Comparative Evaluation of Thermoelectric Energy Conversion Systems for Heat Recovery With and Without a Water-Cooling Thermal Energy Adjustment Structure

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ABSTRACT
The stable exchange of energy and the effective conduction of heat are particularly critical to ensuring the stable operation of thermoelectric components in entire thermoelectric conversion processes. Poor heat exchange and conduction will cause thermal energy in a thermoelectric system to accumulate, leading to the consequence of burning the energy conversion modules. To solve these problems, a thermoelectric energy conversion system equipped with a water-cooling thermal energy adjustment structure settled on the surface of the heat source was proposed. The working temperature of the heat source, the output voltage, current, and power of the thermoelectric system with and without the structure were obtained and compared. Through comparative analysis, benefiting from the above structure, the temperature fluctuation of the heat sink surface of the heat source was found to drop from 10.36 K to 1.18 K, and the maximum output of the system increased from 255 to 290 mV through the process of input voltage from 1 to 6 V. Furthermore, in the process of gradually increasing the load from 0 to 180 ohms, the system achieves an increased output of 53.8 mV, 1.81 mA and 52.1 mV, 1.83 mA when the input voltage was 4 and 5 V, respectively. In conclusion, the application and design of the above structure obviously promotes the stability and output capacity during thermoelectric energy conversion. The combination of the water-cooling thermal energy adjustment structure with pulse-width modulation (PWM) or maximum power point tracking (MPPT) theory is worth further study.

INDEX TERMS Energy conversion, heat recovery, thermoelectric system, water-cooling.

I. INTRODUCTION
As a critical energy conversion method for directly converting heat energy into electric energy, thermoelectric power generation technology has been widely applied in solar energy harvesting [1], [2], aerospace energy supply [3], [4], industrial energy recovery [5]–[7], and other thermoelectric conversion processes. Based on its advantages, such as having no moving parts, no noise, and being clean and healthy, thermoelectric power generation technology has good application value at a low cost [8]. The thermoelectric power generation module, known as the TEG module, is the key component in thermoelectric power generation systems. The thermoelectric power generation application for heat recovery mainly consists of two aspects.

The first situation is when the TEG module is directly in contact with the heat source and absorbs heat energy from the heat source and converts the output into electrical energy. Kim, T. Y. et al. exposed the hot side of TEG module directly to the hot exhaust gas served by a diesel engine, achieving a 43-watt power and 2.0 percent energy conversion efficiency [9]. Zhao, Y. et al. chose wet flue gas as the heat source and performed thermoelectric energy conversion through direct contact between the TEG and wet flue gas, proving that the maximum output power can also be obtained when increasing the humidity of the flue gas and reducing
the heat exchange area [10]. Huang, B. J. et al. directly fit the hot surface of the TEG to the cartridge heater, realizing the efficient output of the power generation piece through the heat dissipation of the loop heat pipe [11]. Teffah, K. et al. directly converted the waste heat into electrical energy through direct contact between the TEG module and the waste heat generated by the thermoelectric cooling (TEC) module; this achieved the effective reuse of waste heat [12]. By bonding the hot side of the TEG to the photovoltaic material that generates high temperatures under light, Marandi, O. F. et al. achieved a high-efficiency energy conversion output of the PV-TEG system [13].

However, since the temperature of the heat source is usually difficult to manually control, a heat source with an excessively high temperature is a huge obstacle in the stable operation of the TEG module. When the temperature is higher than the suitable working temperature of the TEG module operating for a long time, the TEG module is likely to be in danger of being destroyed. Based on the above reasons, the second TEG module application method has been applied.

The second situation is when the TEG module is in contact with the heat source through the heat-transfer medium and absorbs heat energy from the heat-transfer medium and converts the heat energy into electrical energy. Pure copper blocks were used by Zhang, Z. et al. in thermoelectric energy conversion systems by virtue of their good heat-transfer characteristics in the heat-transfer medium, thereby achieving high-performance outputs in terms of thermoelectric energy conversion output [14]–[16]. Tang, S. M. et al. used thermally conductive copper blocks to transfer the heat generated by heat pipes to the hot end of the TEG and obtained an output power of 183.2 watts and an output voltage of 42.2 V [17]. Luo, X. et al. used micro-channel heat pipes to transfer the heat energy generated by the concentrated light to the hot end of the TEG and managed the energy output of the thermoelectric energy conversion system using phase change materials [18]. Zhang, Y. et al. used a selective absorbing coat to absorb light to generate heat and aluminum plates to transfer heat to the hot end of the TEG, achieving a stable thermoelectric energy output of 381.03 mV [19]. Lan, S. et al. transferred the heat end of the TEG and the heat side of the counterflow heat exchangers through the heat-transfer aluminum plate to recover the waste heat energy of a car engine [20]. Mirhosseini, M. et al. developed an efficient thermoelectric waste heat recovery and utilization system by using an arc-shaped absorber as the energy transfer medium between the power generation chip and cement rotary kiln [21].

The appearance of the heat-transfer medium ensures the stable output of heat energy from the heat source, thus avoiding the risk of the TEG module being burned out by an excessively high-temperature heat source. However, the large amount of thermal energy lost in the transmission of heat energy in the heat-transfer medium is a problem. Therefore, in the process of the TEG module working through the heat-transfer medium, further recovery and reuse of the heat energy lost by the heat-transfer medium is of great significance to improvements in the energy utilization of the entire thermoelectric energy conversion system.

In this paper, a thermoelectric energy conversion system equipped with a thermal energy adjustment structure settled on the end surface of the heat source is proposed. Benefiting from the thermal energy adjustment structure, the system effectively removes excess heat energy from the TEG energy conversion module during energy conversion to achieve the purpose of protecting the system from burning down the TEG energy conversion module due to excessively high temperatures.

This design makes up for the shortcomings of the first situation. Furthermore, the excess heat energy transferred by the thermal energy adjustment structure through the heat-transfer medium can be added back to the heat source, thereby reducing the energy loss caused by the heat-transfer medium during the energy transfer process. At this point, this design makes up for the shortcomings of the second situation.

Moreover, based on this thermal energy adjustment structure, the temperature of both ends of the TEC heat source and TEG energy absorption module during the thermoelectric energy conversion is extremely stable, which greatly improves the continuous working ability and stable output ability of the thermoelectric energy conversion system. To better compare and analyze the benefits of the above system, two structural designs with and without the water-cooling thermal energy adjustment structure were experimentally simultaneously studied. The results of this study demonstrate the effectiveness and practicability of removing excess heat energy from the TEG energy conversion module and recovering the lost heat energy from the heat-transfer medium by using the water-cooling thermal energy adjustment structure, which has significant advantages for improving the energy utilization rate of the thermoelectric energy conversion system.

II. MATERIALS AND METHOD

As shown in Figs. 1 and 2, the thermoelectric power generation system for waste heat recovery using a water-cooling thermal energy adjustment structure consists of following parts: the TEC heat source driven by the direct current known as DC power supply, the thermal energy absorption (TEG) module, and a water-cooling thermal energy adjustment structure composed of water-cooling components and the heat-transfer medium.

When the DC power supply powers the heat source, the temperature of the heat source gradually rises. At this time, the high temperature allows the TEG module to work. Under the high temperature, the TEG module converts thermal energy into electrical energy through the Seebeck effect and outputs it to the low-power electrical load, such as low-power sensors or electronic chips. When the above process continues for a certain period of time, the heat generated by the heat source gradually exceeds the work required by the TEG module, so the excess heat will have a negative impact on the entire thermoelectric conversion process. In this
case, the thermal energy quickly diffuses from the hot end to the cold end of the TEG module, the temperature difference between the two ends of the TEG module decreases rapidly, and eventually the TEG module fails to work.

To prevent the occurrence of the above phenomenon, ideally, the excess heat energy is dissipated through a specific structure. In this study, a specific structure called the water-cooling thermal energy adjustment structure was designed. The water-cooling thermal energy adjustment structure is attached to the cold side of the TEG module and the heat-absorbing side of heat source. When the thermal energy quickly diffuses from the hot end to the cold end of the TEG, the water-cooling thermal energy adjustment structure begins to work. Then, the excess heat is quickly collected and transferred by the heat-transfer medium in the water-cooling thermal energy adjustment structure. Here, the excess heat is not wasted but transferred back to the heat source through the heat-transfer medium in the water-cooling thermal energy adjustment structure again as part of the energy inside the heat source. As a result, the TEG module resumes normal functioning.

For the purpose of meeting the requirements of the above process, the heat source must be able to replenish energy while releasing heat. The TEC module was selected as the heat source. When the direct current is connected, the TEC module can generate a large amount of heat energy on the hot end while the TEC module can absorb the heat energy on the cold end and reduce the temperature of the cold end. Therefore, when the excess heat is transferred back to the cold end of the TEC module, it can be directly absorbed and become the part of the thermal energy TEC module supplied to the TEG module.

To further study the influence of the water-cooling thermal energy adjustment structure on the output characteristics of the thermoelectric conversion system, a comparative experiment was conducted by setting an experimental group with a water-cooling thermal energy adjustment structure and a control group without the water-cooling thermal energy adjustment structure. The experiment was carried out in two steps. The first step was to test the effect of the water-cooling thermal energy adjustment structure on the output characteristics under no-load conditions. In the second test, under the condition of gradual load, the research focused on the application of the water-cooling thermal energy adjustment structure to the improvement of the system output performance and system energy utilization.

Specifically, the system with the water-cooling thermal energy adjustment structure and the system without the structure were connected in parallel between the positive and negative poles of the DC power supply in the case of selecting the same heat source to ensure that the DC power supply provides the same power supply for the above two systems. The structure of the system with the water-cooling thermal energy adjustment structure is shown in Figs. 1 and 2 while the system without the structure was identical to the former except that there was no water-cooling thermal energy adjustment structure placed on the heat-absorbing side of the TEC module’s heat source.

### III. THEORETICAL MODEL

#### A. ENERGY BALANCE OF TEG

The heat energy generated by the heat source is accepted by the hot side of the heat-energy absorbing TEG module in the form of heat flow. According to [12] and [16], the accepted heat energy $Q_{HG}$ can be expressed as

$$Q_{HG} = Q_{HC} = Q_{DC} \times (1 + COP)$$

(1)

$$Q_{HG} = \alpha_{TEG}I_{TEG}T_{HG} + K_{TEG}\Delta T_{TEG} - \frac{1}{2}R_{TEG}I_{TEG}^2$$

(2)

where $Q_{HC}$ is the energy produced by the TEC heat source driven by the DC power supply at the hot side of TEC module, $Q_{DC}$ is the energy supplied by the DC power supply, and $COP$ is the coefficient of performance of the TEC heat source. $\alpha_{TEG}$ is the Seebeck coefficient of the TEG known as TEG, $K_{TEG}$ is the thermal conductivity of the TEG module. $I_{TEG}$ and $R_{TEG}$ are the output current and inner resistance of the TEG module, respectively. $T_{HG}$ is the hot-side temperature.
of the TEG module, \( \Delta T_{TEG} \) is the temperature difference between hot and cold side of the TEG module. The energy released at the cold side of TEG module \( Q_{CG} \) can be calculated as
\[
Q_{CG} = \frac{S_{TEG}N_uK_{medium}(T_{CG} - T_{medium})}{d_{channel\_medium}} \quad (3)
\]
\[
Q_{CG} = \alpha_{TEG}I_{TEG}T_{CG} + K_{TEC}\Delta T_{TEG} + \frac{1}{2}R_{TEG}I_{TEG}^2 \quad (4)
\]
where \( S_{TEG} \) is the energy transfer surface area of TEG module, \( N_u \) is the ratio of convective heat to conductive heat across the boundary during fluid heat-transfer, known as Nusselt number, \( K_{medium} \) is the thermal conductivity of the heat-transfer medium in the water-cooling thermal energy adjustment structure, \( T_{CG} \) is the cold-side temperature of the TEG module, \( T_{medium} \) is the temperature of the heat-transfer medium in the water-cooling thermal energy adjustment structure, and \( d_{channel\_medium} \) is the diameter of the heat-transfer medium channel. The output power of thermoelectric power generation module \( P_{OUT} \) can be acquired as follows:
\[
P_{OUT} = I_{TEG}[\alpha_{TEG}(T_{HG} - T_{CG}) - I_{TEG}R_{TEG}] \quad (5)
\]
\[
P_{OUT} = Q_{DC} \times (1 + COP) - \frac{S_{TEG}N_uK_{medium}(T_{CG} - T_{medium})}{d_{channel\_medium}} \quad (6)
\]

### B. ENERGY BALANCE OF TEC

According to [16], the energy produced by the TEC heat source driven by the DC power supply at the hot side of the TEC module \( Q_{HC} \) and absorbed by the TEC in its cold side and the heat-absorbing side \( Q_{CC} \) can be acquired as
\[
Q_{HC} = I_{TEC}\alpha_{TEC}T_{HC} + \frac{1}{2}R_{TEC}I_{TEC}^2 - K_{TEC}\Delta T_{TEC} \quad (7)
\]
\[
Q_{CC} = I_{TEC}\alpha_{TEC}T_{CC} - \frac{1}{2}R_{TEC}I_{TEC}^2 - K_{TEC}\Delta T_{TEC} \quad (8)
\]
where \( \alpha_{TEC} \) is the Seebeck coefficient of the TEC, and is the thermal conductivity of the TEC module. \( I_{TEC} \) and \( R_{TEC} \) are the input current and inner resistance of the TEC module, respectively. \( T_{HC} \) is the hot-side temperature of the TEC module, and \( \Delta T_{TEC} \) is the temperature difference between the hot and cold side of the TEC module. The energy absorbed by the TEC heat source \( Q_{CC} \) can also be calculated as follows:
\[
Q_{CC} = \frac{S_{TEC}N_uK_{medium}(T_{medium} - T_{CC})}{d_{channel\_medium}} \quad (9)
\]
where \( S_{TEC} \) is the energy transfer surface area of the TEC module, and \( T_{CC} \) is the cold-side temperature of the TEC module.

Then, the energy supplied by the DC power supply \( Q_{DC} \) can be calculated as follows:
\[
Q_{DC} = I_{TEC}[\alpha_{TEC}(T_{HG} - T_{CC}) + I_{TEG}R_{TEG}] \quad (10)
\]
\[
Q_{DC} = Q_{HC} - \frac{S_{TEC}N_uK_{medium}(T_{medium} - T_{CC})}{d_{channel\_medium}} \quad (11)
\]

The coefficient of performance of the TEC heat source \( COP \) can be obtained as
\[
COP = \frac{Q_{CC}}{Q_{DC}} = \frac{I_{TEC}\alpha_{TEC}T_{HC} - 0.5R_{TEC}I_{TEC}^2 - K_{TEC}\Delta T_{TEC}}{I_{TEC}[\alpha_{TEC}\Delta T_{TEC} + I_{TEG}R_{TEG}]} \quad (12)
\]

### IV. EXPERIMENTAL RESULTS

The parameters of the experimental instrument were as follows: a 40 × 40 mm TEC-12702 module (Szyileng TECooler) was the heat source; a DC POWER SUPPLY PS-305D (LONGWEI, Hong Kong) provided the power supply; a MIK-R4000D temperature recorder (Asmik, Hzmik, Hang Zhou) monitored and recorded the value changes in the temperature; a series of TT-K-30-SLE K-type thermocouples (Omega, United States) ensured the accuracy of temperature; VICTOR 201 digital multimeter measuring tools were used to obtain the output parameters; a 40 × 40 mm GM-200-127-14-16 TEG module (European thermodynamics); a water-cooling thermal energy adjustment structure composed of 40 × 40 × 12 mm aluminum water-cooling heads with 10 mm diameters of fluid channels; 3 W water pumps; a 410 × 230 × 260 mm water-cooling tank; and a water-cooling fluid hose with an inner diameter of 10 mm.

As shown in Fig. 2, the systems with a water-cooling thermal energy adjustment structure and without the water-cooling thermal energy adjustment structure were tested while the DC power supply provided electricity, and the temperature recorder monitored the temperature. The output power of the thermoelectric conversion system with a water-cooling thermal energy adjustment structure and without the water-cooling thermal energy adjustment structure could be acquired using VICTOR 201 digital multimeter measuring.

As shown in Fig. 3, the main circuit current \( I_N \) rose from 0.44 to 2.37 A when the voltage increased from 1 to 6 V. The total resistance of the load in the parallel circuit \( R_N \) consisted of the TEC module’s resistance and resistance at the junction of wires in the circuit. It is obvious that the values of the total resistance \( R_N \) gradually fluctuated up and down within the overall rising range with the increase in the voltage value \( V_N \). The maximum and minimum of the total resistance in the above processes were 2.21 and 2.53 \( \Omega \). The temperature data of the systems without a water-cooling thermal energy adjustment structure is shown as Fig. 4 (a), while temperature data with the water-cooling thermal energy adjustment structure is shown as Fig. 4 (b). Obviously, except for the temperature change trends on the cold side of the TEC heat source, shown as \( T_{CC1} \) and \( T_{CC2} \), the temperature change trends of \( T_{HG1} \), \( T_{HG2} \), \( T_{GG1} \), and \( T_{GG2} \), which are the mean temperatures of the hot and cold sides of the TEG with a water-cooling thermal energy adjustment structure shown as \( T_{MG1} \), and the mean temperatures of hot and cold sides of the TEG without a water-cooling thermal energy adjustment structure, shown as \( T_{MG2} \), were roughly the same.
A good energy exchange was maintained between the heat-transfer medium and the cold side of the TEC in the systems with a water-cooling thermal energy adjustment structure. As shown in Fig. 4(b), the $T_{CC2}$ continued to be stable when the values of the voltage $V_{IN}$ ranged from 1–6 V. Benefiting from the above process, the work of the TEC module is in a stable and good state, completely avoiding the possibility of being burned.

The output voltages of systems without and with a water-cooling thermal energy adjustment structure are shown in Fig. 5 and are marked $V_{OUT1}$ and $V_{OUT2}$, respectively. The output voltage $V_{OUT2}$ was always higher than the output voltage $V_{OUT1}$ throughout the experimental tests. According to the Seebeck theory, it is easy to draw the following inference; the temperature difference $\Delta T_{HG2-CG2}$ should always be greater than $\Delta T_{HG1-CG1}$ throughout the experimental tests. However, the above inference is inconsistent with the actual measured data results. In fact, the temperature difference $\Delta T_{HG2-CG2}$ was always smaller than $\Delta T_{HG1-CG1}$ during the experimental tests. It is worth mentioning that a large temperature difference producing a small output voltage is not normal; therefore, there must be a serious problem in the energy conversion process. The maximum and minimum of $\Delta T_{HG2-CG2}$ and $\Delta T_{HG1-CG1}$ were 11.28 K, 1.63 K as well as 22.48 K and 0.78 K. It is clear that $\Delta T_{HG2-CG2}$ was always smaller than the temperature difference $\Delta T_{HG1-CG1}$. The maximum and minimum $V_{OUT2}$ and $V_{OUT1}$ were 290 mV and 47.4 mV as well as 255 mV and 11.7 mV.

The data in Fig. 6 gives reasons for the aforementioned unconventional phenomena. When the voltage is less than 5 V, the temperature difference $\Delta T_{CG1-CC1}$ of the TEC heat source without the water-cooling thermal energy adjustment structure changes from 0.94 to 4.51 K. When the voltage is equal to or more than 5 V, the temperature of the $T_{CC1}$ increases rapidly. The increasing value of the $T_{CC1}$ causes the values of $\Delta T_{CG1-CC1}$ to become negative. In this case, the normal operation of the TEC module is difficult to continue. More seriously, the TEC module is at risk of being burned in this condition. The maximum and minimum $\Delta T_{CG1-CC1}$ varies from $-1.2$ to $-6.31$ K. With the increase in the negative value, the possibility of the module burning is greatly increased. Benefiting from the water-cooling thermal energy adjustment structure, the temperature difference value...
of $\Delta T_{CG2-CC2}$ is kept in the range of 0.2–0.62 K. The stable temperature difference plays a vital role in the normal operation of the system with the water-cooling thermal energy adjustment structure.

The values of the output voltage and output current of the two systems are shown in Figs. 7 and 8. Obviously, when the input voltage was 5 V, the output voltage and current of the two systems were larger than that with an input voltage of 4 V. The maximum output voltage and current of the system with a water-cooling thermal energy adjustment structure were 197.3 mV and 7.21 mA when the input voltage was 5 V, which is 39.2 mV and 1.15 mA larger than the that of the system when the input voltage was 4 V. As for the system without a water-cooling thermal energy adjustment structure, the maximum output voltage and current of the system were 143.5 mV and 5.4 mA, respectively, which is 37.5 mV and 1.17 mA larger than the maximum voltage and current of the system when the input voltage was 4 V. The maximum output voltage and current of the system with a water-cooling thermal energy adjustment structure increased 53.8 mV and 1.81 mA relative to the maximum output voltage and current of the system without a water-cooling thermal energy adjustment structure. The values were 52.1 mV and 1.83 mA compared to the maximum output voltage and output current of the water-cooling thermal energy adjustment structure system with no water-cooling thermal energy adjustment structure system when the input voltage was 4 V.

As shown in Fig. 9, under the same load, the output power of the system with the water-cooling thermal energy adjustment structure was greater than the power without the structure. The output power values were sorted from large to small in the order of a 5 V input voltage with a water-cooling thermal energy adjustment structure $P_{D5-OUT}$, a 4 V input voltage with the structure $P_{D4-OUT}$, a 5 V input voltage without the structure $P_{S5-OUT}$, and a 4 V input voltage without the structure $P_{S4-OUT}$. The largest values of the output power of abovementioned systems were 0.215, 0.138, 0.113, and 0.063 mW. When the maximum output power was generated, the total resistances of the abovementioned systems were between 20–40 ohms.
The stability of the proposed water-cooling system is good in this period. As for the situation in which the current is larger than 2.37 A, the stability of the proposed water-cooling system depends on the value of heat accumulated at the cold side of the TEG, and the maximum heat of the proposed water-cooling system can be transferred. When the value accumulated at the cold side of the TEG is less than the maximum heat that the proposed water-cooling system can transfer, the stability of the proposed water-cooling system can be guaranteed.

According to the data from European thermodynamics, the maximum operation temperatures for the hot and cold sides are 473.15 and 448.15 K. During the continuous operation of the TEG modules with water-cooling in our experiment, the temperatures of the hot and cold sides of the TEG were always less than 325 K. Obviously, the TEG modules with water-cooling operated in the ideal working temperature range. The maximum heat the water-cooling structure can transfer has been calculated as 175 W/K per second. The value is much larger than the heat flow value through the European thermodynamic GM-200-127-14-16 TEG module when the temperature difference of the hot and cold sides of TEG is 170 K. The above parameters indicate that the water-cooling structure can fully guarantee the TEG modules’ long-term stability of the working state during continuous heating and thermoelectric conversion. Therefore, the TEG modules with water-cooling has good thermal reliability. The continuous operation of TEG modules with water-cooling in our experiment lasted for two months. Throughout the experiment, the operation of the TEG modules maintained a stable working state without failure. Unlike when the TEG modules did not use a water-cooling structure for heat dissipation, a large amount of heat accumulated in the TEG modules due to the unsatisfactory heat dissipation effect, which eventually caused the TEG modules to become damaged by excessive heat. In summary, water-cooling plays an important role in improving the thermal reliability for the long-term operation of TEG modules.

When the total amount of heat was not very high, a high-velocity cooling medium, a large mass of a cold-connected medium, and a large heat exchange area can promote the water-cooling operation of the water tank without an additional cooling mechanism. Due to the rapid flow rate of the cooling medium of the water-cooling device and the large heat exchange area between the cooling medium and the heat source, the cooling medium will quickly absorb a large amount of heat and transfer it to the heat-absorbing component per unit time. Throughout the process, the greater the quality of the cooling medium, the smaller the amount of heat energy accumulated in the cooling medium. Of course, when the total amount of heat is greater than the ultimate transmission capacity of the cooling medium, auxiliary heat dissipation should be added. In summary, according to the heat generation scale, the selection of a cooling medium suitable for the mass and flow rate is essential for the design of a reasonable heat exchange area. The continuous and
long-term water-cooling operation of a water tank without an additional cooling mechanism can be actualized under these considerations.

B. MODEL VALIDATION

The experimental measurements shown in Figs. 7, 8 and 9 were the first output parameter comparisons of the thermoelectric energy conversion systems for heat recovery with and without a unique water-cooling thermal energy adjustment structure under different load resistances and different input voltages. Because the proposed thermal energy adjustment structure is a new structure and produces unique waste-heat-recycling effects, the optimal working state obtaining of the system under different loads and different input voltages is critical. As shown in Figs. 7, 8 and 9, it is clear that the optimal working range of the system is obtained when the load resistance is in the range of 20-40 ohms. When the system is working at optimal condition, the maximum of output power is acquired. Furthermore, the data in Figs. 7, 8 and 9 indicate a new conclusion that the application of water-cooling thermal energy adjustment structure has a more significant effect on promoting the energy output of the entire system than increasing the input voltage within a certain range.

Comparison of actual measured output power with output power predicted by the theoretical model has been shown in Fig. 10. The output power predicted by the theoretical model is obtained by using equations (3), (5), (6), (9) and (11). Obviously, the actual measured output power $P_{SS\text{-}OUT}$, $P_{DS\text{-}OUT}$, $P_{SA\text{-}OUT}$ and $P_{DA\text{-}OUT}$ are highly consistent with the expected output power of the model shown as $P_{SSM\text{-}OUT}$, $P_{DSM\text{-}OUT}$, $P_{SAM\text{-}OUT}$ and $P_{DAM\text{-}OUT}$. The average value of the ratio of the predicted output power of the model to the actual measured output power is 97.035 percent. The agreement of the data shows the accuracy of the experimental measurements and the correctness of the theoretical model. The reasons for the slight difference between the predicted output power of the model and the actual measured output power are as follows. As the thermoelectric conversion proceeds, the internal temperature of the thermoelectric conversion device gradually changes. The temperature change makes the Seebeck coefficient, thermal conductivity and electrical conductivity of the material inside the thermoelectric conversion device fluctuate. The change of the above parameters has an influence on the output power. In order to eliminate the above effects, stable working conditions and working temperatures are very critical. In this respect, the gentle energy transmission of the water-cooling structure has significant advantages over the strong energy transmission of the air-cooling structure. In summary, the effective establishment of the theoretical model provides a theoretical reference for predicting the output characteristics of the energy conversion module. The actual measured data has effective data support for verifying the accuracy of the theoretical model prediction. The combination of theoretical model and actual measurement has guidance and reference value for verifying the good operation of thermoelectric conversion devices and studying the optimization and improvement of thermoelectric conversion devices.

C. NOVELTY AND IMPROVEMENTS

The novelty of this water-cooling structure is that it is the first structure to connect the excessive waste heat of the TEG cold surface to the heat absorption surface of the TEC through a water-cooling method. The effect produced by this structure is also unique. With the above structure, the excess waste heat accumulated on the cold surface of the TEG is well absorbed and transferred back to the heat source for recycling. This greatly reduces the heat energy loss in the thermoelectric conversion process. In traditional air-heat dissipation or water-cooled heat dissipation, the residual heat accumulated in the cold end of the TEG is often discharged into the external environment through aluminum fins or water flow, which leads to the generation of thermal pollution in the external environment. Compared to traditional air- or water-cooling, the proposed structure eliminates the thermal pollution of the external environment and recycles waste heat. It demonstrates significant progress and unique energy transmission and recovery effects.

The improvements in the water-cooling thermal energy adjustment structure are as follows. First, it contributes to enhancing the working stability of a heat source and the thermometric energy conversion process. Second, it increases thermoelectric production without increasing cooling-power consumption. Third, it suggests a new strategy for the mixed application of water-cooling, waste heat recovery, and thermoelectric conversion-device technologies. The strategy may be applied to a composite thermoelectric energy collection and conversion system containing multiple heat sources.

From data shown in Figs. 7–9, there is no doubt that the water-cooling thermal energy adjustment structure is of great significance for improving the heat source and working stabilities of the entire thermoelectric energy conversion system.
Furthermore, under the premise of the stable operation of the thermoelectric energy conversion system, the heat source with a low heat output can achieve a greater thermoelectric energy conversion output after using the water-cooling thermal energy adjustment structure. In fact, after using the water-cooling thermal energy adjustment structure, the output power value of the heat source with a low heat output is even greater than the normal working heat source with a high heat output but no water-cooling thermal energy adjustment structure. Within a certain range, the use of the water-cooling thermal energy adjustment structure has a greater impact on the output performance of a thermoelectric energy conversion system than the amount of heat coming from the heat source.

With the rapid development of the thermoelectric energy conversion system and its large-scale application to heat energy recovery and utilization processes, it is of great significance to the achievement of a high stability in a heat source through the water-cooling thermal energy adjustment structure. The application of the structure is not limited to the application of a single heat source with a low heat output. In fact, the application of the water-cooling thermal energy adjustment structure is not limited to a single heat source. Benefiting from the energy cycle characteristics of the water-cooling thermal energy adjustment structure and the flow characteristics of the heat-transfer medium inside the water-cooling thermal energy adjustment structure, the water-cooling thermal energy adjustment structure can be applied to a composite thermoelectric energy collection and conversion system containing multiple heat sources. The above operation is of great significance to increase the economic benefits of the structure without increasing costs. Therefore, greater in-depth analysis and research should be conducted on the above structures, especially in their application and assembly methods.

D. PRACTICALITY AND FUTURE PROSPECTS

The proposed system can be applied to electrical appliances with semiconductor cooling functions, such as in semiconductor cooling refrigerators, water dispensers, and humidifiers. Through the thermal energy adjustment structure, the waste heat generated during the operation of the above devices can be recycled. This has a positive impact on reducing heat loss and heat pollution and improving the efficiency of heat energy utilization. Compared to a system without the thermal energy adjustment structure, the improvement of the output voltage and the current of the proposed system was 0.075 mW when the input voltage was 4 V. The improvement was 52.1 mV and 1.83 mA when the input voltage was 5 V. As for output power, the improvement was 0.138 mW when the input voltage was 4 V. This value is 0.025 mW larger than the output of a system without the structure. The system with the structure reached 0.138 mW when the input voltage was 4 V. This value is 0.025 mW larger than the output of a system without the structure when the input voltage was 5 V.

VI. CONCLUSIONS

A thermoelectric energy conversion system with a water-cooling thermal energy adjustment structure was devised and tested in this study. The composition and assembly method of the water-cooling thermal energy adjustment structure are unique and beneficial. The heat source of the proposed system achieved continuous stable energy conversion and output throughout the entire experiment. The output voltage and power of the energy conversion system were significantly improved. The primary results and contributions of the paper are listed below.

1. The stable operation of the heat source is indispensable for the normal operation of the entire thermoelectric energy conversion system. For low-output heat sources, such as semiconductor heat sources TEC modules, unstable heat exchange and excessive heat energy accumulation produces a negative effect on stable operation of a heat source.

2. A water-cooling thermal energy adjustment structure was designed to provide stable heat exchange for heat sources and eliminate excessive heat energy accumulation. With the structure, the temperatures of TEC module’s heat source and the TEG module were extremely stable during the thermoelectric energy conversion. The structure provides a powerful guarantee for the effective implementation of thermoelectric energy conversion.

3. The maximum output voltage and current of the system with the water-cooling thermal energy adjustment structure increased 53.8 mV and 1.81 mA compared to the system without the structure. The system with the structure reached 0.138 mW when the input voltage was 4 V. This value is 0.025 mW larger than the output of a system without the structure when the input voltage was 5 V.

4. The research potential of the water-cooling thermal energy adjustment structure is significant. It can recover and reuse heat energy lost by the heat-transfer medium from the heat source and support more than one heat source through its stable ad powerful heat-exchange capabilities. Furthermore, control methods for the structure, such as PWM or MPPT, can
be continuously developed with the progress of science and technology. In conclusion, the application and development of a water-cooling thermal energy adjustment structure has a key promotional effect on the improved stability and output capacity of thermoelectric energy conversion processes.

**NOMENCLATURE**

- $Q_{IN}$: Energy accepted by hot side of TEG.
- $Q_{OUT}$: Energy produced by hot side of TEC.
- $Q_{DC}$: Energy produced by direct current supply.
- $Q_{CG}$: Energy released at cold side of TEG.
- $Q_{CC}$: Energy absorbed by cold side of TEC.
- $P_{OUT}$: Output power of TEG.
- $V_{IN}$: Input voltage of direct current supply.
- $I_{IN}$: Input current of direct current supply.
- $R_{N}$: Total resistance of the load in the parallel circuit.
- $T_{MG}$: Mean temperature of TEG’s both sides.
- $V_{OUT}$: Output voltage of TEG.
- $I_{OUT}$: Output current of TEG.
- $\Delta T$: Temperature difference.
- $COP$: Coefficient of performance of the TEC.
- $V_{SS-OUT}$: Output voltage without thermal energy adjustment structure when input voltage is 5V.
- $V_{DS-OUT}$: Output voltage with thermal energy adjustment structure when input voltage is 5V.
- $V_{SA-OUT}$: Output voltage without thermal energy adjustment structure when input voltage is 4V.
- $V_{DA-OUT}$: Output voltage with thermal energy adjustment structure when input voltage is 4V.
- $I_{SS-OUT}$: Output current without thermal energy adjustment structure when input voltage is 5V.
- $I_{DS-OUT}$: Output current with thermal energy adjustment structure when input voltage is 5V.
- $I_{SA-OUT}$: Output current without thermal energy adjustment structure when input voltage is 4V.
- $I_{DA-OUT}$: Output current with thermal energy adjustment structure when input voltage is 4V.
- $P_{SS-OUT}$: Output power without thermal energy adjustment structure when input voltage is 5V.
- $P_{DS-OUT}$: Output power with thermal energy adjustment structure when input voltage is 5V.
- $P_{SA-OUT}$: Output power without thermal energy adjustment structure when input voltage is 4V.
- $P_{DA-OUT}$: Output power with thermal energy adjustment structure when input voltage is 4V.
- $P_{SSM-OUT}$: Model expected output power without thermal energy adjustment structure as input voltage is 5V.
- $P_{DSM-OUT}$: Model expected output power with thermal energy adjustment structure as input voltage is 5V.

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