JPhys Energy

TOPICAL REVIEW

Energy harvesting using thermoelectricity for IoT (Internet of Things) and E-skin sensors

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Keywords: thermoelectricity, IoT, energy harvesting, body-heat harvesting

Abstract

With the increasing demand for Internet of Things (IoT) with integrated wireless sensor networks (WSNs), sustainable power supply and management have become important issues to be addressed. Thermal energy in forms of waste heat or metabolic heat is a promising source for reliably supplying power to electronic devices; for instance, thermoelectric power generators are widely being researched as they are able to convert thermal energy into electricity. This paper specifically looks over the application of thermoelectricity as a sustainable power source for IoT including WSNs. Also, we discuss a few thermoelectric systems capable of operating electronic skin (e-skin) sensors despite their low output power from body heat. For a more accurate analysis on body heat harvesting, models of the human thermoregulatory system have been investigated. In addition, some clever designs of heat sinks that can be integrated with thermoelectric systems have also been introduced. For their power management, the integration with a DC–DC converter is addressed to boost its low output voltage to a more usable level.

1. Introduction

In 1999, Kelvin Ashton first introduced the concept of 'Internet of Things (IoT)' which emphasized human dependency on internet and computers to gather information [1]. IoT integrates many objects with their surroundings through networks affecting the users’ quality of life [2–4]. Typical IoT systems include sensors, processors, a transmission component and a power source to allow interaction between the user and the electronic system [4]. Moreover, the demand for wireless sensor networks (WSNs) has increased where efficient sustainable energy harvesting and energy management still remain key issues [5]. Since the past decade, the market for internet-connected smart devices has grown to reach over a trillion dollars [6]. IoT systems consist of several components: sensors to acquire information from objects, communication and processing devices to deliver information, and a cloud service to collect and transfer information. IoT systems using smart devices allow a wide range of applications including, but not limited to, home appliances, health care devices, transportation, and industry. For example, a monitored terrestrial ecosystem which collects and transfers the consequential information to a data storage has been proposed [7]. IoT systems are also applied in homes and industries in various forms such as transceivers, receivers, and sensors to detect any changes in motion, ambient conditions, smoke/fire, and security [8]. IoT systems are also widely used in fields of airborne wireless networks to communicate with a ground station or a satellite system [9]. In means of their continuous operation, energy harvesting from the surrounding environment can act as the sustainable power source for WSNs [10]. Common forms of harvestable energy from the ambient environment include solar energy [11–15], wind energy [16–20], and thermal energy [21–23]. Of these forms, we mainly focus on thermal energy and its conversion to electricity (widely known as thermoelectricity). The thermoelectric effect is the energy conversion process between thermal and electrical energy [24]. An advantage of thermoelectric power generation is its sustainable and reliable conversion of thermal energy into electricity with no moving parts. With the increasing demand of WSNs, the thermoelectric generators (TEG) have received the spotlight as a source of sustainable power supply. The
researches about the application of thermoelectricity for WSNs in various environments will be introduced in section 2. While the demand for smart devices related to monitoring the health of a human has been increasing, the human body heat has been focused as the power source for sustainable operation. At the beginning of section 3.1, body heat harvesting using flexible TEG will be introduced. A more detailed system including body heat harvesting, power management and operation of sensors will also be addressed. To reproduce the human body behavior more accurately, a detailed analysis on body heat harvesting is conducted by examining various human thermoregulatory models in section 3.2. In addition, various heat sink models with the potential of being integrated with thermoelectric systems are also explored in section 3.3 for further enhancement of the system. As the output voltage from body heat harvesting-based thermoelectric systems stands only at about several tens of mV [25, 26], a voltage converter or a voltage booster is required to operate sensors. Researches on voltage converters will be explored in detail, section 3.4, as their integration with thermoelectric systems is yet an unfamiliar field of research.

2. Sustainable energy harvesting for IoT system

As mentioned before, for continuous use of IoT systems, especially for WSNs, a sustainable power source based on energy harvesting is required. To convert diverse forms of energy from the ambient environment such as solar, wind, thermal, and mechanical energy into electrical energy, various methods of energy harvesting have been researched as followed. Piezoelectric effects have been widely researched to harvest energy from fluid motion [27, 28], human motion [29–34], and wind [16, 19, 20]. Although they harvest notable amounts of energy from various conditions as mentioned above, they do not guarantee sustainability as energy is not harvested with any motion. Energy harvesting using the triboelectric effect through contact electrification has also been researched for a broader usage [35–40]. Such effect has been demonstrated [41] by harvesting energy from water drops [42, 43] and also in micro-scales—water waves [44, 45]. Despite its possibility to be used as an energy source for WSNs, it still requires an actuating part, similar to piezoelectric energy harvesting. Solar energy, a widely used source of energy, is a suitable candidate for sustainable power supply of WSNs [11–15]. Although solar energy harvesting advances in high sustainability, its biggest drawback lies in the short duration of its operation time.

Unlike solar and wind energy, an imponderable amount of thermal energy from the industrial field is released as waste heat [46]. Thus, energy harvesting from this waste heat has also been widely researched in fields of transportation [47–50] and industry [51, 52]. Where there is thermal energy, TEG can be a sustainable power supply for WSNs. Nakagawa et al [53] demonstrate a thermoelectric generator system with an internal heat storage made of paraffin. When installed on a bridge, it successfully harvests 58.5 J of heat energy per day, demonstrating its possible outdoor use with WSNs. Samson et al [54] demonstrate the installation of a thermoelectric generator with a heat storage, voltage converter, and a wireless sensor unit on an aircraft fuselage, as shown in figure 1(a). The heat storage unit contains water as the phase change material (PCM) to maintain a temperature difference along the thermoelectric generator. The thermoelectric system successfully operates the wireless sensor unit with a power consumption of 189 μW under the converted output voltage of 3.3 V. Zhu et al [55] demonstrate the thin-film based thermoelectric device integrated with solar energy source, as in figure 1(b). To enhance the concentration of illumination intensities on hot side of thermoelectric device, a Fresnel lens was incorporated into the system. With increasing illumination intensities, the harvested energy from thermoelectric device is also enhanced, in which output voltage represents light intensity acting as light sensor. This work demonstrates the thermoelectric device for harvesting solar energy which also acts as a light sensor.

For a broader application of thermoelectric systems, the demand for flexible TEG has grown incomparably. Conventional thermoelectric modules are in rigid forms with ceramic plates on top and bottom sides which limit their application to flat surfaces. To overcome such limitation, thermoelectric devices based on a flexible substrate using a printing method [56–62] or structural design with inorganic bulk thermoelectric materials [25, 26, 47, 63] have been researched. Thermoelectric materials used near room temperature are mainly Bi–Te based compounds, Bi$_2$Sb$_3$Te$_3$ for p-type and Bi$_2$Te$_3$–Se$_x$ for n-type, due to its high thermoelectric performance [64, 65]. Materials for both printing and inorganic bulk thermoelectric materials are based on Bi–Te compounds. For the material for printing, Bi–Te powders mixed with solvents are adopted for the manufacturing [58, 61]. Inorganic bulk thermoelectric materials used near room temperature are normally Bi–Te compounds in polycrystalline structure. Kim et al [66] demonstrate a flexible thermoelectric generator that powers a wireless sensor node while attached to a curved heat pipe, as in figure 2(a). For flexibility, the device consists of inorganic bulk thermoelectric materials embedded in a flexible polymer [25]. With the temperature of the heat pipe and ambient air set constant at 70 °C and 20 °C, respectively, in an experimental setup, a maximum power density of about 2.2 mW cm$^{-2}$ is harvested. The harvested power transferred to the power management IC is then boosted to 4.2 V with a voltage converter and down to 3.3 V for operation while the surplus power is used to charge a battery. WSNs integrated with TEG successfully collect and transfer
information on the temperature of ambient air and the circular pipe, CO₂ concentration, and open circuit voltage. Iezzi et al. [67] demonstrate a flexible thermoelectric generator integrated with wireless sensors that are manufactured from a printing process. To fabricate the thermoelectric device, bulk metallic materials, Ag and Ni, are used as the p- and n-type, respectively. The devices, as shown in figure 2(b), are installed vertically on a heat pipe in an experimental setup. The output voltage is then boosted with a commercial DC–DC converter (LTC 3108) to charge a super capacitor. The charged capacitor successfully operates WSNs to transmit information on temperature to the user.

Researches on operating WSNs by harvesting energy from thermoelectricity have been widely conducted in various environments as mentioned above. With the existence of a reliable heat source, WSNs powered with
thermoelectric devices can be applied. For efficient energy conversion, however, other components such as heat sink should also be considered. More details about heat sink will be addressed in section 3.3.

3. IoT system using body heat harvesting

3.1. Body heat harvesting

Recently, there has been a great amount of interest in health care and medical applications; thus, sensors capable of monitoring the patient’s health conditions for a long period of time are longed for. There are numerous kinds of medical sensors that measure the conditions of a patient. For example, blood pressure sensors,
electromyography sensors, electrocardiography (ECG) sensors, and SpO₂ pulse oximetry sensors are widely used to monitor patients with health issues. The most important requirement of the aforementioned medical sensors is a stable and continuous power supply. To supply sustainable power for medical sensors, thermoelectric devices capable of generating power by harvesting heat from a human body are used. The human body can be used as a heat source as it generates heat continuously though metabolism; however, to do so, it is important to understand the human thermoregulatory system. The thermoregulatory system of the human body controls its skin temperature and therefore certain parts of the body are more suitable to operate certain devices than the rest as shown in figure 3. However, the conventional TED is hard to adapt on to the human skin due to its rigidity. To make thermoelectric devices more applicable to the human skin, researches on flexible TEG are being actively conducted. Majority of flexible TEG for body heat harvesting are based on inorganic bulk thermoelectric materials instead of printed materials. Since thermal energy from a human body is so called the ‘low-grade heat’, it is hard to yield a sufficient amount of temperature difference in a film-type thermoelectric device due to its small thickness for flexibility. Kim et al [59] demonstrates the body heat harvesting using thin-film based flexible thermoelectric device while generating only an output power of 3 μW. Most researches recently published on flexible thermoelectric devices for body heat harvesting adopt inorganic bulk thermoelectric materials which have sufficient height to retain enough temperature difference.

Table 1 shows the experimental results of body heat harvesting using TEG. Researches referenced in table 1 have used inorganic bulk thermoelectric materials based on Bi-Te compounds. Suarez et al [69] use inorganic bulk BiTe compounds and EGaIn as the flexible metal liquid electrodes which are placed on both top and bottom sides of their FTED, as in figure 4(a). The liquid metal is encapsulated in polydimethylsiloxane (PDMS) to prevent leakage. The device was able to generate a voltage ranging from 1.47 to 2.96 mV and power from

| References | Number of TE couples | Output power density (μW cm⁻²) | Open circuit voltage (mV) | Device flexibility |
|------------|----------------------|--------------------------------|---------------------------|-------------------|
| Kim et al [25] | 72                  | 2.28                           | 21.2                      | Flexible          |
| Suarez et al [69] | 32                  | 0.37                           | 3.5                       | Flexible          |
| Park et al [26] | 15                  | 5.60                           | 8.8                       | Flexible          |
| Eom et al [68] | 20                  | 3.20                           | 6.6                       | Flexible          |
| Kim et al [59] | 11                  | 0.70                           | 2.9                       | Flexible          |
| Hyland et al [70] | 25                  | 4.60                           | 12.0                      | Rigid            |
| Wang et al [71] | 52                  | 0.50                           | 6.6                       | Flexible          |
| Kim et al [72] | 50                  | 13.00                          | 60.0                      | Flexible          |

Figure 3. Schematic of body heat powered E-skins by using thermoelectric generator and wireless sensor system [68]. Reprinted from [94]. Copyright 2019, with permission from Elsevier.
1.48 to 6.0 μW under varying air velocity conditions. Eom et al [63] demonstrate a bracelet-shaped thermoelectric device based on rigid inorganic bulk thermoelectric materials which has a hinge structure, so it can be structurally flexible as in figure 4(b). The bracelet-shaped thermoelectric device attains an output power ranging from 40 to 80 μW with open circuit voltage from 6.7 to 9.1 mV. Park et al [26] propose a mat-shaped flexible thermoelectric device. It is specialized to be applied to a curved surface. Cubic-shaped inorganic bulk thermoelectric materials are inserted into holders that can be connected to each other with a wire. Considering
that the radius of curvature of an adult human arm is more than 30 mm, the radius of curvature of the mat-
shaped FTED is less than 12 mm; thus, it is suitable for human body heat harvesting. The
flexible thermoelectric device harvests energy from body heat and was able to obtain an output power of 138.67 μW with an 8.8 mV open circuit voltage. Kim et al [25] demonstrate a flexible thermoelectric device in which inorganic bulk thermoelectric materials are embedded in a flexible polymer, as shown in figure 4(c). Body heat harvesting is conducted under various conditions: varying height of thermoelectric materials, fill factor, and air velocity, while the maximum output power and voltage are 1.46 mW and 38.24 mV, respectively.

As mentioned above, many studies on body heat harvesting using a flexible thermoelectric generator are reported and are still ongoing. Further applications on self-powered WSNs driven by body heat harvesting are being carried out widely. Thielen et al [73] propose an application of TEG on a human’s wrist integrated with a DC–DC converter as in figure 5(a). Two different types of TEG are demonstrated: μTEG which has a low thermal resistance with a high output voltage and mTEG which has a high thermal resistance with a low electrical resistance. Proposed TEGs show high output power densities, which range from 13 to 14 μW cm⁻², with a maximum of 24% converting efficiency. Magno et al [74] propose a multi-source harvesting circuit which consists of a solar harvester and a TEG for body heat harvesting. While harvesting an average power up to 550 μW by photovoltaic in indoor situations, the TEG harvests 98 μW with a 3 K temperature difference from a human body. The multi-source harvesting system successfully operates several devices such as a camera, microphone, accelerometer and temperature sensor. Myers et al [75] present a thermoelectric body heat generator integrated with components that transmit power management data and various sensors, as shown in

Figure 5. (a) A body heat powered wearable thermoelectric system and its conversion performance [73, 76, 77]. (b) Thermoelectric generating system operating sensors powered by body heat [73]. (a) Reprinted from [73], Copyright 2017, with permission from Elsevier. All rights reserved. (b) Reprinted from [75], Copyright 2017, with permission from Elsevier. All rights reserved.
The proposed system demonstrates a successful operation of sensors under varying temperature and humidity conditions while the subject is either running, walking or resting. Necessity for consideration of wet bulb temperature while body heat harvesting is also demonstrated. Wang et al [71] demonstrate the operation of a miniaturized accelerometer powered by body heat harvesting on a human’s wrist, as in figure 5(b). The proposed flexible TEG is made of inorganic bulk thermoelectric materials which are embedded in PDMS. It successfully generates an open circuit voltage of 6.6 mV from a human body under indoor conditions. To operate a miniaturized accelerometer which requires 2.4 μW of power with a 1.6 mV voltage, a DC–DC converter with an efficiency of 50% is adopted to boost the voltage up to 2.2 V. A demonstrated thermoelectric system successfully operates the miniaturized accelerometer powered from body heat, as in figure 6(a). Kim et al [72] represent a self-powered wearable ECG system using a DC–DC converter, as in figure 6(b). The system consists of a DC–DC converter, VDD shifter and an ECG module. The ECG sensor is fabricated on a flexible printed circuit board while the power is supplied through the flexible TEG using human body heat. The flexible TEG harvests 1 mW of power with 40–100 mV of open circuit voltage. To operate the ECG sensor, voltage is boosted up to 3.3 V using a commercial DC–DC converter (LTC3108) and dropped down to 1.0 V through a VDD shifter. Due to the existence of efficiency for voltage converting, 70 μW of power is supplied, in which it successfully operates the ECG sensor.
In designing the thermoelectric system, the thermal contact resistance between the thermoelectric device and the heat source or sink should also be considered. Especially when applied to a human body in which the temperature difference between the top and bottom side of thermoelectric device is relatively small compared to industry applications, the reduction of thermal contact resistance is crucial in achieving high power generation.

### 3.2. Human thermoregulatory model

For accurate prediction or analysis of body heat harvesting by a flexible TEG, understanding of the human thermoregulatory system must be preceded. The human body has an intricate built-in system to regulate its temperature to maintain a balance between metabolic heat production and heat loss to the environment. This balance between heat production and loss is important in maintaining a constant core temperature of the human body [78]. This thermoregulatory system is divided further into two parts consisting of active and passive systems [79, 80]. The active system directly controls the temperature of the body through means of sweating, shivering, vasoconstriction, and vasodilation [80]. This leads to the rise and fall of the skin temperatures to maintain a balance between heat production and heat loss. The passive system represents the geometry of the human body, metabolic heat production, and the thermal interaction of the human body with the environment (convection, radiation, and evaporation) [81]. Throughout the years, many models have been developed to simulate the thermoregulation of the human body. The thermoregulatory models can be divided into two major categories as in figure 7(a). The first simpler model is the two-node model. The key feature of the two-node model is the representation of the human body as cylinders (single-segment) consisting of its core and skin [82]. This simplification allows for a quick analysis of the human thermal system. The multi-node model is more complicated as it represents the human body as cylinders subdivided into usually the core, muscle, fat, and skin layers [78].

The most well-known two-node model was developed by Gagge in 1971 [82]. The human body in Gagge’s model is treated as two coaxial cylinders each representing the core and the skin. The metabolic heat generated from the core is transferred to the skin through conduction and blood flow. The boundary condition is set on the surface of the skin surface and given as evaporation, convection, and radiation heat losses. The active system here is modeled using vasodilation, vasoconstriction, and sweating functions.

The Stolwijk model is the basis of many multi-node thermoregulatory models [84]. The human body geometry consists of six segments (head, trunk, arms, hands, legs, and feet), each with four nodes (core, muscle,
fat, and skin), and one central blood pool. Each node exchanges heat with each other through conduction and with the blood pool through convection. The active system in Stolwijk’s model is divided into three parts. In first part, the thermoreceptors sense the hot or cold state. Then the second part sends this information to the third part which controls the action of the active system according to the information received to induce actions such as vasodilation and constriction [84]. This model was developed for NASA to simulate the thermoregulatory system of astronauts and is capable of predicting the skin temperature in low-activity conditions [85]. Another well-known multi-node thermoregulatory model is the Fiala model [79, 80, 86, 83]. The human body is constructed as 15 cylindrical or spherical segments each containing multiple layers of tissue accordingly (figure 7(b)). The skin layer in this model is divided into the inner and outer layer. The inner layer is responsible for blood perfusion while the outer layer is responsible for heat exchange with the environment through evaporation [86]. Penne’s so called bio-heat equation [87], is expressed in equation (1)

\[
\frac{k}{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + Q_m + c_v m_{bl}(T_{bl} - T) = \rho \frac{\partial T}{\partial t},
\]

where \(k\), \(\rho\) and \(c\) are the thermal conductivity, density and specific heat of each layer respectively. Also, \(Q_m\) is the metabolic heat generation and \(m_{bl}\) is the volumetric blood flow rate. Equation (1) was applied to each tissue layer with appropriate material properties of an average man. Heat is transferred between the tissue layers through conduction and at the surface of the skin through convection, radiation, and evaporation to the environment. The Fiala model also takes into account countercurrent heat exchange to simulate a more accurate arterial blood temperature [79, 86]. The active system was modeled based on a regression analysis of physiological responses from multiple subjects which resulted in a temperature-based system driven by the body core temperature and

Figure 8. (a) Analysis of finned heat sink with PCM [90]. (b) Schematic and performance of heat sink composed of copper metal foam and paraffin composites [91]. (c) Heat sink with a double layer microchannel using various fluids [92]. (a) Reprinted from [90], Copyright 2017, with permission from Elsevier. All rights reserved. (b) Reprinted from [91]. Copyright 2012, with permission from Elsevier. All rights reserved. (c) Reprinted from [92]. Copyright 2015, with permission from Elsevier. All rights reserved.
the mean skin temperature [80]. The Fiala model was later adapted by the UTCI-Fiala model which is the basis of the Universal Thermal Climate Index [86]. A simplified thermoregulatory model was proposed by Wijethunge et al [88] that focuses on the forearm segment. The forearm was the main focus of this model as the purpose was to provide a simplified model for designing wearable thermoelectric devices. The boundary conditions at the skin surface were given as convection, radiation, and evaporation heat fluxes. Assuming the body core temperature as constant, shivering was neglected as it occurs when the body core temperature is considerably low. In addition, this model used thermal resistance of the skin to express the temperature difference across the thermoelectric elements. This temperature difference was then used to calculate the voltage and in return the power generated by a TEG.

3.3. Heat sink for TEG

As widely known, the temperature difference across the length of a thermoelectric material is a dominant factor in determining the performance of a thermoelectric device. A larger temperature difference leads to a higher power output and thus, an appropriate heat sink is necessary to achieve this large temperature difference. In that point of view, integration of heat sinks with a thermoelectric device is critical in improving its performance but is very poorly investigated. In this section, some clever designs of heat sinks, not specifically designed for TEGs, but possible to be integrated with thermoelectric systems are demonstrated.

Among the various designs of heat sinks that can be integrated with thermoelectric devices, ones with PCMs have shown great promise in reducing the temperature of a heat source. PCMs are known to possess high latent heat and thus, such property has been researched widely for its potential use in heat sinks. The mechanism behind PCMs is utilizing its high latent heat when it changes phase from solid to liquid to absorb the heat from its heat source. To enhance the performance of the heat sink based on PCMs, researches to increase thermal conductivity have been widely conducted. Wang et al [89] investigate the effect of using a porous metal fiber sintered felt (PMFSF) to increase the thermal conductivity of PCMs. They use a high-power LED with a power consumption ranging from 1 to 5 W as the heat source and used red copper as the metal foam to prepare the paraffin/PMFSF composite. The thermal conductivity of the composite was enhanced from 0.2 W m⁻¹ K⁻¹ (pure paraffin) to 26.76 W m⁻¹ K⁻¹. Bayat et al [90] also attempt to increase the thermal conductivity of a PCM heat sink by adding a low percentage of nanoparticles. They only numerically simulate the effects of nanoparticles due to complexities in nanoparticle fabrication and were able to obtain enhanced thermal conductivities as shown in figure 8(a). Unlike their expectations, adding only 2% of nanoparticles shows the best performance and the performance gradually decreases with further addition of nanoparticles. Qu et al [91] also design a passive thermal management system by utilizing a metal foam saturated with PCM in a heat sink to reduce the temperature of a heat source. Similar to the work done by Wang et al [89], copper is used as the metal foam and compared to a pure PCM and pure copper basement, the foam-PCM composite was the most efficient at preventing the increase in temperature of the heat source (figure 8(b)). Despite all these efforts, the biggest problem of the PCM heat sink still stands even with an alteration- passive thermal management. Without doubt, as it changes phase, it can absorb more heat than in its solid form due to its high latent heat; however, when the PCM reaches its maximum heat capacity after some time, the surface temperature of the heat source starts to increase rapidly. Thus, thermally managing an electronic device with a PCM heat sink for a long period of time is not pragmatic and is only appropriate for a short duration of time.

Another well-known type of heat sinks is a system composed of micro-channels with a circulating fluid. First proposed by Tuckerman and Pease [93], a liquid-cooled heat-exchanger design by using fluid channels in microscopic dimensions allows the operation of circuits with power densities higher than 1000 W cm⁻². The idea behind micro-channels is to use numerous separate channels, rather than a single channel to flow over the surface of the heat source and to increase the surface area of the heat sink that the fluid makes contact with. Rajabifar [92] adds an additional channel on top of the bottom channel, ultimately designing a double layered counter-flow micro-channel with nanofluids and PCM slurries as the coolants as shown in figure 8(c). With different types of fluid employed in the upper and the lower channel, the heat flux absorbed by the heat sink is the greatest when the nanofluids and the PCM slurries are deployed in the upper and lower channel, respectively.

Different from heat sinks with PCMs or micro-channels mentioned above, not much research has been done on flexible heat sinks as their demand has been low. There have been several works [26, 72, 94] which adopt a flexible heat sink on a thermoelectric generator for body heat harvesting. Although the performance of body heat harvesting has been enhanced with the existence of a flexible heat sink, those research have aimed more on the flexible thermoelectric system rather than flexible heat sink. The demand for flexible heat sinks with sustainability and high performance is expected to be increased for broader applications.

3.4. DC–DC converter for power management

To operate an IoT system integrated with WSNs, management of the harvested energy is as important as energy harvesting. The management is mainly focused on the design of a DC–DC voltage converter which boosts up
harvested voltage, normally ranging from a few mV in body heat harvesting to several hundred mV-level in industry application, to a usable level for operating with high efficiency. Conventional DC–DC converters have a two-stage circuit [66], boost converter and a buck converter. Chen et al [95] demonstrate a one-stage DC–DC converter in which the input voltage is 100 mV and the output voltage ranges from 500 to 600 mV. Owing to the capacitive bootstrapping technique, the proposed DC–DC converter shows a maximum conversion efficiency of 76.4% over various loads ranging from 1 to 500 μW. Luo et al [96] demonstrate a power converter for a thermoelectric generator with low input voltage integrated with a self-start circuit. Once the chip self-starts at 210 mV, only 7 mV input voltage is required to continuously operate the main converter. The proposed power converter shows a maximum output power of 229 μW with 73.5% end-to-end efficiency. V et al [97] also demonstrate a voltage converter with a single-stage regulator. Since the proposed converter is aimed to be driven by human body heat, it possesses low input voltage ranging from 25 to 210 mV. The converting system shows maximum efficiency of 65% with a peak delivering power of 1.03 mW.

4. Conclusion

With the rapid increase in demand for smart devices, the market for IoT systems is also consequently growing. Concurrently, research on sustainable power supplies is being widely conducted. This paper explores the recent progress in TEG as a power supply for IoT systems integrated with WSNs. Although TEG are able to harvest enough energy, the output voltage is not enough to operate commercial or micro-fabricated sensors. In this paper, not only the energy harvesting by thermoelectricity but energy management using a DC–DC converter to boost the output voltage is also discussed. Considering the increase in application of TEG on a human body, an accurate analysis of the human thermoregulatory system is required. For further enhancement of thermoelectric systems, candidates for integrable heat sinks with TEG have been presented as well. Not forget to mention, thermoelectric systems for wearable applications also show the potential for commercialization with well-designed flexible TEG and power management systems.

Acknowledgments

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIP) (NRF-2015R1A5A1036133 & NRF-2018K1A3A1A20026439).

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