

The feasibility of hot wall temperature monitoring by the proposed thermal energy harvesting WSN node is verified in the experimental setup as well. The result shows that the designed WSN node can work autonomously and complete temperature signal monitoring successfully.

V. CONCLUSIONS

A novel thermal energy harvesting WSN node for temperature monitoring in IIoT is proposed and described in this paper. The feasibility of the designed self-powered WSN node is verified by a set of experiments with a range of different sleep periods for the WSN node. The experimental results demonstrate that the energy conversion rate of the boost circuit is about 27%, and the proposed thermal energy harvester is able to power a commercial WSN node with an active period of 0.9s when the sleep period exceeds 16s, equivalent to a duty cycle of 5.4%. The result also demonstrates that the proposed WSN node can work autonomously and can monitor the temperature of the industrial equipment successfully.

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