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Enhanced Heat Transfer in Thermoelectric Generator Heat Exchanger for Sustainable Cold Chain Logistics: Entropy and Exergy Analysis

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Abstract: This study investigates the application of thermoelectric power generation devices in conjunction with cold chain logistics transport vehicles, focusing on their efficiency and performance. Our experimental results highlight the impact of thermoelectric module characteristics, such as thermal conductivity and the filling thickness of copper foam, on the energy utilization efficiency of the system. The specific experimental setup involved a simulated logistics cold chain transport vehicle exhaust waste heat recovery thermoelectric power generation system, consisting of a high-temperature exhaust heat exchanger channel and two side cooling water tanks. Thermoelectric modules (TEMs) were installed between the heat exchanger and the water tanks to use the temperature difference and convert heat energy into electrical energy. The analysis demonstrates that using high-performance thermoelectric modules with a lower thermal conductivity results in better utilization of the temperature difference for power generation. Additionally, the insertion of porous metal copper foam within the heat exchanger channel enhances convective heat transfer, leading to an improved performance. Furthermore, the study examines the concepts of exergy and entropy generation, providing insights into the system energy conversion processes and efficiency. Overall, this research offers valuable insights for optimizing the design and operation of thermoelectric generators in cold chain logistics transport vehicles to enhance energy utilization and sustainability.

Keywords: cold chain logistics; enhanced heat transfer; thermoelectric generator; metal copper foam; entropy; exergy

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1. Introduction

Thermoelectric power generation technology, with its unique advantages, has garnered widespread attention and application across various fields. It efficiently harnesses low-grade thermal energy like waste heat and wastewater, contributing to energy reuse and minimizing wastage. Moreover, its adaptability to diverse environments, including extreme climatic conditions, ensures consistent power generation efficiency without emissions, aligning with environmental protection goals.

Notably, Jeng et al. [1] developed a tailored thermoelectric generator system for capturing waste heat from engine exhaust, offering insights into its efficiency and feasibility. Qasim et al. [2] proposed a promising maximum power point tracking technique, enhancing the energy conversion efficiency of thermoelectric generator modules. Furthermore, Jabbar et al. [3] provided valuable insights into thermoelectric generator system designs, particularly focusing on heat exchangers and coolers, vital for energy recovery from internal combustion engines. Additionally, research by Riyadi et al. [4] highlighted the synergistic benefits of combining photovoltaic cells with thermoelectric generators, while studies by Ben Abdallah et al. [5] and Yang et al. [6] explored optimization approaches and innovative system designs for enhanced energy harvesting. Moreover, investigations by Zhou et al. [7]

and Liao et al. [8] emphasized the potential of thermoelectric generators in automotive applications, contributing to energy-efficient propulsion systems for next-generation vehicles. Liu et al. [9] demonstrated the viability of thermoelectric technology in enhancing automotive energy efficiency and sustainability. Ghoreishi et al. [10] provided insights into optimizing thermoelectric generator modules for waste heat recovery, emphasizing the importance of channel dimensions and configuration. Studies by Yu et al. [11] and Lan et al. [12] highlighted the significance of dynamic factors in optimizing thermoelectric generator performance under varying driving conditions. Wang et al. [13] contributed theoretical insights into utilizing vehicle exhaust gas for thermoelectric power generation, while Liu et al. [14] experimentally validated a two-stage thermoelectric generator prototype in real-world vehicle exhaust systems. Furthermore, research by Kim et al. [15], Abbasi and Tabar [16], and Marvao et al. [17] explored the application and optimization of thermoelectric generators in different vehicle types, providing empirical data and numerical techniques to enhance energy recovery. Additionally, Li et al. [18,19] investigated various thermoelectric module characteristics and configurations, offering valuable insights for optimizing thermoelectric generator efficiency. Zhao et al. [20] explored the performance of an intermediate fluid thermoelectric generator for automobile exhaust waste heat recovery, presenting a novel approach to thermoelectric generator design with potential implications for improving energy harvesting efficiency in automotive applications. Zhao et al. [21] also experimentally investigated heat pipe thermoelectric generators, contributing to the understanding of their performance characteristics. Li et al. [22,23] studied the influence of foamed metal core flow heat transfer enhancement on thermoelectric generator performance, providing insights into the optimization of thermoelectric generator design for enhanced energy recovery. Collectively, these studies contribute to the advancement of thermoelectric generator technology and its application in vehicle waste heat recovery systems.

Recovering automotive exhaust waste heat using thermoelectric generators offers multiple benefits, evaluated from the perspectives of entropy and exergy: (1) Recovering waste heat reduces entropy increase in the system, enhancing thermal energy utilization efficiency. Directly emitting waste heat into the atmosphere without recovery can lead to thermal pollution, accelerating environmental entropy increase. Converting waste heat into electricity or other useful forms mitigates thermal pollution, aiding in slowing down environmental entropy increase. (2) Recovering automotive exhaust waste heat increases the system exergy value, as waste heat is high-temperature energy. Converting waste heat into electricity enhances energy utilization efficiency, increasing the system exergy value. Additionally, recovering waste heat improves energy utilization efficiency, reducing energy waste and increasing the overall system's exergy value. From the perspectives of entropy and exergy, recovering automotive exhaust waste heat is advantageous in reducing system and environmental entropy increase, enhancing energy utilization efficiency, and achieving sustainable energy utilization.

This paper incorporates foam metal to enhance the heat transfer capacity of the hot-end heat exchanger channels in thermoelectric generators and conducts analysis from both entropy and exergy perspectives. Utilizing automotive exhaust waste heat recovery with thermoelectric generators offers multiple benefits, particularly with the addition of foam metal. Foam metal, due to its high surface area and porous structure, enhances heat transfer efficiency by facilitating better contact between the hot gases and the heat exchanger surfaces. This addition optimizes the utilization of waste heat, improving the overall performance of the thermoelectric generator system. The addition of foam metal enhances the exergy value of the system by improving the effectiveness of energy utilization, especially in converting high-temperature waste heat into electrical energy. Therefore, the integration of foam metal in thermoelectric generators for automotive exhaust waste heat recovery not only enhances heat transfer capabilities but also contributes significantly to the efficiency and sustainability of energy utilization. Nilpueng et al. [24] studied plate heat exchangers filled with copper foam, finding that copper foam enhances convective heat transfer and fluid mixing, improving overall performance. Bianco et al. [25] optimized microchannel heat sinks with metal foams, showing improved heat dissipation and thermal management in electronics. Mauro et al. [26] optimized graded foam-filled channels, demonstrating superior heat transfer and fluid flow distribution compared to conventional channels.

Furthermore, this paper highlights the crucial role of thermoelectric power generation technology in enhancing the sustainability and resilience of logistics cold chain transport vehicles. Logistics cold chain transport vehicles are tasked with maintaining specific temperature conditions to ensure the quality and safety of temperature-sensitive goods during transit. However, traditional electricity supply disruptions due to vehicle breakdowns or power outages pose significant risks to the cold chain system, potentially leading to product damage or spoilage. By integrating thermoelectric power generation systems into logistics cold chain transport vehicles, an alternative power supply solution is provided for such emergencies. These systems effectively convert waste heat into electrical energy, eliminating the reliance on external power sources and ensuring continuous power support to the cold chain system. Consequently, even in the event of a power outage, the cold chain system can operate seamlessly, safeguarding the quality and safety of the goods and reducing losses. Thus, the integration of thermoelectric power generation systems not only enhances the energy utilization efficiency and sustainability of cold chain transport vehicles but also strengthens their capacity to respond to unforeseen emergencies. This underscores the critical role of thermoelectric power generation technology in supporting the sustainability and reliability of logistics cold chain transport.

2. Methods

The heat transfer of high-temperature hot air from the inlet to the outlet in the thermoelectric generator heat exchanger can be represented by Equation (1) [27].

$$Q_{\mathrm{g}} = c_{\mathrm{g}} m_{\mathrm{g}} \left(T_{gin} - T_{gout} \right) \tag{1}$$

Q_{g}—gas heat transferred (W); c_{g}—specific heat (J/kgK); m_{g}—mass flow rate (kg/s); T_{gin}—hot gas inlet temperature (°C); T_{gout}—hot gas outlet temperature (°C).

The heat absorbed by the thermoelectric module can be represented by Equation (2) [28]:

$$H_{TEM} = \frac{\lambda_{TEM} A_{TEM}}{\delta_{TEM}} \Delta T_{TEM} \tag{2}$$

H_{TEM}—TEM heat absorbed (W); λ_{TEM}—thermal conductivity (W/mK), A_{TEM}—surface area (m^2), δ_{TEM}—Thickness (m); ΔT_{TEM}—temperature difference across the thermoelectric generator (°C).

The output power of the thermoelectric generator (TEG) can be represented by Equation (3):

$$P_{TEG} = V_{TEG} I_{TEG} \tag{3}$$

P_{TEG}—TEG power output (W); V_{TEG}—voltage (V); I_{TEG}—current (A).

The thermal efficiency of the thermoelectric generator can be represented by Equation (4) [29]:

$$\eta_{Thermal} = \frac{P_{TEG}}{H_{TEM}} \times 100\% \tag{4}$$

η_{energy}—TEG thermal efficiency (%).

The exergy heat input and exergy efficiency of the thermoelectric generator can be represented by Equations (5) and (6), respectively [30]:

$$H_{E,TEG} = H_{TEM} \left(1 - \frac{T_A}{T_{hot,TEM}} \right) \tag{5}$$

$$\eta_{exergy} = \frac{P_{TEG}}{H_{E,TEG}} \times 100\% \tag{6}$$

$H_{E,TEG}$—exergy heat absorbed (W); T_A—ambient temperature (°C); $T_{hot,TEM}$—TEM hot side temperature (°C); η_{exergy}—exergy efficiency (%); $H_{E,TEG}$—exergy heat input (W).

The entropy generation of the thermoelectric power generation system can be represented by Equation (7) [31]:

$$\Delta S = \left[m_g c_g \ln\left(\frac{T_{gin}}{T_{gout}}\right)\right] - \left[m_g R_g \ln\left(\frac{P_{gin}}{P_{gout}}\right)\right] \tag{7}$$

ΔS—entropy generation (J/K); m_g—mass flow rate (kg/s); c_g—specific heat (J/kgK); T_{gin}—hot gas inlet temperature (°C); T_{gout}—hot gas outlet temperature (°C); R_g—gas constant (J/kgK); P_{gin}—hot gas inlet pressure (Pa); P_{gout}—hot gas outlet pressure (Pa).

The exergy heat transferred by entropy generation through the hot air in the heat exchanger of the thermoelectric generator can be represented by Equation (8) [32]:

$$Q_{E,g} = Q_g - T_A\left[\left\{m_g c_g \ln\left(\frac{T_{gin}}{T_{gout}}\right)\right\} - \left\{m_g R_g \ln\left(\frac{P_{gin}}{P_{gout}}\right)\right\}\right] \tag{8}$$

$Q_{E,g}$—exergy heat transferred (W).

3. Experimental System

In this experiment, a simulated logistics cold chain transport vehicle exhaust waste heat recovery thermoelectric power generation system was utilized. The system consists of three main components: the high-temperature exhaust heat exchanger channel and the two side cooling water tanks. Stainless steel was chosen as the material for structural stability. Thermoelectric modules (TEMs) are installed between the heat exchanger and the water tanks, as shown in Figure 1. During the experiment, high-temperature air at 300 °C was sent into the heat exchanger channel at a rate of 60 m^3/h and exchanged heat with the channel walls. The heat was transferred through the wall to the outer side of the TEMs, while the heat on the other side of the TEMs was absorbed by the cooling water in the low-temperature cooling water tanks. As a result, a temperature difference was generated at the two ends of the TEMs. Using thermocouples, the temperatures at both ends were measured to determine the temperature difference. Utilizing the Seebeck effect, the TEMs converted heat energy into electrical energy. Two types of TEMs with different performances were used in this study, and their basic parameters are listed in Table 1.

Table 1. Basic parameters of different TEMs.

TEM	M1	M2
Length (mm)	56	55
Width (mm)	56	51.5
Height (mm)	5	4.4
Specific conductance σ (S/m)	2.75	0.78
Thermal conductivity κ (W/Mk)	1.12	0.48
Seebeck coefficient α (V/K)	0.03	0.058
Figure of merit ZT (-)	0.66	1.64

In order to enhance the performance of the thermoelectric generator, this study incorporated metal copper foam (porosity 98%) into the central part of the heat exchanger channel. On one hand, this utilization leverages its complex pathway structure and efficient uniform temperature performance to improve the heat transfer capacity of the fluid inside the channel. On the other hand, due to the permeability and the fact that it is only filled in the central area, the metal foam helps to effectively reduce the pressure drop loss caused by the filler. The dimensions of the heat exchanger structure are 350 mm × 70 mm × 20 mm, and the dimensions of the cooling water tank structure are 300 mm × 70 mm × 20 mm, both with a thickness of 5 mm. The experiment was divided into seven operating conditions, as listed in Table 2. By conducting triplicate measurements for each experimental condition listed in Table 2 and employing rigorous calibration procedures for our instrumentation to minimize measurement errors, we verified the reliability of the experimental results, resulting in an error of less than 5.2%. Hence, it can be concluded that the experimental results are reliable.

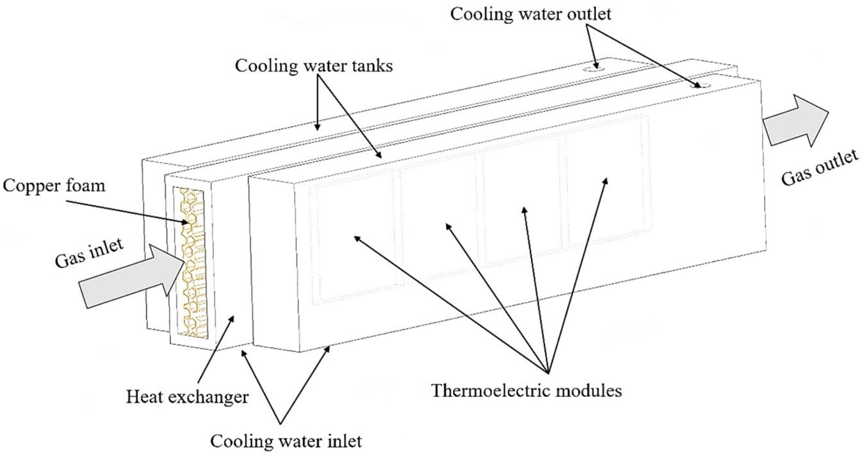

Figure 1. Schematic diagram of thermoelectric generator structure.

Table 2. Basic parameters under different experimental conditions.

Condition	C0	C1	C2	C3	C4	C5	C6
TEM	0	M1	M1	M1	M2	M2	M2
PPI	0	10	20	40	10	20	40
Thickness	0	10 mm	10 mm	10 mm	15 mm	15 mm	15 mm

4. Results and Discussion

In the experimental system of this study, a thermoelectric power generation device was used to fully utilize the high-temperature thermal energy in the exhaust channel of logistics cold chain transport vehicles. The application of thermoelectric modules in the high-temperature exhaust heat exchanger channel is of significant importance for improving energy utilization efficiency. The difference in thermal conductivity directly affects the performance of the thermoelectric modules. Compared to M1, the thermoelectric module M2 has a lower thermal conductivity, indicating its relatively poorer ability to conduct heat. This difference effectively prevents the heat in the high-temperature exhaust heat exchanger channel from being taken away by the cooling device at the cold end of the thermoelectric module, thus directly influencing the thermoelectric power generation effect.

When M2 is placed on the surface of the high-temperature exhaust heat exchanger channel, the lower thermal conductivity prevents heat from rapidly conducting to the cold end of the thermoelectric module on the outer side. In contrast, the higher thermal conductivity of M1 allows heat to conduct more quickly to the cold end of the module, where it is carried away by the cooling water, resulting in a lower temperature at the hot end and a higher temperature at the cold end, thus reducing the temperature difference between the hot and cold ends, as shown in Figure 2. Additionally, it can be observed from the figure that, within the high-temperature exhaust heat exchanger channel, the temperature difference between the cold and hot ends of the thermoelectric module inserted with porous copper foam in the central part of the channel surface is significantly higher than that of the unfilled foam metal condition. As the thickness of the metal copper foam increases, the temperature difference between the cold and hot ends also increases. Similarly, with the increase in the PPI (pores per inch) of the metal copper foam, the temperature difference between the cold and hot ends shows an increasing trend. This is because the presence of metal copper foam promotes convective heat transfer within the channel. By increasing the filling thickness and PPI, the subtle structure of gas flow within the channel can be altered, thereby enhancing convective heat transfer. This helps to effectively transfer heat from the high-temperature exhaust gas to the hot end of the thermoelectric module, thereby increasing the temperature difference between the cold and hot ends. Furthermore, the observed increase in temperature difference with higher PPIs and thicknesses can be attributed to enhanced local heat transfer via convection within the foam structure. The study reveals that a higher PPI and thickness result in a larger surface area and more complex pore structures, thereby promoting convective heat transfer processes. Additionally, increased thickness provides additional pathways for heat conduction through the foam material, further enhancing heat transfer. This phenomenon emphasizes the significance of understanding the physics occurring inside the foam.

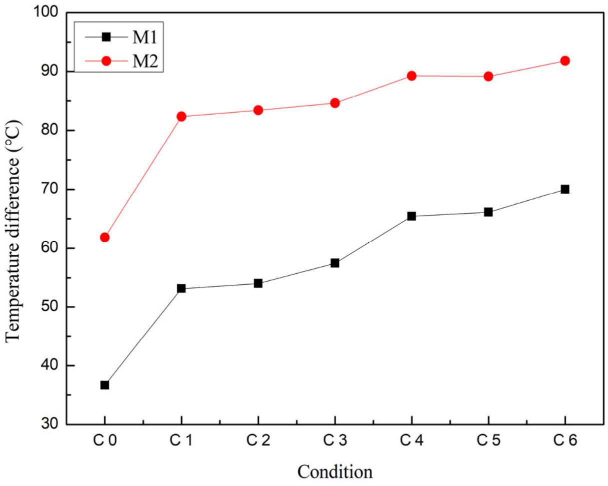

Figure 2. Temperature difference under different conditions.

When the gas inlet temperature remains constant, the lower thermal conductivity of M2 results in it playing a certain role in insulation on the surface of the heat exchanger channel. Therefore, when the high-temperature gas passes through the heat exchanger channel of the thermoelectric generator using M2, the heat of the gas is not easily carried away by the outer cooling water, resulting in less heat loss. Consequently, the gas outlet temperature is higher compared to that of the thermoelectric generator using M1. This difference in inlet and outlet temperatures directly affects the effectiveness of heat transfer within the channel. A larger temperature difference implies greater heat transfer. Therefore, the heat transfer within the high-temperature exhaust heat exchanger channel using the M2 thermoelectric generator is relatively small, as shown in Figure 3. Within the high-temperature exhaust heat exchanger channel, the gas heat transfer effect with the central part inserted with metal copper foam is significantly higher than that of the unfilled condition. With the increase in the filling thickness of the metal copper foam, the gas heat transfer effect also increases. Similarly, with the increase in the PPI of the metal copper foam, the gas heat transfer effect shows an increasing trend. This phenomenon occurs because, firstly, with the increase in the filling thickness, more metal copper foam is filled in the high-temperature exhaust gas channel, meaning that more effective heat conduction paths are added within the channel. The excellent thermal conductivity of metal copper foam allows more heat to be rapidly conducted to the channel wall, thereby improving the heat transfer efficiency. Therefore, as the filling thickness increases, the gas heat transfer effect also increases. Secondly, with the increase in the PPI of the metal copper foam, the surface area of the metal copper foam within the channel increases. This increases the contact surface area between the gas and the metal copper foam, enhancing the surface heat dissipation effect of heat transfer. Additionally, more pores increase the heat exchange efficiency between the gas and metal copper foam, promoting heat transfer. Consequently, as the PPI increases, the gas heat transfer effect also shows an increasing trend. From Figure 3, it can also be observed that the heat transfer among C1, C2, and

C3 are similar, while a significantly higher heat rate is observed in C6. As observed in Figure 2, this can be attributed to the nonlinearity of the impact of filling thickness and PPI on heat transfer within the thermoelectric generator system. As filling thickness and PPI increase, the surface area of the metal foam within the system also increases. This results in the creation of more intricate gas flow pathways, thereby enhancing convective heat transfer effects. Consequently, the augmented surface area and complexity facilitate more efficient heat transfer and lead to a larger temperature difference, consequently increasing the heat transfer. However, for conditions characterized by lower filling thicknesses and PPIs (such as C1, C2, and C3), the enhancement of convective heat transfer effects remains relatively minor due to the limited amount of foam metal filling present. As a result, despite an increase in temperature difference, the impact on heat transfer is not significant. In contrast, conditions with higher filling thicknesses and PPIs (such as C6) exhibit a more pronounced enhancement of convective heat transfer effects, leading to a noticeable increase in heat transfer.

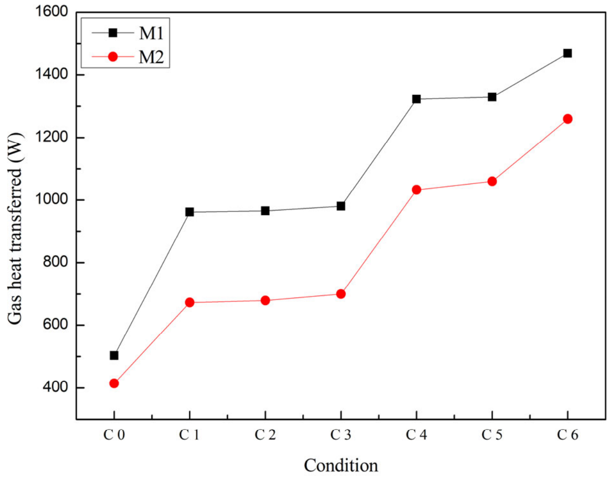

Figure 3. Gas heat transferred under different conditions.

Most of the heat within the heat exchanger channel of the thermoelectric generator using M1 is carried away by the cooling water due to the M1 higher thermal conductivity. However, M2, with its lower thermal conductivity, allows for better utilization of the temperature difference between the hot and cold ends to convert heat energy into electrical energy. Furthermore, the improved thermoelectric efficiency of M2 ultimately leads to superior thermoelectric power generation effects compared to the low-performance M1. Therefore, the difference in thermal conductivity directly affects the heat conduction capability of the thermoelectric modules on the surface of the high-temperature exhaust heat exchanger channel, thereby influencing the performance of thermoelectric power generation. This finding is significant for improving the efficiency of utilizing energy from the exhaust emissions of logistics cold chain transport vehicles. However, in contrast to the use of the high-performance M2 and the low-performance M1, it is observed that the outlet temperature of the high-temperature exhaust gas channel is higher when using the high-performance M2 compared to when using the low-performance M1, as shown in Figure 4.

The reason for the phenomenon shown in Figure 4 is that the high-performance M2 has a lower thermal conductivity compared to the low-performance M1. This means that heat transfers more slowly in the thermoelectric module M2. Therefore, although M2 can convert the temperature difference into electrical energy more efficiently, it also results in more heat remaining in the exhaust heat exchanger channel, leading to an increase in the outlet temperature of the channel. Due to M2 higher Seebeck coefficient and superior ZT value, it is more efficient in converting the temperature difference into electrical energy. Consequently, M2 can more effectively convert the temperature difference into electrical energy, but this also leads to more heat being retained in the exhaust heat exchanger channel, increasing the outlet temperature. Furthermore, it can be observed from the figure that in the heat exchanger channel that the outlet temperature of the gas is lower when metal copper foam is inserted in the center compared to when it is not filled with foam metal. As the filling thickness and PPI of the copper foam increase, the outlet temperature of the gas shows a decreasing trend. This is because filling more metal copper foam increases the effective heat exchange surface area in the exhaust gas channel. More surface area means more heat can be exchanged with the thermoelectric module, allowing more effective removal of heat from the channel and reducing the outlet temperature. Moreover, a higher filling thickness and PPI can enhance the flow structure of the gas within the channel, promoting convective heat transfer effects. Through increased convective heat transfer, heat can be transferred more quickly from the channel to the thermoelectric module hot end, thereby reducing the outlet temperature of the channel. Additionally, filling with metal copper foam can improve the internal heat conduction paths of the channel, allowing heat to transfer more quickly from the exhaust gas channel to the thermoelectric module hot end. By increasing the heat conduction efficiency, the heat from the channel can be more effectively utilized and transferred, thus reducing the outlet temperature of the channel.

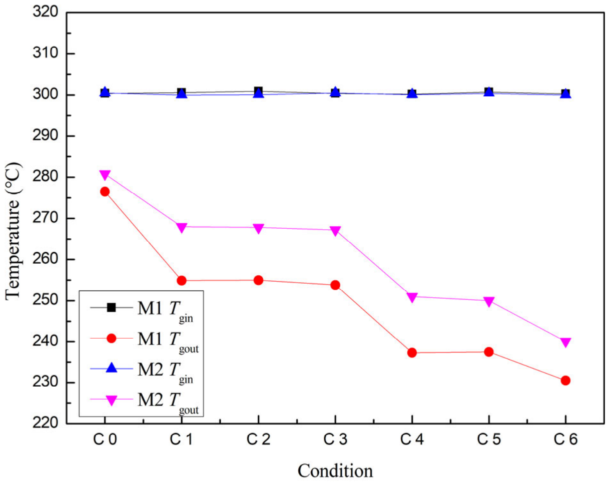

Figure 4. Gas inlet and outlet temperature under different conditions.

In summary, when using the high-performance M2, the outlet temperature of the high-temperature exhaust heat exchanger channel is higher than when using the low-performance M1. This is mainly due to the influence of thermal conductivity, which results in more heat remaining in the high-temperature exhaust heat exchanger channel, thereby increasing the outlet temperature. However, the enhancement of the Seebeck effect also allows heat to be more efficiently converted into electrical energy, so the thermoelectric effect of M2 is still superior to that of the low-performance M1. Additionally, the thermal conductivity of M2 is lower than that of M1. This means that, relative to M1, M2 has more difficulty in conducting heat from the hot end to the cold end. As a result, the thermal conductivity of M2 is lower than that of M1, leading to a larger temperature difference, as shown in Figure 5. Similarly, with the increase in the thickness and PPI of the metal copper foam, the thermal conductivity increases due to the rise in the hot end temperature.

In the experiment, high-temperature air enters the thermoelectric generator heat exchanger channel and exchanges heat with the channel wall. Heat is conducted through the wall to the outer side of the thermoelectric module, while the heat on the other side of the thermoelectric module is carried away by the low-temperature cooling water in the cooling water tank. As a temperature difference is generated across the thermoelectric module, the module converts thermal energy into electrical energy through the Seebeck effect. When using the high-performance M2, the output power of the thermoelectric generator is greater than that when using the low-performance M1, as shown in Figure 6.

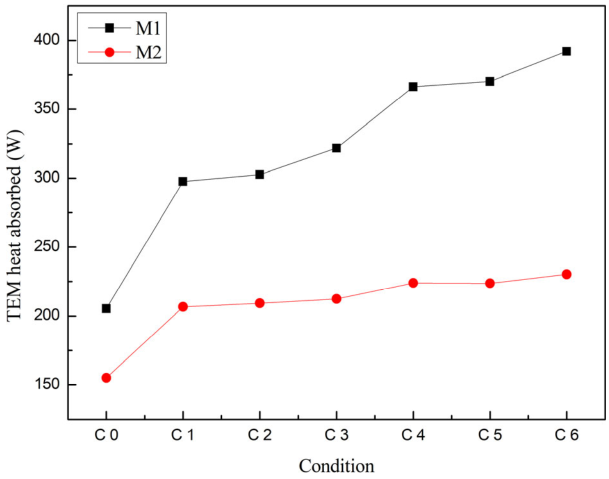

Figure 5. TEM heat absorbed under different conditions.

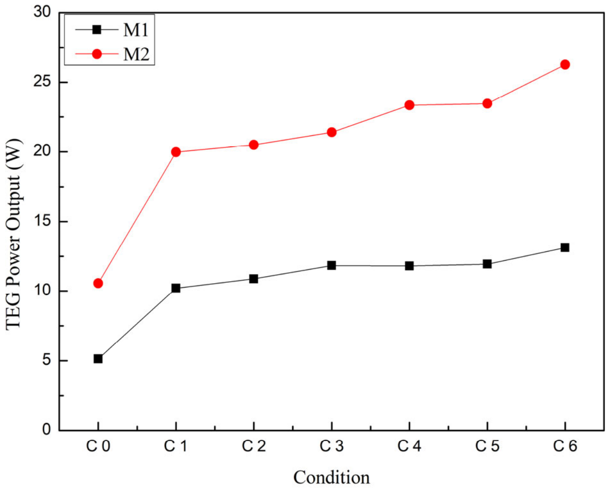

Figure 6. TEG power output under different conditions.

The reasons for the phenomenon shown in Figure 6 are as follows: (1) The high-performance M2 has a higher Seebeck coefficient, which means it can more effectively convert the temperature difference into electrical energy. Therefore, M2 can generate more electrical energy output under the same temperature difference. (2) The thermal conductivity of M2 is lower than that of M1. A lower thermal conductivity means that heat transfer within M2 is slower. Therefore, at a constant inlet temperature, M2 can more fully utilize the heat to generate more electrical energy output. (3) As shown in Table 1, the ZT value of M2 is higher than that of M1, indicating that M2 has a superior thermoelectric performance. A higher ZT value means that M2 is more efficient in converting heat into electrical energy, thus generating a higher output power. Additionally, with the increase in the thickness and PPI of the metal copper foam, the output power increases due to the higher temperature difference between the hot and cold ends of the thermoelectric module. Therefore, when using the high-performance M2, the output power of the thermoelectric generator is greater than that when using the low-performance M1. This is mainly due to the enhancement of the Seebeck effect, the influence of thermal conductivity, and the performance indicators of the thermoelectric module. Additionally, the filling of foam metal also enhances the output power of the thermoelectric generator.

In practical applications, understanding the characteristics and performance of thermoelectric modules is crucial for improving the utilization efficiency of exhaust emissions. By optimizing the design of thermoelectric generator system, it is possible to maximize the utilization of thermal energy in high-temperature exhaust gas, reduce energy waste, and achieve environmentally friendly transportation. As shown in Figure 7, when using the high-performance M2, the thermal efficiency of the thermoelectric generator is greater than that when using the low-performance M1. M2 has a higher Seebeck coefficient, which means it can more effectively convert the temperature difference into electrical energy. Therefore, under the same temperature difference, M2 can generate a higher voltage output, thereby improving the thermal efficiency of the thermoelectric generator. Additionally, the thermal conductivity of the high-performance M2 is lower than that of the low-performance M1. A lower thermal conductivity means that M2 is less able to conduct heat from the hot end to the cold end, resulting in less heat loss through M2 and a larger temperature difference between the cold and hot ends, thus improving the thermal efficiency of the thermoelectric generator. According to Table 1, the "Figure of merit" (ZT) value of M2 is significantly higher than that of M1, indicating that M2 has a superior thermoelectric performance. A higher ZT value means that M2 can convert the temperature difference into electrical energy more efficiently, thereby improving the thermal efficiency of the thermoelectric generator. Moreover, with the increase in the thickness and PPI of the metal copper foam, the thermal efficiency of the thermoelectric generator also increases.

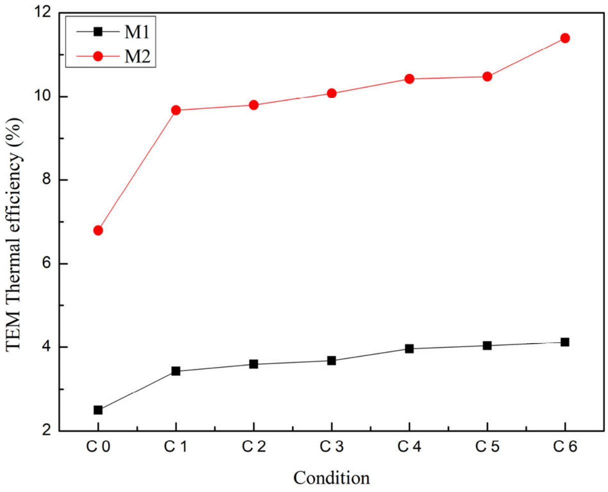

Figure 7. TEM thermal efficiency under different conditions.

Exergy is an important concept used in thermodynamics and engineering, representing the available or usable energy within a system, i.e., the energy capable of performing useful work. Exergy can be described as the energy within a system that not only considers the system physical thermal energy but also factors such as the system position, velocity, and chemical composition. In other words, exergy is the energy that can be converted into useful work. In practical systems, exergy typically varies with changes in the system, such as heat conversion and mechanical work conversion. Analyzing exergy can help researchers to assess and optimize the performance of energy systems, identifying sources of energy loss or waste to enhance the efficiency and sustainability of the system. Overall, exergy is an important concept in thermodynamics for evaluating the effective energy within a system, considering all aspects of energy conversion, and aiding in the optimization of energy system design and operation.

As shown in Figure 8, when using the high-performance M2, the exergy heat absorbed by the thermoelectric generator is smaller than that of using the low-performance M1. This is because M2 has a lower thermal conductivity compared to M1. The lower thermal conductivity means that M2 encounters greater resistance when transferring heat, resulting in a slower conduction of heat within the material. Therefore, even though the temperature at the hot end of M2 may be higher, the exergy heat absorbed is limited and reduced because heat cannot effectively conduct to the cold end of the thermoelectric module. The exergy heat absorbed refers to the usable energy absorbed by the thermoelectric generator, which is exergy. In the thermoelectric generator, the temperature difference is one of the key factors in producing the thermoelectric effect. In the Seebeck effect, the larger the temperature difference, the greater the voltage difference within the thermoelectric module. According to the Seebeck effect, voltage is proportional to the temperature difference, and a larger temperature difference results in the generation of more electrical energy within the thermoelectric module. The TEM heat absorbed represents the total heat absorbed by the thermoelectric generator. Even though the high-performance M2 has a larger temperature difference, if it absorbs relatively less heat, the exergy heat absorbed will correspondingly decrease. Additionally, as shown in the figure, with the increase in the thickness and PPI of the metal copper foam, the exergy heat absorbed by the thermoelectric generator also increases. This is because increasing the thickness and PPI significantly enhances the absorption of heat from the high-temperature gas within the heat exchanger channel by the thermoelectric module.

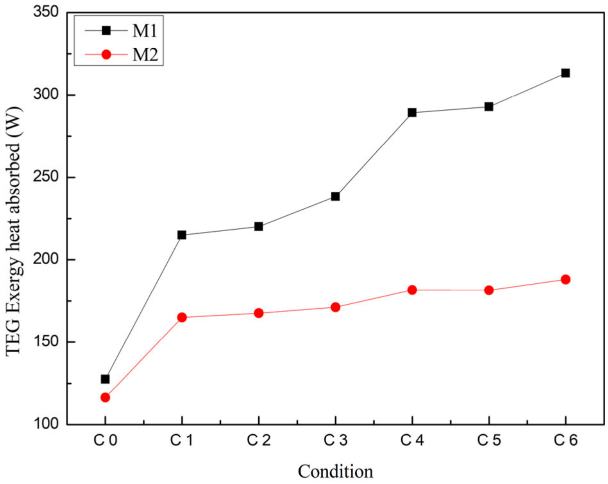

Figure 8. TEG exergy heat absorbed under different conditions.

Exergy efficiency refers to the efficiency with which a thermoelectric generator converts absorbed usable energy into electricity. In this study, exergy efficiency is defined as the ratio of the electrical energy generated by the thermoelectric generator to the absorbed exergy. As shown in Figure 9, when using the high-performance M2, its superior performance, such as a higher Seebeck coefficient and lower thermal conductivity, leads to the generation of a larger temperature difference and higher voltage. Therefore, under the same input energy, M2 can produce more electrical energy. Since exergy efficiency is the ratio of electrical energy output to the absorbed exergy, and M2 generates more electrical energy, its exergy efficiency will be higher. Consequently, compared to the low-performance M1, M2 can more effectively utilize the absorbed exergy and convert it into electrical energy, resulting in a higher exergy efficiency. Similarly, the filling of foam metal with a higher thickness and higher PPI also contributes to the improvement of exergy efficiency.

Entropy generation refers to the change in entropy that occurs within a system during a particular process. Entropy is a physical quantity used to describe the level of disorder or randomness in a system, often employed to measure the system randomness or uncertainty. In thermodynamics, entropy generation can describe changes in the energy distribution within a system and alterations in microscopic states. In the context of a thermoelectric generator, entropy generation is a crucial concept that characterizes the level of disorder and uncertainty during energy conversion processes. It is primarily influenced by two effects: the Seebeck effect and the Peltier effect. In the Seebeck effect, a voltage difference is generated when a temperature gradient exists between two different materials, leading to the production of electric current. Even with a small temperature difference, the Seebeck effect still induces a certain level of entropy generation because of the generation of electric energy, representing the conversion of thermal energy into electrical energy. Consequently, the Seebeck effect contributes to higher levels of entropy generation due to the production of electric energy, even with a small temperature difference. In the Peltier effect, heat transfer occurs due to the flow of electric current, resulting in an increase in the temperature difference. As the temperature difference increases, the heat transfer and energy conversion processes intensify, leading to greater uncertainty and disorder within the system and, consequently, higher levels of entropy generation. Overall, while both the Seebeck effect and the Peltier effect contribute to entropy generation, they operate through slightly different mechanisms. The Seebeck effect primarily increases entropy through the generation of electric energy, whereas the Peltier effect enhances entropy generation by increasing heat transfer and energy conversion processes.

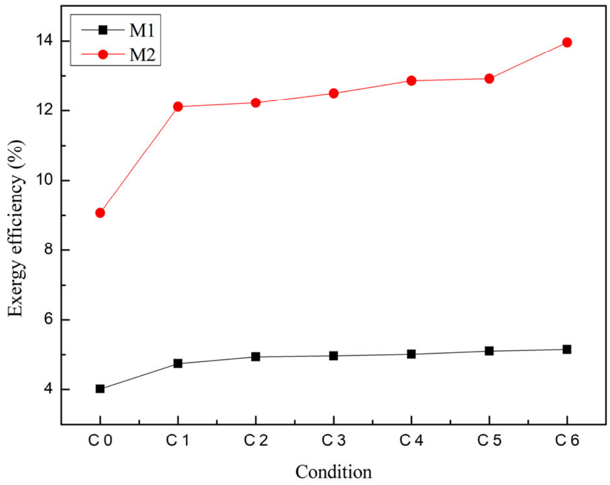

Figure 9. Exergy efficiency under different conditions.

When using M2, the entropy generation of the thermoelectric generator is lower than that when using M1, as shown in Figure 10. This is because M2 exhibits a superior performance, making the thermoelectric conversion process more efficient and reducing irreversible processes within the system. Firstly, the high efficiency of M2 means that more thermal energy is converted into electrical energy rather than being wasted, thereby reducing unnecessary thermal energy losses. Secondly, due to the lower thermal conductivity of M2, heat transfer within the system is more efficient, reducing the heat losses. These characteristics collectively result in a reduction in irreversible processes within the system when using M2, thereby decreasing the generation of entropy. In terms of waste heat recovery, higher entropy generation may imply an exacerbation of the system impact on the environment, as an increase in entropy indicates a greater irreversibility within the system, leading to more difficult recovery of heat energy that may be lost to the environment. Therefore, by optimizing the design of thermoelectric generators to reduce entropy generation, the efficiency and performance of waste heat recovery systems can be improved, reducing energy waste and achieving more effective energy utilization.

It can also be seen from the figure that, with an increase in the filling thickness and PPI, the entropy generation of the thermoelectric generator also increases. This is because an increase in filling thickness and PPI leads to additional thermal conduction paths within the thermoelectric generator, resulting in more heat transfer. This introduces more paths for heat flow and heat loss, thereby increasing entropy generation within the system. As the filling thickness and PPI increase, the irreversibility of the heat transfer processes also increases. During heat transfer processes, temperature gradients result in uneven energy flow, thereby increasing the irreversibility of heat transfer and further contributing to entropy generation within the system. Additionally, an increase in the filling thickness and PPI enhances the complexity of heat flow paths within the system, leading to increased disorder in heat flow. This increased disorder amplifies the uncertainty of heat flow, consequently contributing to higher entropy generation within the system. Therefore, factors such as the increase in heat conduction paths, irreversibility of heat transfer, and complexity of heat flow contribute to the increase in the entropy generation of the thermoelectric generator with the increase in filling thickness and PPI.

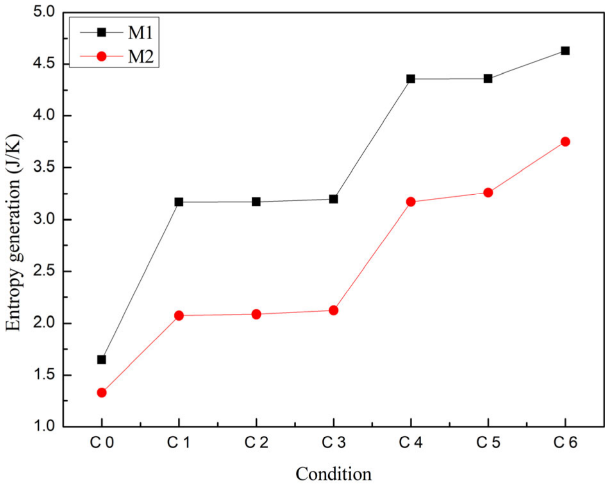

Figure 10. Entropy generation under different conditions.

In the research of waste heat recovery using thermoelectric generators, scholars often focus on the energy transfer and conversion processes within the system, as well as the efficiency and feasibility of these processes. Thermoelectric generators play as crucial a role as energy conversion devices in practical applications. To gain a deeper understanding of the behavioral differences of thermoelectric generators under different performance thermoelectric modules, it is necessary to explore thermodynamic concepts such as exergy and entropy generation.

Exergy heat transferred represents the effective energy transferred during the energy transfer process of the thermoelectric generator. Equation (8) indicates that exergy heat transferred is influenced by two factors: gas heat transferred and entropy generation. Gas heat transferred refers to the thermal energy transmitted through the thermoelectric generator, while entropy generation represents the entropy generated in the system due to irreversible processes. When using M2, it is expected that the irreversible processes in the system will be relatively reduced because high-performance thermoelectric materials typically have a higher efficiency and lower thermal conductivity. This performance advantage effectively reduces irreversible processes such as heat losses and thermal resistances in the system, thereby reducing the generation of entropy. In contrast, the use of the low-performance M1 may lead to more irreversible processes, thereby increasing the value of entropy generation. Therefore, due to the relatively fewer irreversible processes in the system under M2, the entropy generation is lower, and the gas heat transferred using M1 is higher than M2, resulting in the exergy heat transferred of the thermoelectric generator being smaller when using M2 compared to M1, as shown in Figure 11. This observation further emphasizes the importance of high-performance thermoelectric modules in thermoelectric generators and provides guidance for optimizing the design and performance of thermoelectric generators. Additionally, as the filling thickness and PPI of the metal copper foam increase, the internal heat conduction pathways and thermal conductivity of the thermoelectric generator will also increase. Metal copper foam has a high thermal conductivity, increasing the efficiency of heat transfer from the high-temperature side to the low-temperature side, thereby enhancing the magnitude of heat transfer. Meanwhile, the increase in temperature gradient inside the thermoelectric generator leads to higher thermal energy transfer rates. The increase in heat conduction pathways enables more efficient transfer of thermal energy from the high-temperature side to the low-temperature side, further improving the rate and magnitude of heat transfer. Thus, with the increase in the filling thickness and PPI of the metal copper foam, the exergy heat transferred of the thermoelectric generator will also increase.

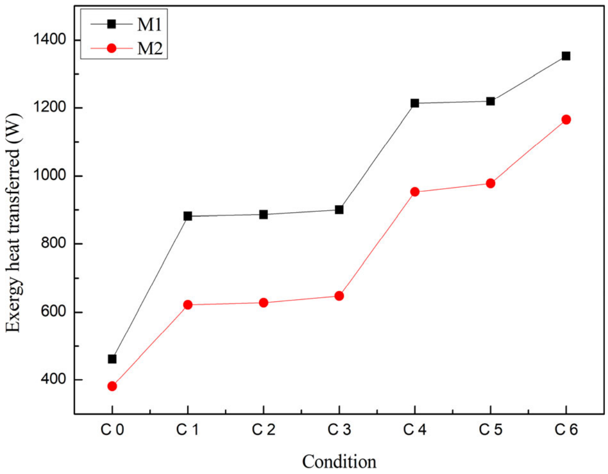

Figure 11. Exergy heat transferred under different conditions.

5. Conclusions

This study investigates the utilization of thermoelectric power generation systems in cold chain logistics transport vehicles, with a focus on the characteristics of thermoelectric modules and the impact of enhancing heat transfer through the insertion of copper foam. The experimental results showed the following significant conclusions:

1. The experimental investigation underscores the significance of thermoelectric module characteristics, particularly thermal conductivity, in determining the efficiency of thermoelectric power generation systems. The utilization of the high-performance thermoelectric module M2 with lower thermal conductivity exhibits the superior performance compared to the module M1, enabling the better utilization of the temperature difference for power generation;
2. The insertion of porous metal copper foam within the heat exchanger channel significantly enhances convective heat transfer, leading to the improved performance of the thermoelectric generator system, with the efficiency increasing three times. The study reveals that increasing the filling thickness and PPI of the copper foam contributes to a higher temperature difference and more efficient heat transfer, thereby enhancing the overall energy utilization efficiency;
3. Incorporating thermodynamic concepts such as exergy and entropy generation provides valuable insights into the energy conversion processes within the thermoelectric generator system, with a 28% reduction in entropy generation and a 52% improvement in exergy efficiency. The analysis highlights the importance of minimizing irreversible processes and optimizing heat transfer pathways to improve system efficiency and sustainability;
4. The findings of this research offer practical implications for the design and operation of thermoelectric generators in cold chain logistics transport vehicles. By optimizing thermoelectric module characteristics and heat transfer mechanisms, it is possible to enhance energy utilization efficiency, reduce energy waste, and achieve more sustainable transportation practices.

Overall, this study contributes to the understanding of thermoelectric power generation in the context of cold chain logistics transport vehicles and provides a foundation for further research aimed at improving the efficiency and sustainability of energy systems in transportation applications.

The potential challenges or limitations and future work subsequent to this study include the following: Implementing thermoelectric power generation systems in cold chain logistics transport vehicles still faces several challenges and limitations. Firstly, the efficiency and stability of the thermoelectric power generation system require further investigation. In actual transportation environments, external factors such as vibration and temperature variations may impact the system performance and reliability. Therefore, future research needs to focus on enhancing the stability of thermoelectric power generation systems and developing more reliable systems. Secondly, the integration and installation of thermoelectric power generation systems in cold chain logistics transport vehicles may also pose challenges. Due to space and structural constraints of the vehicles, the installation of the thermoelectric power generation system may be limited, necessitating the design of more compact and suitable systems for practical application scenarios. In future work, efforts will also be devoted to simulating the experimental system and validating the results based on experimental results. Identifying the optimal copper foam filling thickness and PPI to achieve a balance among system efficiency, exergy efficiency, entropy generation, and other pertinent factors related to the experimental system will be a key focus. Additionally, exploring techniques to enhance the heat transfer enhancement potential of the thermoelectric power generation system heat exchanger channel will be pursued. In future work, efforts will also be dedicated to conducting a comprehensive economic analysis and exploring methods to scale up the system for different types and sizes of cold chain logistics transportation vehicles. Additionally, field trials and case studies will be conducted to validate the system's performance and feasibility in real-world transportation environments, contributing to its sustainability and commercial viability.

Author Contributions: Y.L. designed this work, designed and established the thermoelectric power generation system, and wrote and edited this manuscript. Y.F. performed the calculations, carried out the data curation, and analyzed the experimental data. All authors have read and agreed to the published version of the manuscript.

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