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A Study on Thermoelectric Hybrid Heat Exchanger Concept for Heat Pipe Cooled Micro Reactors

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1. Introduction

In recent years, heat pipe cooled micro reactors have emerged as a promising innovation in the constantly evolving landscape of nuclear energy. These compact, passive systems, with their innate ability to leverage heat pipes, facilitate the effective transfer of heat from the reactor core directly to power conversion mechanisms, minimizing energy losses and maximizing output. However, a significant challenge in this design emerges from the heat transfer limits of the heat pipes. The activation of working fluid causes new isotope production which leads the system to become over or under the operation temperature limits . Additionally, cascading failures also cause the pressure and temperature increase in monolith core and neighboring heat pipes [1]. When these limits are exceeded, the subsequent temperature increases can lead to heat pipe failures, compromising both efficiency and safety.

To address and counteract these challenges, the integration of thermoelectric generators (TEGs) with a closed Brayton cycle power conversion system becomes especially pertinent. TEGs, capitalizing on the Seebeck effect, can directly convert thermal energy into electricity. This capability not only enhances the system's reliability but also provides a valuable tool for modulating and controlling energy transfer. By adjusting the operational parameters of the TEGs, it becomes feasible to regulate heat extraction rates, thereby averting scenarios where heat pipes approach or breach their transfer limits. Besides, one of the most important features of TEGs is its inherently passive behaviors; as the temperature difference increases between hot and cold sides, their power generation correspondingly rises. This self-regulating characteristic serves as a protective mechanism in TEGs integrated power conversion system by preventing heat pipes from exceeding their transfer capacities. When a heat spike occurs, TEGs naturally produce more electricity, thus pulling away more heat and averting potential heat pipe overloads.

This study embarks on a initial investigation of TEGs and the closed Brayton cycle integration as a hybrid power conversion system on heat pipe cooled micro reactors. It also examines the effect of TEGs' external load and temperature increase in heat pipe on efficiency and heat pipe safety. The design concept of this heat exchanger is presented in section 2. In section 3, a brief explanation and mathematical models of thermoelectric generator system are explained. Lastly, in section 4, the TEG power outputs, and efficiency are discussed by CFD results of the conceptual design.

2. Design Concept of Heat Exchanger

The design concept for the heat exchanger is an integration of both passive and active cooling mechanisms to optimize energy extraction and enhance reactor safety. The dimensions of heat pipe and operating conditions which are listed in Table I are based on Special Purpose Reactor (SPR) [2]. As shown in the simplified cross-sectional model in figure 1, to mitigate the effect of thermal expansion difference and localized wall heating, the heat pipes are enveloped within a coolant integral to the closed Brayton cycle system. This layering ensures that, as heat is transferred from the reactor, it first encounters the coolant, which acts as an initial barrier, efficiently absorbing the majority of the thermal energy.

Table I: Design and Flow Analysis Parameters

HP Inner Diameter	1.575 cm
HP Outer Diameter	1.775 cm
HP Condenser Length	210 cm
HP Surface Temp.	727 °C
HX Inlet Temp.	486.1 °C
HX Flow Rate	0.02 kg/s
HX Operating Pressure	246.3 kPa
HP-to-HP Pitch	2.771 cm
HX Coolant	Air
HX Structure Material	SS 316

Further complementing this design is the TEGs which is integrated into the walls enclosing the Brayton cycle coolant. TEGs are unique in that they operate passively, relying on the Seebeck effect. As the temperature difference across a TEG module grows, its passive nature enhances its ability to produce electricity, with a larger differential leading to increased energy output. To bolster this temperature difference across the TEGs, the design employs a counter flow approach for the Brayton cycle coolant, as illustrated in the accompanying figure. After the primary thermal energy is absorbed by the Brayton cycle, TEGs convert any residual heat directly to electricity with their certain conversion efficiencies, helping that no thermal energy goes wasted.

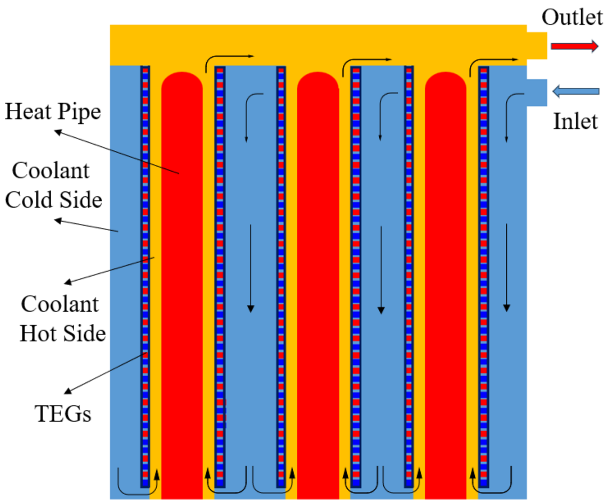


Fig. 1. Simplified cross-sectional model of hybrid heat exchanger.

The CFD simulations are based on the seven heat pipes model which is shown in figure 2. It has seven inlet and outlet ports to have more uniform coolant flow distributions in both regions.

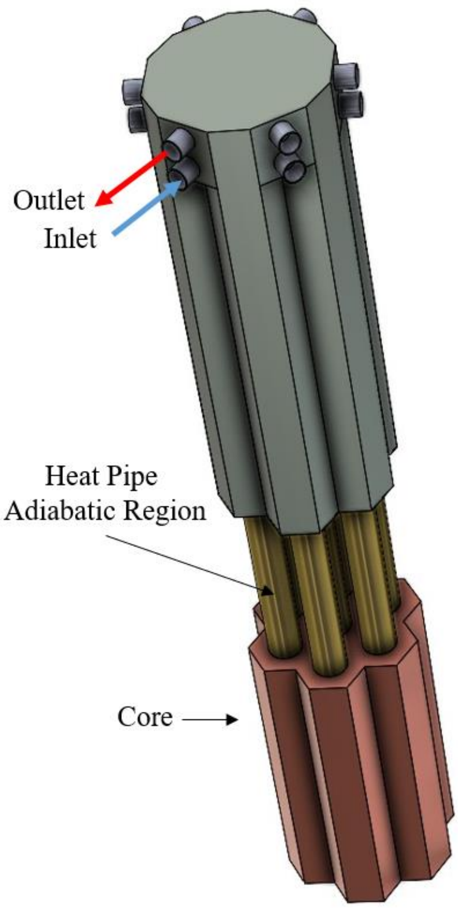


Fig. 2. 3D representation of the design featuring seven heat pipes.

3. Mathematical Model of Thermoelectric Generator

Thermoelectric generators convert thermal energy to electric energy by using Seebeck, Peltier, and Thomson effects. The working principle of these devices is based on electron motion from hot region to cold region by the effect of temperature gradient between two sides. TEGs contain p and n semiconductor legs which operate between hot and cold sides. Table II shows the design parameters of these legs. The energy conversion equations that are used below are based on reference [3]. The calculation is based on the steady-state condition. As shown in 3D view of p-n units (figure 3) and axially segmented model of heat pipe channel (figure 4), the number of p-n couples ranges from 1 to n_r radially, and superscript i is used for axial numbering which ranges from 1 to n_x. The thermal input from hot air fluid to TEG modules Q_h and thermal output from modules to cold air side Q_c are defined as:

$$Q_h^i = n_r\left[\alpha_{pn}^i I^i T_h^i + K_{pn}^i\left(T_h^i - T_c^i\right) - \frac{1}{2}{I^i}^2 R_{pn}^i\right] \quad (1)$$

$$Q_c^i = n_r\left[\alpha_{pn}^i I^i T_c^i + K_{pn}^i\left(T_h^i - T_c^i\right) + \frac{1}{2}{I^i}^2 R_{pn}^i\right] \quad (2)$$

where α_{pn}, I, T_h, T_c, R_{pn}, and K_{pn} are Seebeck coefficient difference between legs (V/K), electrical current (A), p-n unit hot side temperature (K), p-n unit cold side temperature (K), overall internal electrical resistance (Ω) and overall thermal conductivity (W/K), respectively. The Seebeck difference, overall thermal conductivity and internal resistance are expressed as:

$$\alpha_{pn}^i = \alpha_p^i - \alpha_n^i \quad (3)$$

$$K_{pn}^i = K_p^i + K_n^i = k_p^i \frac{A_p}{L_p} + k_n^i \frac{A_n}{L_n} \quad (4)$$

$$R_{pn}^i = R_p^i + R_n^i = \left(\sigma_p^i \frac{A_p}{L_p}\right)^{-1} + \left(\sigma_n^i \frac{A_n}{L_n}\right)^{-1} \quad (5)$$

where k, A, L, and σ are thermal conductivity (W/m.K), cross-sectional area (m^2), length (m), and electrical conductivity (S/m) of p-n units, respectively. The figure of merit of TEG modules is an important parameter to evaluate the thermoelectric performance. It is defined as [4]:

$$ZT^i = \left(\frac{\alpha_{pn}^2 T}{\left(\sqrt{k_p/\sigma_p} + \sqrt{k_n/\sigma_n}\right)^2}\right)^i \quad (6)$$

The thermoelectric elements are connected electrically in series and thermally in parallel. Figure 4 shows the simplified 3D model of one heat pipe channel. The external load R_L (Ω) is connected to the modules in series to form a closed loop. The power output and conversion efficiency of each thermoelectric ring is defined as:

$$P^i = {I^i}^2 R_L = \left[\frac{n_r \alpha_{pn}^i (T_h^i - T_c^i)}{R_L + n_r R_{pn}^i}\right]^2 R_L \tag{7}$$

$$\eta^i = \frac{P^i}{Q_h^i} \tag{8}$$

Table II: p-n units design parameters for a channel.

x_1	1 mm
x_2	1 mm
Length of legs ($\boldsymbol{L}$)	1.2 mm
TEG material	Skutterudite
# of p-n couple ($\boldsymbol{n_r}$)	26
# of axial ring ($\boldsymbol{n_x}$)	1655

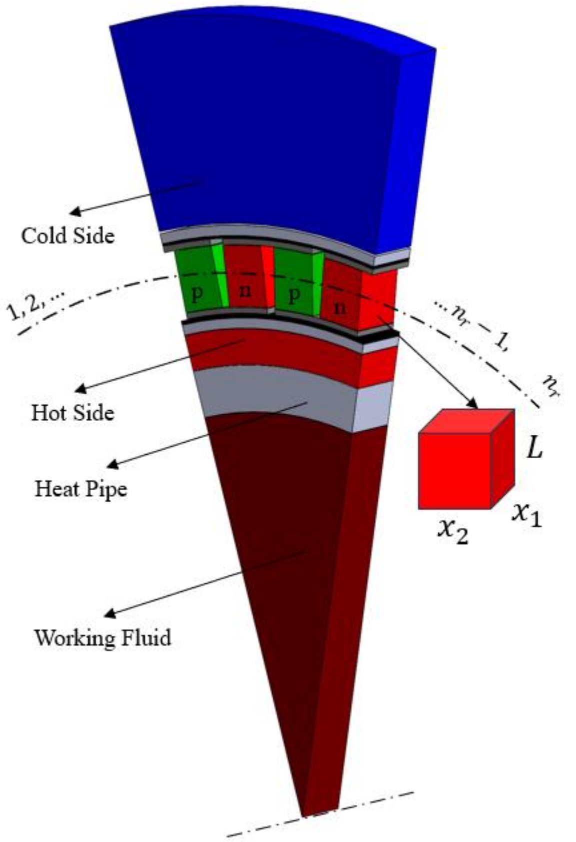


Fig. 3. Cross-sectional 3D view of thermoelectric p-n units.

The temperature-dependent properties of p-n units' material which are thermal conductivity, electric conductivity and Seebeck coefficient are determined [5],

for p legs,

$$k_p^i = 1.55 + 0.0049T^i - 1.38(10^{-5})(T^i)^2 \\ +1.18(10^{-8})(T^i)^3 - 7.66(10^{-13})(T^i)^4 \tag{9}$$

$$\sigma_p^i = 7.24(T^i)^{-0.335}(10^5) \tag{10}$$

$$\alpha_p^i = -2.74(10^{-5}) + 5.48(10^{-7})T^i \\ -4.10(10^{-10})(T^i)^2 + 4.30(10^{-14})(T^i)^3 \tag{11}$$

and for n legs,

$$k_n^i = 5.54 - 0.0078T^i + 8.20(10^{-6})(T^i)^2 \\ -1.89(10^{-9})(T^i)^3 \tag{12}$$

$$\sigma_n^i = 58.65(T^i)^{-0.533}(10^5) \tag{13}$$

$$\alpha_n^i = 3.18(10^{-6}) - 6.88(10^{-7})T^i \\ +1.48(10^{-9})(T^i)^2 - 1.92(10^{-12})(T^i)^3 \\ + 9.80(10^{-16})(T^i)^4 \tag{14}$$

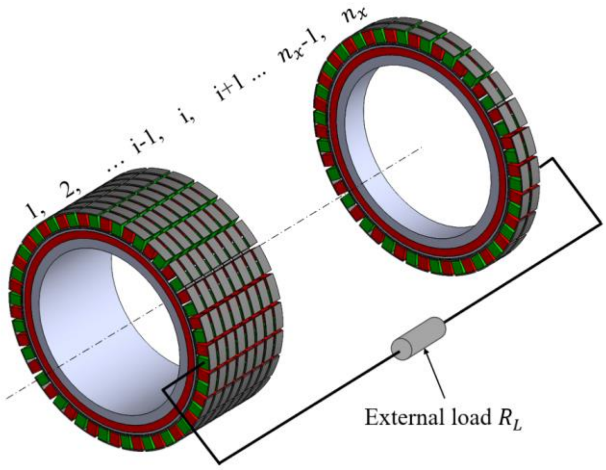
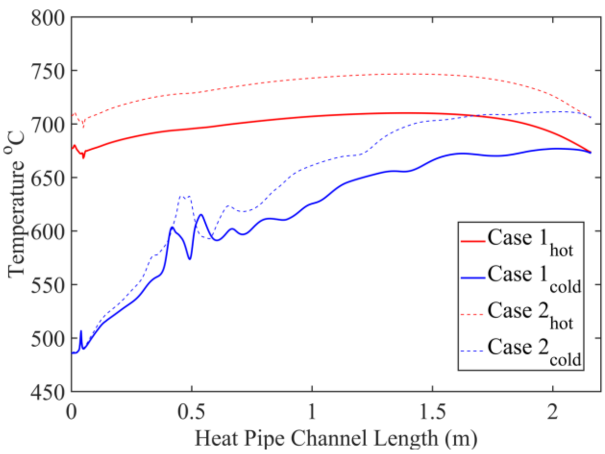


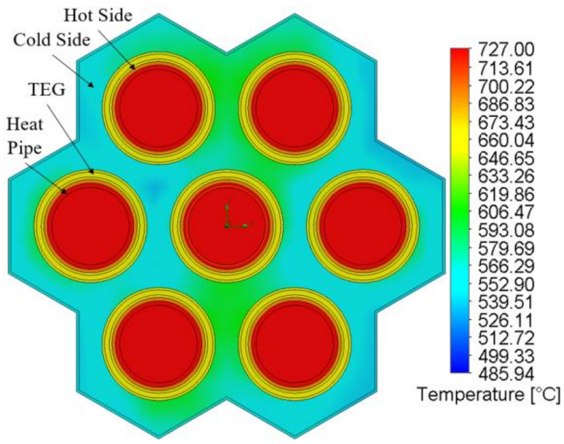
Fig. 4. Axially segmented 3D model of one heat pipe channel.

4. Results

By using the presented parameters from Table I and Table II, steady-state CFD analysis was performed in SolidWorks Flow Simulation. Totally, 2 069 930 mesh cells had been used in the simulation. The TEG modules are assumed as a whole body in the simulation. In case of the cascading failures of heat pipes, the maximum operating temperature increases to 765 °C [6]. In the analysis, the normal operating temperature of 727 °C and failure scenario operating temperature of heat pipe had been analyzed. In the plots, they are named as case 1 and case 2, respectively. In (a) of Figure 5, the temperature distributions for both scenarios are shown, clearly illustrating the variances on both the hot and cold sides of the system. The temperature difference between hot and cold sides is decreased via the channel length. By the time the flow reaches the channel's end, this difference has nearly vanished, approaching a value close to zero. This trend can be attributed to the channel design, which inherently balances out the temperatures as one progresses towards its end. In the analyzed system, the maximum temperature gradients were observed at the inlets of the channel. In those specific regions, case 1 exhibits a maximum temperature difference of 194.06°C, whereas case 2 displays a gradient of 224.02°C, which is an increase of 30°C compared to the normal operating conditions. Additionally, while the hot sides exhibit a more uniform temperature distribution, fluctuations are observed on the cold sides. When the coolant is heated, the density changes of fluid can lead to buoyancy effects which also lead to flow instabilities. The temperature fluctuations, which can also easily be seen in (b) of Figure 5, are typically caused by such flow instabilities. Moreover, the cross-sectional area of cold side flow has a significant effect on the buoyancy effects, particularly in the context of flow instabilities.



(a)



(b)

Fig. 5. Temperature distribution of hot and cold sides, (a) via the channel length for both scenarios, and (b) midplane view of case 1 at 0.5 m.

The figure of merit is a crucial metric in the realm of thermoelectric materials and devices, representing the efficiency and potential performance of a thermoelectric generator (TEG) module. This non-dimensional parameter of the system is shown in Figure 6. The subplot clearly demonstrates that skutterudite delivers optimal performance at temperatures around 500 °C. However, as the average temperature significantly rises towards the channel's end, there's a corresponding decline in the figure of merit, ZT. This decline subsequently leads to a drop in the performance towards the end of the channel. Same as Figure 5 (a), the graph for the figure of merit also displays fluctuations. This is because instabilities on the cold side directly affect the temperature distribution of thermoelectric modules.

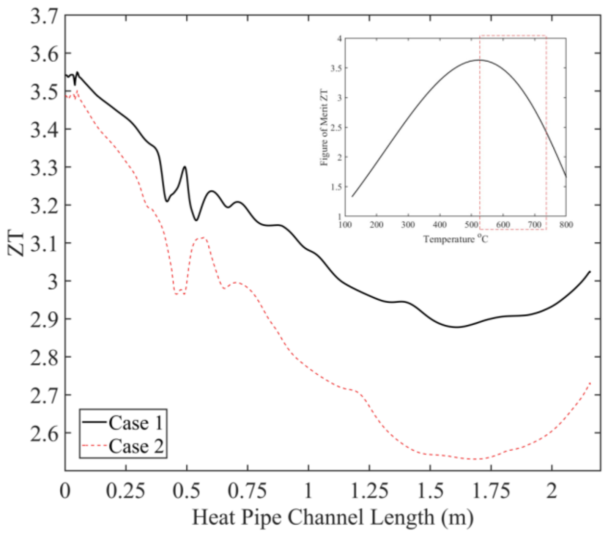


Fig. 6. The change of ZT (figure of merit) through the channel for both cases.

The external load connected to the TEG modules, which is shown in Figure 4, is of paramount importance in determining its operational efficiency and overall power output. Essentially, the external load represents the resistance to which the modules supply power, and it influences the current flow and voltage across the generator. When optimized, the resistance of the external load is matched to the internal resistance of the TEG, maximizing power output. As shown in Figure 7, the resistance at point 1 matches with the internal one and has the highest power output generation for both cases.

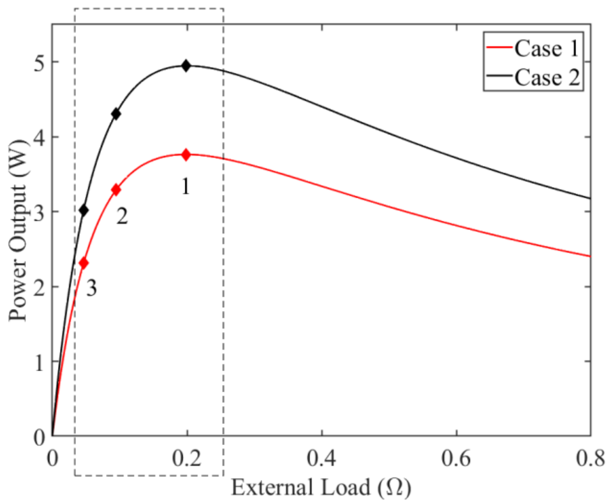


Fig. 7. External load effect on power output of both cases.

Regarding the point 2 and 3 which have lower resistances, TEG modules extract less power. In other words, the external load can also serve as a means to modulate and control the heat extraction rate from the TEG, offering a valuable tool for thermal management in systems utilizing these generators.

The results for output power density and efficiency under an external load of 0.1988 **Ω** ,as represented by point 1, are shown in Figure 8. The highest power densities of case 1 and case 2 are 7.43e+04 W/m^2 and 9.66e+04 W/m^2, respectively. On the other hand, the efficiency percentages are 6.17 % and 6.87 %, respectively. These values occur in the inlet rings of TEG system.

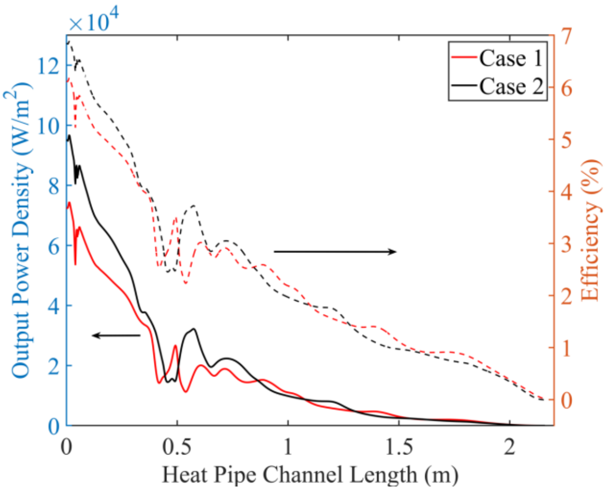


Fig. 8. TEG rings output power density and efficiency change via the channel.

The selected external load values, which are 0.1988, 0.0946, and 0.0465 Ω, are analyzed by using case 1 operating conditions. As Figure 9 shows, the power densities from the inlet rings vary as 7.43e+04 W/m^2, 6.49e+04 W/m^2, and 4.56e+04 W/m^2, respectively.

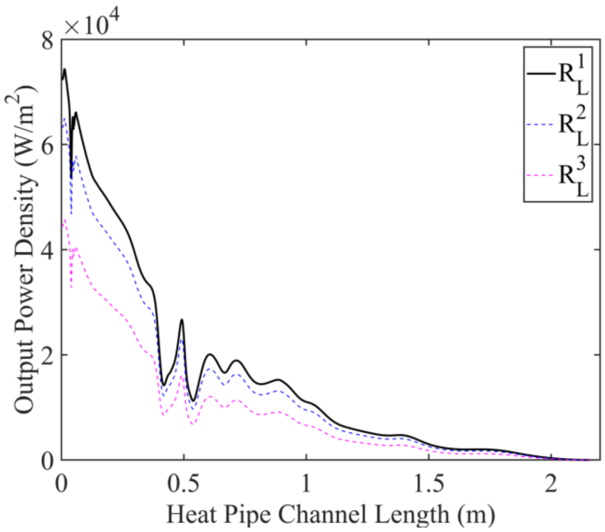


Fig. 9. TEG rings output power density change of case 1 under the selected external loads.

As presented in Table II, a single heat pipe channel comprises 26 p-n units arranged in radial rings, with a total of 1655 such rings aligned axially. The cumulative summation of these rings is shown in Table III. Due to the temperature rise in the failure scenario of case 2, the TEGs extract an additional 0.29 kW of power from a single heat pipe autonomously, without any external intervention. This value can be increased to 0.81 kW by allocating a safety margin of external load which varies between 0.0465 Ω and 0.1988 Ω.

Table III: Cumulative power output of 1655 TEG rings under chosen external loads.

	0.1988 **Ω**	0.0946 **Ω**	0.0465 **Ω**
Case 1	1.32 kW	1.15 kW	0.80 kW
Case 2	1.61 kW	1.39 kW	0.97 kW

5. Future Works

Under the certain operating conditions, each p-n materials have its own performance and efficiency ranges. The TEG structure is also an important parameter to affect efficiency. On the other hand, the Brayton cycle operating fluids and conditions have a big effect on the system's total efficiency. In the further study, it will be delved deeper into the parameters affecting the efficiency of both the TEG and the Brayton cycle system.

6. Conclusions

The integrated thermoelectric and Brayton cycle heat exchanger for heat pipe cooled reactor was designed. The normal operating conditions of heat pipe and the conditions during a cascading failure scenario are investigated on the current design. Due to the passive cooling feature of thermoelectric generators, the extracted heat increased from 1.32 kW to 1.61 kW, converting the additional 0.29 kW heat energy into electricity from a single heat pipe. This design also claims to manage the heat extraction rate by controlling the external load of TEG's modules. The safety margin of thermoelectric system allows to increase heat extraction from 0.80 kW to 1.61 kW in case of temperature increase in heat pipe. These substantial power extractions enhance the system's safety.

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