A thermoelectric generation system using waste heat recovery from petrochemical pipeline to power wireless sensor

Bo Li a,b, Xiaoliang Guo a,b, Tianyang Li a,b, and Yu-Tao Li a

*College of Information Science and Technology, Beijing University of Chemical Technology, Beijing, China; †School of Mechatronical Engineering, Beijing Institute of Technology, Beijing, China

ABSTRACT

Wireless monitoring sensor gradually replaces wired equipment for data support in petrochemical industry production. This paper presented a design of a thermoelectric generator (TEG) system-based petrochemical pipeline waste heat recovery for wireless sensor. The TEG is assembled using an easy-to-modify structure that can be mechanically adjusted to different pipelines. Besides, we designed a new zero-power, micro-vibration, and easy-to-install heat sink for TEG applied in high-temperature petrochemical pipelines. The proposed TEG prototype has been fabricated and tested. The experimental results show that the system proposed in this work can supply enough energy to sustain the operation of a wireless sensor node that measures petrochemical fluid temperature and pressure for precision industrial production applications. The minimum output power is 24.7 mW at the hot side of thermoelectric generation (TEG) temperature of 100 °C –190 °C. This work presents a promising, cost-effective new approach to the conversion of waste heat into electricity for self-powered sensor networks.

1. Introduction

Wireless sensor network technology has become increasingly popular as scientific and technological advancements have occurred in petrochemical industry production. One of the main problems yet to be solved is the finite power capacity of batteries in sensor nodes (Nurlan et al. 2021). The battery power supply is the main method for wireless monitoring sensors. Due to the limited power stored in the battery that needs to be replaced regularly, it not only increases the workload and cost in the monitoring process but also causes a certain amount of waste (Jin, Kwak, and Yoo 2020; Yao et al. 2022). The power required for wireless monitoring sensors has been reduced to a few microwatts thanks to advancements in power electronics technology (Agbossou et al. 2010). As a result, the use of a low-power hot spot power generation system for wireless monitoring sensors is becoming increasingly appealing.

A thermoelectric power generation is a form of energy conversion that converts thermal energy directly into electrical energy (Ioffe et al. 1959; Liu et al. 2015). It has been used in a wide range of applications, including automobile engines, internal combustion engines, portable equipment powered by body temperature, and personal thermal management equipment (Qiu and Hayden 2008). Over the last 30 years, there has been growing interest in applying this thermoelectric technology to improve the efficiency of waste heat recovery, using various heat sources such as geothermal energy, power plants, automobiles, and other industrial heat-generating process (Suzuki Ryosuke 2004; Tang et al. 2022).
In the case of TEG for waste heat recovery power generation, there have been many conceptual designs of a power conversion system which are potentially capable of obtaining application in this area. A dynamic analytical model for the TEG working on automotive exhaust waste heat recovery was developed by (Lan et al. 2018). The calculations were founded on the basics of the thermal conductance and electrical resistance to develop their model. Gao et al. (2012) explored various models of compact plate-fin heat exchanger designs to accommodate thermoelectric generators for heat recovery from high-temperature fuel cell stacks. Fernández-Yañez et al. (2018) studied the potential of energy recovery from the exhaust gases from diesel engines chimney by the means of TEG.

However, at present, the low conversion efficiencies of the materials used in TEGs hinder their popularization and utilization (Huang and Xu 2017). There are currently three major research directions in thermoelectric generation technology. The first is to investigate semiconductor materials with a high ZT value but low thermal conductivity and resistance to effectively improve semiconductor thermoelectric conversion rates (Karbaschi et al. 2020; Yatim et al. 2018). For instance, Li et al. (2020) deposited n-type Bi$_2$Te$_3$ nanocrystals on an SWCNT network to prepare a flexible TE hybrid using a magnetron sputtering technique. Over the investigated temperature range of 273 K–373 K, the material yields a TE figure of merit (ZT) value of 0.23. The second is to create higher-conversion-efficiency energy harvesting circuits and components. Wang et al. (2019) adopted the MPPT scheme, the ZCS scheme, and the optimal inductor current scheme. And the system can achieve a maximum efficiency of 75.2% at a temperature difference of 8 K and has better efficiency than the commercial chip BQ25504.

The third is to investigate the temperature difference between the two sides of the thermoelectric generation system, which has the greatest influence on thermoelectric generation output power. Traditional cooling methods are typically used with low efficiency or high power consumption, even without cooling, in the actual use of thermoelectric technology (Abramzon 2007). As a result, the output power of thermoelectric power generation technology is limited in the case of low-temperature difference. In general, the heat source in the petrochemical pipeline is more fixed and stable. However, the challenges that limit temperature difference direction research are the cooling of the cold side temperature and thermoelectric materials (Liu and Bai 2019; Wang et al. 2021). There are two modes of cooling for TEG: passive cooling and active cooling. Active cooling includes liquid cooling and air cooling, among others (Alghoul et al. 2018; Rutberg 2012). They can achieve an excellent cooling effect, but a certain amount of electrical energy is lost in the process, which makes the power generation device itself and its contradiction. Passive cooling is not as effective as active cooling, it has the advantages of low noise, micro-vibration, and low energy consumption (Date et al. 2015).

In this work, the design and fabrication of a waste heat recovery TEG system is addressed for the self-powered operation of a wireless sensor node. The proposed system extracts heat from the outer wall of the petrochemical pipeline and turns the heat into electricity to power the wireless sensor that is applied to the petrochemical pipelines. The focus is on the design of a heat sink, which is inexpensive zero-power, micro-vibration, and easy-to-install, which is adapted with an energy harvester circuit and a commercial TEG module.

The paper is organized as follows: Section 2 presents the design and fabrication of a waste heat recovery TEG prototype that can be easily assembled and adapted to different scenarios. Section 3 presents the measured performance and optimization of the heat sink we designed and the TEG prototype. Section 4 presents the result of experiment of heat sink and the discussion of the TEG’s capacity to power a wireless sensor node is demonstrated. Section 5 summarizes our results and concludes this paper.

2. Design of waste heat recovery TEG system

Figure 1 illustrates the TEG system-based petrochemical pipeline waste heat recovery for wireless sensor node concept. The system in this work is made up of three subsystems. It consists of a power
generation device made up of a high-performance TEG, a heat sink, an energy harvesting circuit module, and a wireless sensor node.

2.1. Thermoelectric generator

Thermoelectric generator is the main component of converting temperature difference into electricity is a thermoelectric generator. Figure 2(a) shows a typical integral thermoelectric power generation model. The Seebeck effect causes holes and electrons to move, resulting in an open-circuit voltage \( \Delta U = \alpha_{pn} \Delta T' \). Where \( \alpha_{pn} \) is the relative Seebeck constant of the thermoelectric material. \( \Delta T' \) is the temperature difference between the hot side \( (T_h') \) and cold side \( (T_c') \) of the TEG leg terminal. Figure 2(b) presents the thermal resistance network corresponding to the TEG system with a heat source temperature of \( T_h \) and a heat sink temperature of \( T_c \).

The semiconductor thermoelectric generator has an internal resistance \( R_{TEG} \), when a load is applied to the outside. The thermoelectric electromotive force produced by the Seebeck effect is applied to both the internal resistance \( R_{TEG} = R_c + R_h + R_i \). The external load resistance \( R_L \), \( R_c \), \( R_h \) and \( R_l \) are the thermal resistance of TEG cold side, hot side, and conduction-induced, respectively. As a result, without taking into account the voltage consumption in the transmission circuit process, the output voltage \( U \) of a thermoelectric generator with load resistance is

\[
U = \alpha_{pn} \Delta T' \frac{R_L}{R_L + R_{TEG}}
\]

The theoretical output power of the thermoelectric generator with load resistance is
\[ P = UI = \frac{\alpha_{pn}^2 \Delta T^2 R_L}{(R_L + R_{TEG})^2} \] (2)

The output power of thermoelectric generation can theoretically reach its maximum when the load resistance \( R_L \) of the external connection equals the internal resistance \( R_{TEG} \) of the power generation original itself. And the maximum is

\[ P_{max} = \frac{(\alpha_{pn} \Delta T)^2}{4R_{TEG}} \] (3)

2.2. Analysis of heat transfer processes of TEG

In the whole process of temperature difference power generation, due to the existence of a certain internal resistance of the semiconductor material itself, a certain amount of Joule heat is generated during the working process. When the heat exchange between the outer wall of the semiconductor and the outside is ignored, the heat absorbed at the hot end \( Q_h \) and the heat released at the cold end \( Q_c \) are obtained according to the theory of non-equilibrium thermodynamics and Fourier’s law as

\[ Q_h = \alpha_{pn} IT_h + \lambda \Delta T - 0.5I^2 R_{TEG} \] (4)

\[ Q_c = \alpha_{pn} IT_c + \lambda \Delta T + 0.5I^2 R_{TEG} \] (5)

where \( \lambda \) is the total thermal conductivity of the entire semiconductor material, \( I \) is the output current of the temperature difference generation unit.

2.3. Heat sink design and principle

It is discovered through comparison that various cooling methods have advantages and disadvantages, and the results are frequently different when the standards are different. From the standpoint of practical application, taking into account the use of the petrochemical pipeline wall as the heat source for thermoelectric power generation, it is required that large noise and vibration be avoided during the cooling process, and the temperature difference between the cold and hot sides be maximized. The cost, cooling effect, and working environment of thermoelectric power generation systems are all thoroughly considered. The main research goal of thermoelectric generation in this work is to obtain greater temperature differences while using the least amount of power. In this work, a passive cooling method of liquid phase change cooling is applied to a thermoelectric power generation system.

To obtain greater temperature differences while using the least amount of power, we apply a passive heat dissipation method based on liquid phase change. **Figure 3** shows the heat sink designed in this work for the cooling of TEG. This heat sink can effectively avoid vibration and noise while ensuring heat dissipation efficiency.

This heat sink consists of four parts: coolant, cooling chamber, condensing coil, and expansion body. The cooling chamber is connected to the cold end of the TEG through high-temperature heat transfer glue. A certain volume of coolant is added to the cooling chamber (not filling the entire chamber) as the main cooling medium. The top of the cooling chamber is connected to the condensing coil through seal welding, which is used to naturally condense and return the phase change coolant. The spiral coil can increase the heat dissipation area in a limited space and improve the heat dissipation efficiency. Due to the internal circulation of the spiral coil, the cooling medium can flow more evenly through the entire coil, thus achieving better heat dissipation. The top of the condensing coil is connected by sealing glue to an expansion body used to balance the internal pressure of the heat sink.

Operating principle of the heat sink:
(1) The cooling chamber receives heat from the cold end of the TEG by heat conduction or heat radiation and performs the first cooling of the TEG by heat exchange with air.

(2) The coolant absorbs part of the heat through direct contact with the cooling chamber. As the temperature rises, the coolant gradually undergoes a phase change and evaporates into a gas. A portion of the gas comes into direct contact with the cooling chamber and condenses on the inner wall of the chamber before flowing back into the coolant again. Another part of the gas enters the condensing coil through the hole at the top of the cooling chamber, and again condenses into liquid with the inner wall of the coil after heat exchange and flows back to the cooling chamber along the pipe. The heat generated by the gas phase change occurs within the wall of the tube and air heat is exchanged to form a secondary cooling.

(3) As the air pressure inside the heat sink gradually becomes larger throughout the cooling process, the expansion body at the top of the condensing coil begins to expand to balance the air pressure. The gas can condense again in the expansion body and flow back into the coil.

2.4. Energy harvesting circuit

The energy harvesting circuit consists of DC–DC converter, energy storage, and energy management. The DC–DC converter is a critical component in the circuit design of thermoelectric power generation modules. It can maintain a constant output voltage when the input voltage varies or the load changes, preventing damage to electrical equipment or the charging module. In this work, we used an energy management circuit-based LTC3108 DC–DC converter as shown in Figures 4(a–c). The LTC3108 from ADI is a highly integrated, low-power DC–DC converter that is ideal for harvesting the power generated by TEG. The step-up topology operates from input voltages as low as 20 mV. The power management unit is responsible for adjusting the voltage of wireless sensor network nodes and transmitting extra output energy to lithium batteries.

The CN3052A chip as shown in Figure 4(b) used in this work is a charging chip capable of charging monitoring equipment using rechargeable lithium batteries as the primary source of power supply with a constant current or constant voltage.

The maximum power consumption of the energy harvesting system ranges between 1.11 mW and 3.34 mW.
2.5. Wireless monitoring sensor node

The IT380 wireless monitoring sensor we used is designed specifically for equipment with dispersed on-site measurement points and complicated wiring. It can acquire a single-channel vibration signal and a temperature signal and wirelessly transmit the collected data onsite.

There is a consumption of $0.3 \mu A$ during sleep (standby) state and of 5–13 $mA$ during signal transmission. An average current consumption of 0.6 $mA$ (with the transmitter activating every 1 min) is achieved with this prototype. To guarantee the continuity of the sensor power supply, we choose a lithium battery with a working voltage of 3.7 $V$ and a charging voltage of 4.2 $V$ as backup power.

3. Experiment

A prototype of the waste heat recovery thermoelectric generator was fabricated and its performance characterized in the field. To make a greater temperature difference between the two sides of the TEG, we have conducted experiments to optimize the parameters of the designed heat sink.

3.1. Experimental setup

The performance parameters of the TEG used in the device designed in this paper are listed in Table 1. The TEG is installed on the hot side of the heater (model HP550 - S) which is used to simulate the wall of petrochemical pipelines. Figure 5 shows the overall thermoelectric power generation experimental system.

| Model       | Thermocouple logarithm | Internal resistance ($\Omega$) | Load current (A) | Open Circuit Voltage (V) | Size (mm) |
|-------------|-------------------------|--------------------------------|-----------------|--------------------------|-----------|
| TEC1–24106  | 241                     | 4                              | 1.7             | 10.5                     | 55*55*3.6 |

Figure 4. Energy harvester. (a) and (c) DC-DC converter and Power management section, (b) Energy storage module.
All experiments were done indoors under windless conditions. The ambient temperature to complete the experiment is 23–25°C, and the ambient air velocity is 0.1–0.15 m/s.

3.2. Optimization of the performance of heat sink

To verify the effect of heat sink properties on cooling performance, we changed several aspects of heat sink material, coolant type, coolant volume, and structural parameters of the coils for experiments. The heat transfer capacity of the heat sink is directly affected by the material used to make it. Metal materials with high thermal conductivity include iron, copper, stainless steel, and aluminum alloy, as well as for nonmetallic materials such as ceramics, silicon, and Si₃N₄. The heat sink of a metal material is chosen based on the thermal conductivity λ shown in Table 2. Taking current processing technology and material properties into account, it is necessary to select an aluminum alloy material with sufficient strength and good thermal conductivity. We choose aluminum alloy 6063 as the main material for the heat sink after comparing the yield strength of several materials with high thermal conductivity.

To verify the effect of heat sink properties on cooling performance applied on TEG, heat sink we design was glued on the TEG cold side, while its hot side was placed onto the heated surface of the constant temperature. The generated voltage was recorded by the oscilloscope. Table 3 shows the open-circuit voltage of TEG as some parameters of heat sink are changed. The coil diameter (Dc), spiral diameter (Ds), number of spirals (Nc), volume of coolant, and volume were discovered to have a linear relationship with

| Type of Metal       | λ (W/(m·K)) | Type of Aluminum alloy | λ (W/(m·K)) |
|---------------------|-------------|------------------------|-------------|
| Copper              | 401         | 1050                   | 210         |
| Aluminum            | 237         | 1060                   | 234         |
| Iron                | 80          | 1070                   | 226         |
| Steel               | 54          | 5050                   | 101         |
| Stainless steel     | 17          | 6010                   | 202         |
| Brass               | 109         | 6061                   | 166         |
| Bronze              | 26          | 6063                   | 209         |

Figure 5. Thermoelectric power generation experimental setup.
Table 3. Open-circuit voltage of TEG under some process parameters of the heat sink (Heating temperature $T_{\text{heat}} = 150^\circ C$, Heat time $t_h = 60$ min).

| No. | Material       | $D_c$ (mm) | $D_h$ (mm) | $N_c$ | $V_c$ (mm$^3$) | $U_o$ (V) |
|-----|----------------|------------|------------|-------|----------------|-----------|
| 1   | nylon          | 6          | 60         | 8     | 280800         | 1.77      |
| 2   | Aluminum alloy | 6          | 60         | 8     | 280800         | 2.05      |
| 3   | Aluminum alloy | 6          | 60         | 6     | 280800         | 2.01      |
| 4   | Aluminum alloy | 6          | 60         | 10    | 280800         | 2.1       |
| 5   | Aluminum alloy | 6          | 80         | 8     | 280800         | 2.14      |
| 6   | Aluminum alloy | 6          | 60         | 8     | 210600         | 1.58      |
| 7   | Aluminum alloy | 6          | 60         | 8     | 140400         | 1.35      |
| 8   | Aluminum alloy | 3          | 60         | 8     | 280800         | 1.69      |
| 9   | Aluminum alloy | 4          | 60         | 8     | 280800         | 1.77      |
| 10  | Aluminum alloy | 8          | 60         | 8     | 280800         | 1.91      |

Figure 6. Performance of heat sink. (a) the open-circuit voltage of TEG based on different heat sinks, (b) the temperature was measured both at the hot side of the TEG, and at the heat sink in the cold side of TEG. (Heating time $t_h = 60$ min).

cooling performance. For the consistency of the experimental results, we choose the No.5 heat sink for TEG.

To characterize the performance of the heat sink, TEG systems with different coolants, aluminum heat sink and without heat sink, were used to conduct thermoelectric power generation experiments at heating temperatures ranging from 100°C to 190°C after the structural parameters of the heat sink were optimized. The open-circuit voltage of TEG changes after 1 h of heating, as shown in Figure 6(a). When the hot side temperature of TEG rises 100°C, the heat sink with ethanol outperforms the heat sink with water in terms of cooling. The heat sink with water performs better than the former when the heating temperature reaches 145–155°C. This is because the ethanol gasification rate is too fast at these temperatures, and the cooling liquid after liquefaction in the secondary heat sink and expansion body cannot be refluxed in time. The experiment concludes that when the heating temperature is lower, the effect of using a cooling liquid with a lower boiling point is better and vice versa.

The temperature was measured both at the hot side of the TEG and at the heat sink in the cold side of TEG. The ambient temperature in a shaded region next to the prototype was also measured. The measured temperatures as heat temperature are shown in Figure 6(b).

4. Results and discussion

In the experiment, we find that with the increase in the heating temperature of the hot side of TEG, the open-circuit voltage of the TEG gradually increased under same heat sink. It proves that the system we designed will perform better at higher temperatures. The experimental results show that the heat sink property parameters have a large impact on the cooling performance, which in turn directly affects the
output voltage of the system. As shown in Figure 6, compared to conventional heat sinks, our designed heat sinks have better performance in high-temperature operation.

A 10 Ω resistance is connected to the TEG output side to measure the power of the system (while ignoring the power of the circuit loss). The measured output voltage is 0.497 V, and the actual output power is approximately 24.7 mW (The heating temperature is 100°C). When the heating temperature is 100°C–150°C, the output voltage and output power of the thermoelectric generation system are shown in Figure 7(a).

To demonstrate the effect of thermoelectric power generation more clearly, we applied this TEG to power the LEDs. The experimental results are shown in Figure 7(b). LED lights can work normally and continuously.

5. Conclusions

In this work, a new thermoelectric generator system-based petrochemical pipeline waste heat recovery for wireless sensor was presented. The prototype has been fabricated and experimentally characterized. It was observed that the waste heat recovery TEG was capable of delivering up to a maximum of over 24.7 mW, which permitted the autonomous operation of the wireless sensor system. Experimental results demonstrate that the TEG generates enough power to sustain the operation of a wireless sensor node for industrial field condition monitoring. Therefore, the proposed TEG architecture is conducive to the implementation of a low-cost wireless sensor system.

Acknowledgements

This work was supported by the National Natural Science Foundation (61904010), the Startup fund of Beijing Institute of Technology, the Grant of State Key Lab of Space Medicine Fundamentals and Application (SMFA17B02 and SMFA20C01).

Disclosure statement

The authors declare that they have no relevant financial or non-financial competing interests that could have appeared to influence the work reported in this paper.
**Notes on contributors**

**Bo Li** received the B.S. degree in automation in 2021 from the Beijing University of Chemical Technology, China, where he is currently working toward the M.S. degree in control science and engineering. His research interests include embedded system and semiconductor energy conversion.

**Xiaoliang Guo** received the B.S. degree in measurement and control technology and instruments from the Harbin Institute of Technology, Harbin, China, in 2011 and the Ph.D. degree from Tsinghua University, China, in 2009, in instrument science and technology. He was working at the School of Information of Beijing University of Chemical Technology as an Associate Professor from March 2018 to December 2021. He is currently with the School of Mechatronical Engineering, Beijing Institute of Technology, as an Associate Professor. His research interests include micro and nano sensors, advanced microfluidic chips with biological instruments and smart wearable sensors.

**Tianyang Li** received the B.S. degree in automation in 2022 from the Beijing University of Chemical Technology, Beijing, China, where he is currently working toward the M.S. degree in control science and engineering. His research interests include semiconductor energy conversion.

**Yu-Tao Li** graduated from the School of Optics and Electronic Information, Huazhong University of Science and Technology with a B.S. degree in 2015, and from the Department of Microelectronics and Nanoelectronics, Tsinghua University with a Ph.D. degree in Engineering in 2020. He is on a visiting research trip to Lawrence Berkeley National Laboratory, USA, from November 2018 to May 2019 to work on chalcogenide based optoelectronic devices. He is currently with the College of Information Science and Technology, Beijing University of Chemical Technology, as an Associate Professor. His research interests include Optoelectronic devices, nano-sensors and artificial intelligence systems.

**ORCID**

Bo Li [http://orcid.org/0000-0001-5094-9300](http://orcid.org/0000-0001-5094-9300)
Xiaoliang Guo [http://orcid.org/0000-0002-2413-341X](http://orcid.org/0000-0002-2413-341X)
Tianyang Li [http://orcid.org/0000-0003-3064-1979](http://orcid.org/0000-0003-3064-1979)
Yu-Tao Li [http://orcid.org/0000-0002-0665-0683](http://orcid.org/0000-0002-0665-0683)

**References**

Abramzon, B. 2007. Numerical optimization of the thermoelectric cooling devices. *Journal of Electronic Packaging* 129 (3):339–347. doi:10.1115/1.2753959.

Agbossou, A., Q. Zhang, G. Sebald, and D. Guyomar. 2010. Solar micro-energy harvesting based on thermoelectric and latent heat effects. Part i: Theoretical analysis. *Sensors and Actuators A: Physical* 163 (1):277–83. doi:10.1016/j.sna.2010.06.026.

Alghoul, M., S. Shahahmadi, B. Yeganeh, N. Asim, A. Elbreki, K. Sopian, S. K. Tiong, and N. Amin. 2018. A review of thermoelectric power generation systems: Roles of existing test rigs/prototypes and their associated cooling units on output performance. *Energy Conversion and Management* 174:138–56. doi:10.1016/j.enconman.2018.08.019.

Date, A., A. Date, C. Dixon, R. Singh, and A. Akbarzadeh. 2015. Theoretical and experimental estimation of limiting input heat flux for thermoelectric power generators with passive cooling. *Solar Energy* 111:201–17. doi:10.1016/j.solener.2014.10.043.

Fernández-Yañez, P., O. Armas, A. Capetillo, and S. Martínez-Martínez. 2018. Thermal analysis of a thermoelectric generator for light duty diesel engines. *Applied Energy* 226:690–702. doi:10.1016/j.apenergy.2018.05.114.

Gao, X., S. J. Andreassen, M. Chen, and S. K. Kaer. 2012. Numerical model of a thermoelectric generator with compact plate-fin heat exchanger for high temperature PEM fuel cell exhaust heat recovery. *International Journal of Hydrogen Energy* 37 (10):8490e8. doi:10.1016/j.ijhydene.2012.03.009.

Huang, S., and X. Xu. 2017. A regenerative concept for thermoelectric power generation. *Applied Energy* 185:119–25. doi:10.1016/j.apenergy.2016.10.078.

Ioffe, A. F., L. Stil׳bans, E. Iordanishvili, T. Stavitskaya, A. Gelbstuch, and G. Vineyard. 1959. Semiconductor thermoelements and thermoelectric cooling. *Physics Today* 12 (5):42. doi:10.1063/1.3060810.

Jin, Y., K. S. Kwak, and S.-J. Yoo. 2020. A novel energy supply strategy for stable sensor data delivery in wireless sensor networks. *IEEE Systems Journal* 14 (3):3418–29. doi:10.1109/JSYST.2019.2963695.
Karbaschi, H., N. Nouri, M. Rezaei, and G. Rashedi. 2020. Thermoelectric power generation efficiency of zigzag monolayer nanoribbon of bismuth. Nanotechnology 31 (37):375403. doi:10.1088/1361-6528/ab946f.

Lan, S., Z. Yang, R. Chen, and R. Stobart. 2018. A dynamic model for thermoelectric generator applied to vehicle waste heat recovery. Appl Energy 210:327–38. doi:10.1016/j.apenergy.2017.11.004.

Li, Y., J. Qiao, Y. Zhao, Q. Lan, P. Mao, J. Qiu, K. Tai, C. Liu, and H. Cheng. 2020. A flexible thermoelectric device based on a bi2te3-carbon nanotube hybrid. Journal of Materials Science and Technology 58:80–85. doi:10.1016/j.jmat.2019.04.004.

Rutberg, M. J. 2012. Modeling water use at thermoelectric power plants. Ph.D. thesis. Massachusetts Institute of Technology.

Suzuki Ryosuke, O. 2004. Mathematic simulation on power generation by roll cake type of thermoelectric double cylinders. Journal of Power Sources 133 (2):277–85. doi:10.1016/j.jpowsour.2004.02.014.

Tang, L.-S., Y.-C. Zhou, L. Zhou, J. Yang, L. Bai, R.-Y. Bao, Z.-Y. Liu, M. B. Yang, and W. Yang. 2022. Double-layered and shape-stabilized phase change materials with enhanced thermal conduction and reversible thermochromism for solar thermoelectric power generation. Chemical Engineering Journal 340430:132773. doi:10.1016/j.cej.2021.132773.

Wang, K., M. Guan, F. Chen, and W. H. Liao. 2019. A low-power thermoelectric energy harvesting system for high internal resistance thermoelectric generators. Journal of Electronic Materials 48:5375–89. doi:10.1007/s11664-019-06925-0.

Wang, N., J.-N. Zhang, Z.-Y. Liu, C. Ding, G.-R. Sui, H.-Z. Jia, and X.-M. Gao. 2021. An enhanced thermoelectric collaborative cooling system with thermoelectric generator serving as a supplementary power source. IEEE Transactions on Electron Devices 68 (4):1847–54. doi:10.1109/TED.2021.3059183.

Yao, B., H. Zhu, Y. Ding, C. Luo, T. Chen, J. Zhou, Y. Chen, and P. Lin. 2022. Thermal management of electronics and thermoelectric power generation from waste heat enabled by flexible kevlar@ sic thermal conductive materials with liquid-crystalline orientation. Energy Conversion and Management 251:114957. doi:10.1016/j.enconman.2021.114957.

Yatim, N. M., N. Z. I. M. Sallehin, S. Suhaimei, and M. A. Hashim. 2018. A review of zt measurement for bulk thermoelectric material. In AIP Conference Proceedings, Melaka, Malaysia, Vol. 1972, 030002. AIP Publishing LLC.