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Research and Application of Thermoelectric Energy Conversion Device Based on Heat Dissipation of Coal Pile

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Abstract

In view of the spontaneous combustion of coal piles, waste of resources and environmental pollution, gravity heat pipes are inserted into coal piles, and the heat inside the coal piles will be extracted in time because of the high-efficiency thermal conductivity of the heat pipe phase change. In order to achieve energy conservation and environmental protection, a thermoelectric energy conversion device based on gravity heat pipe was designed, which can convert heat energy extracted from the coal pile into electrical energy for supply of low power loads. The results show that the gravity heat pipe can effectively suppress the temperature rise inside the coal pile; the coal body within 0.03m away from the gravity heat pipe is better in cooling effect; the thermoelectric energy conversion system is capable of converting thermal energy inside the coal pile into electric energy and supplying a low power load such as a wireless sensor.

Keywords: spontaneous combustion of coal pile, gravity heat pipe, temperature field, thermoelectric energy conversion

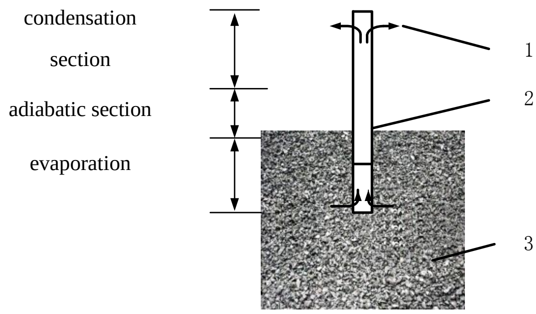
1. Introduction

There are many advantages of gravity heat pipe, such as high heat transfer coefficient, high amount of heat transfer, good isothermal performance and wide temperature range. Therefore it is regarded as an ideal component for heat dissipation of coal piles. In order to investigate the cooling effect of the heat pipe, Rui (2014) used the U type electric heating rod on the coal heating. Then it was concluded that: reducing heat pipe arrangement angle and the distance between heat pipes, increasing the depth of gravity heat pipe inserted into coal pile and adding fins in condensing section of heat pipe can improve the heat dissipation efficiency of coal pile. Jun and Bei (2015, pp. 62-67) designed a set of cooling performance test system made of hot rod and heated the coal pile with flat plate a heater. It was concluded that the effective radius of heat pipe heat transfer was 20mm, the maximum radius of effect was 420mm, and the maximum cooling efficiency was 29%. YaPing and Jian-guo (2017, pp. 100-102) investigated the cooling effect of heat pipe on the spontaneous combustion suppression of coal, and concluded that under the effect of heat pipe, the average cooling range and average cooling rate of the measured points in the coal pile were 8.7℃ and 1.06℃/h respectively.

There are some researches on the cooling effect of gravity heat pipe on loose coal in existing literatures. Those researches include of release of heat from the inside of the coal into the atmosphere, but lack follow-up waste heat utilization. In this line of work, this paper chooses the spherical heat source which is more conerent with the actual situation to study the feasibility of thermoelectric energy conversion device based on gravity heat pipe.

2. Physical Model

Coal piles have spontaneous combustion tendencies. In the external environment exposed for a long time, oxidation reaction will occur in the coal pile, causing the coal pile temperature to rise and even spontaneous combustion (Hong-kui, 2019, pp. 74-75). In this paper, a gravity heat pipe is used to transfer heat in order to cool down this system. The heat inside the coal body is extracted from the evaporating section of the heat pipe, transferred to the condensing section through the adiabatic section, then released to the external environment. The physical model is shown in figure (1):



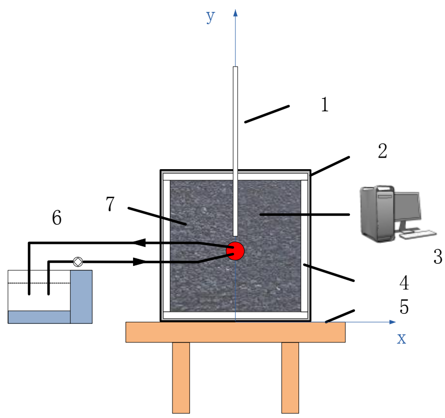
1—heat flow direction; 2—gravity heat pipe; 3—coal

Figure 1. Physical model

3. Analysis of Cooling Effect of Gravity Heat Pipe on Coal Pile

3.1 Test Device and Test Methods

In course of this work, the cooling effect of gravity heat pipe on coal pile is tested and studied. The test device is shown in figure 2.



1—gravity heat pipe 2—container of coal pile 3—system of data collection 4—Insulation cotton 5—bracket
6—Constant temperature water bath heating device 7—Coal sample volume

Figure 2. Test device structure

Coal density is 940 kg/m3, thermal conductivity is 0.1347 W/m·K, specific heat capacity is 915 J/kg·K, and porosity is 0.3. The length of gravity heat pipe is 1500mm, the outer diameter is 20 mm, the base tube wall thickness is 3mm, carbon steel material. The size of the coal pile container is 0.8×0.8×0.8m and the container wall is filled with high-temperature resistant insulation cotton to achieve adiabatic conditions. The heat source inside the coal pile is a stainless steel ball, which is heated by a constant temperature water bath (Huan & Yonggang, 2015, pp. 120-124) with a heat source radius of 0.1 m and a temperature of 353.15 K.

The heat source is placed at a distance of 0.35 m above the inner base surface of the tank and the gravity heat pipe is placed at a position 0.05 m above the heat source. The coal temperature detection system with 8 points of temperature measurement is selected, and the collected value is wirelessly transmitted to the computer through the GPRS module SIM300 wireless Internet access.

3.2 Analysis of Test Results

Figure 3 shows the temperature changes at the measuring points 0.016m, 0.02m, 0.03m and 0.075m away from the heat pipe center respectively in the x direction when the heat pipe is inserted into the coal pile depth of 0.35m. When x=0.016m, the measuring point was very close to the heat pipe and the cooling effect of the gravity heat pipe on the measuring point was much greater than that of the heat source, so the temperature only increased by 3.52k. When x=0.02m, the trend of temperature rise is the same as when x=0.016m, but the maximum temperature rise is significantly increased, and the maximum temperature rise is 5.14k. When x=0.03m, the distance between the measuring point and the heat pipe increases further, and the range of temperature rise also increases further, and the maximum temperature rise reaches 8.67k. When x=0.075m, because the measuring point was far away from the heat pipe, the measuring point temperature rises by 22.45k under the action of heat source heating and heat pipe cooling. This shows that the closer the coal is to the heat pipe, the better the cooling effect is. Conversely, the further the coal is to the heat pipe the worse the cooling effect.

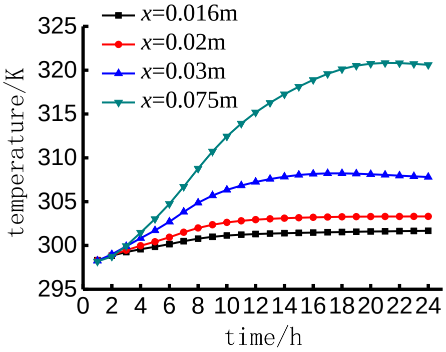


Figure 3. The trend of measuring point temperature with distance

4. Research on Thermoelectric Energy Conversion Device Based on Gravity Heat Pipe

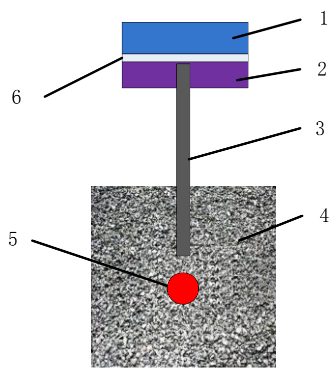
Using gravity heat pipe to transfer heat and reduce temperature can effectively restrain the rise of internal temperature and avoid spontaneous combustion of coal pile. In order to realize energy reuse, a set of thermoelectric energy conversion device based on gravity heat pipe is designed, which converts the heat energy extracted from the coal pile into electric energy to supply the use of low power load.

4.1 The Experimental Principle

The Seebeck effect is the experimental principle of the thermoelectric energy conversion device (Zhe, 2016). The Seebeck effect refers to a thermoelectric phenomenon in which the difference in voltage between two substances is caused by the difference in temperature between two different electrical conductors or semiconductors.

4.2 Test Design

Thermoelectric energy conversion device based on gravity heat pipe consists of the following parts: coal pile, gravity heat pipe, radiator, copper sheet, thermoelectric power generation component, and external energy conversion circuit, as shown in figure 5.



1—radiator 2—copper sheet 3—gravity heat pipe 4—coal pile 5—heat source 6—thermoelectric plate

Figure 4. Schematic diagram of thermoelectric energy conversion system of gravity heat pipe

Loose coal pile with internal heat source is regarded as the energy acquisition component of thermoelectric energy conversion device.

Gravity heat pipe is regarded as the power transmission medium of thermoelectric hybrid power generation. The heat transfer from the coal body to the evaporating section of the heat pipe causes phase change in the working medium of the heat pipe and transfers the heat to the condensing section of the heat pipe. Heat from the condensing section is first transferred to the copper sheet and then to the hot end of the semiconductor thermoelectric sheet.

Copper sheet has high thermal conductivity and acts as a heat transfer module.

The radiator is placed in the condensing section of the gravity heat pipe, which is an important part of the thermoelectric system.The condensing section of the heat pipe adopts water-cooled heat dissipation (Sun & Yang, 2017, pp. 4909-4914) The water pipe channel is arranged directly above the cold end of the temperature difference generating sheet. Water flows in the pipe through the cold end of the generating sheet to achieve the purpose of cooling down.The water cooling method can not only reduce the temperature of the cold end of the semiconductor thermoelectric sheet quickly and effectively, but also avoid the problem of uneven temperature distribution.

Thermoelectric power generation components consist of semiconductor thermoelectric sheet. The reason being that the Seebeck coefficient of semiconductor materials is large and the thermoelectric effect is obvious. The higher the conductivity, the smaller the joule heat, so when thermal conductivity is small and heat is not easily lost at the node. The hot end surface of the semiconductor thermoelectric sheet and the copper sheet are tightly bonded. On the other hand, the cold end surface is equally tightly bonded to the radiator. Heat conducting silicon grease is applied on the semiconductor thermoelectric sheet to prevent burning.

The performance parameters of the selected semiconductor thermoelectric generator are shown in table 1:

Table 1. TECI-12706 performance parameter table

MPN	Couples	$R(\Omega)$	I_{max}(A)	P_{max}(W)
TECI-12706	127	2.1	6	60

The external energy conversion circuit converts the output energy of thermoelectric generator into electric energy to supply low power load. It consists of voltage amplifier, external energy conversion module control circuit and energy output interface. Among them, voltage amplifier (Zhang & Li, 2015, pp. 178-187) is the most important component in the circuit, which can increase the output voltage of the semiconductor thermoelectric generator. The voltage amplifier starts to work, only when the output voltage of the semiconductor thermoelectric generator reaches the starting voltage of the external energy conversion circuit. After the output voltage of the semiconductor thermoelectric generator is raised to the minimum threshold operating voltage of low power load such as wireless sensor, the load starts to work.

4.3 Heat Transfer Model

According to the three forms of heat transfer (Shi-ming & Wen-quan, 1998), the heat lost in the coal body Q_{coal} can be judged by: the heat lost by Qcon in the form of heat conduction, the heat lost by Q_{cov} in the form of convection, the heat lost by Q_{rad} in the form of radiation.

The heat lost by convection Q_{cov} is assumed as 0, because the box is closed around and there is no convection boundary.

The heat lost by radiation in Q_{rad} can be calculated by Stefan-Boltzmann law:

$$Q_{rad}=\varepsilon A_1 \sigma T^4 \tag{1}$$

In the formula: ε -- emissivity, $\varepsilon <1$; A_1 -- radiant surface area, m^2; σ -- Stefan-Boltzmann constant, $\sigma =5.67\times10^{-8}$ W/(m^2•K^4); T -- the thermodynamic temperature of the black body, K.

The heat lost, Q_{con} in the form of heat conduction includes the heat transferred, by coal to the evaporation section of Q_{eva} the gravity heat pipe and the heat transferred, by coal to the box Q_{box}.

Since the boundary of the box is adiabatic, the heat loss in the form of heat conduction is equal to the heat transferred from coal to the evaporating section of the heat pipe. The value can be calculated by Fourier law:

$$Q_{con}=-\lambda A_2 \frac{dt}{dx} \tag{2}$$

In the formula: λ -- thermal conductivity of coal, W/(m•K); A_2 -- surface area of evaporation section of gravity heat pipe, m^2.

The heat transferred from coal to the gravity heat pipe can be divided into four parts: the overall gravity heat pipe temperature increase Q_{pipe}, the heat released to the environment by the gravity heat pipe condenser Q_{cold}, the heat absorbed by the thermoelectric energy collection module Q_{ele} and the convection heat loss Q_{vect} due to the thermoelectric energy conversion system in the environment. Its numerical value can be calculated by the formula:

$$Q_{\mathrm{vect}} = -h_{\mathrm{sys}} A_{\mathrm{sys}} \left(t_{\mathrm{w}} - t_{\mathrm{f}}\right) \tag{3}$$

In the formula: h_{sys}—the convective heat transfer coefficient between the thermoelectric energy conversion system and the air during the test, W/(m^2•K); A_{sys}—thermoelectric energy conversion system with air convection area, m^2; t_w—wall temperature of thermoelectric energy conversion system, K; t_f—air temperature, K.

The heat, Q_{ele} absorbed by the surface of the thermoelectric energy collection module includes the energy loss, Q_{loss1} of the copper heat transfer module and the connection part of the hot end of the semiconductor thermoelectric sheet. Due to the fact that the connection is coated with heat-conducting silicone grease, the energy loss, Q_{loss1} is very small. The energy absorbed by the thermoelectric energy collection module is Q_{loss2}. The final energy obtained by the thermoelectric energy conversion system is Q_{work}.

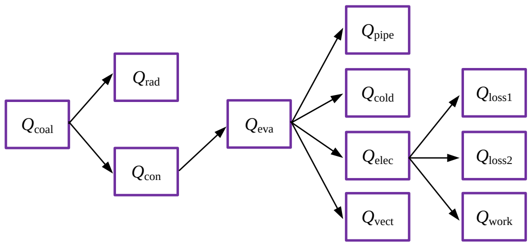


Figure 5. Energy conversion structure diagram

4.4 Performance Parameters of Thermoelectric Generator

4.4.1 Output Power of Semiconductor Thermoelectric Generator

Output voltage of semiconductor thermoelectric generator:

$$U_O = \alpha_{ab}\left(T_r - T_l\right)\frac{R_L}{R + R_L} \tag{4}$$

Current generated in the closed loop:

$$I = \frac{\alpha_{ab}\left(T_r - T_l\right)}{R + R_L} \tag{5}$$

The output power of semiconductor thermoelectric generato:

$$P = U_O I = \frac{\alpha_{ab}^2\left(T_r - T_l\right)^2 R_L}{\left(R + R_L\right)^2} \tag{6}$$

$$P = \frac{\alpha_{ab}^2\left(T_r - T_l\right)^2}{4R_L} \tag{7}$$

In the formula: Uo—the output voltage of semiconductor thermoelectric generator, V; α_{ab}—Seebeck coefficient, V/K; T_r—cold end temperature of generator blade, K; T_l—cold end temperature of generator blade, K; R—semiconductor thermoelectric plate internal resistance, Ω; R_L—semiconductor thermoelectric plate internal resistance; Ω; I—loop current. A; P—thermoelectric conversion power of semiconductor thermoelectric sheet, W;

4.4.2 Efficiency of Thermal Power Generation

Considering the Seebeck effect, Fourier heat and joule heat, the heat at the hot end of the generator blade can be obtained (Kossyvakis & Vossou, 2015, pp. 150-161).

$$Q_r = \alpha_{\mathrm{ab}} I T_r + k\left(T_{\mathrm{r}} - T_{\mathrm{l}}\right) - \frac{1}{2} I^2 R \tag{8}$$

Thermoelectric conversion efficiency is:

$$\eta = \frac{P}{Q_r} = \frac{\alpha_{ab}^2\left(T_r - T_l\right)^2 R_L \big/ \left(R + R_L\right)^2}{\alpha_{\mathrm{ab}} I T_r + k\left(T_{\mathrm{r}} - T_{\mathrm{l}}\right) - \frac{1}{2} I^2 R} \tag{9}$$

In the formula: Q_l—the heat released at the cold end of the generator, W; *k*—thermal conductivity of semiconductor thermoelectric generator, W/K.

Semiconductor thermoelectric power resistance $R = 2.1\ \Omega$. This is so, in order to make the output power of the thermoelectric energy conversion device be maximum. When the output voltage of TECI-12706 semiconductor thermoelectric generator reaches the starting voltage of external energy conversion circuit, the DC-DC booster module increases the output voltage of TECI-12706 semiconductor thermoelectric generator to 5V and stimulates the wireless sensor to work. The current of the thermoelectric energy conversion system is 338mA, the output power of the thermoelectric energy conversion system is 258.62mw, and the power generation efficiency is 0.7%.

The wireless sensor is a low-power component that works intermittently. It only needs a small temperature difference supply to work normally. Thus the electricity from thermoelectric devices can supply wireless sensors.

5. Conclusion

1) The gravity heat pipe can effectively inhibit the rise of the internal temperature of the coal pile and prevent the spontaneous combustion of the coal pile. Hence, the coal body 0.03m away from the gravity heat pipe has a better cooling effect.

2) The boost device can increase the output voltage of the semiconductor thermoelectric generator to 5V, stimulating the low-power load to work.

3) The thermoelectric energy conversion device designed in this paper converts the heat extracted from the coal pile by gravity heat pipe into electric energy, which does not only recycle the waste energy, but also prevent the spontaneous combustion of the coal pile. The thermoelectric energy conversion system can generate 9.31KJ of electricity in a day and 3,351.72 KJ in a year.

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