Application of Thermoelectric Technology in Direct Air Cooling System of Thermal Power Plant

Xuhui Zhang1,2, Xinwang Zhang1,*
1School of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi, 710000, China
2Shaanxi Key Laboratory of Intelligent Monitoring for Mine Electromechanical Equipment, Xi'an, Shaanxi, 710000, China
* Corresponding author: 16143332@chnenergy.com.cn

Abstract. In recent years, with the improvement of the coefficient of merit of thermoelectric materials, the research of thermoelectric power generation has entered a new climax. The developed countries have listed the development of thermoelectric power generation technology into the medium and long-term energy development technology. The research on thermoelectric power generation in China started relatively late, mainly focusing on the theory and preparation of thermoelectric materials. At present, the field of semiconductor thermoelectric power generation is just introduced, and its practical application is still blank. Thermal power generation technology is used to recover waste heat from direct air cooling system of thermal power plant. Power supply of wireless temperature sensor can be realized through energy storage components or integrated power management system, which can reduce energy waste and environmental pollution. It is of great significance for industrial waste heat recovery and clean energy development.

1. Introduction
China's coal resources are mainly distributed in northwest, North China and Northeast China. The lack of water resources restricts the development of thermal power plants in coal rich areas. The cooling mode of air cooling unit can effectively solve the problem of water shortage. The back pressure of direct air cooling system is high, which is easily affected by the environment and temperature. Therefore, it is particularly important to monitor the operation status of direct air cooling system. Using wireless temperature sensor to build wireless monitoring network is one of the effective ways for condition monitoring of direct air cooling system. In view of the wide adaptability of thermoelectric generation theory to energy grade and the practice of thermoelectric generator in industrial waste heat recovery and application, this paper puts forward a method of using thermoelectric generation technology to recycle waste heat of air cooling system according to the energy supply demand of wireless monitoring node of air cooling unit [1-2].

2. Theoretical analysis of thermoelectric technology

2.1. Seebeck effect
In 1821, German scientist Thomas Johann Seebeck found that in the closed circuit composed of two semiconductors A and B with different conductors or conductive types, the temperature is different
between connection point 1 and connection point 2, there is a temperature difference \((T_1 - T_2)\). The emf \(\Delta U\) will be generated in the loop between the two connection points. This phenomenon is called Seebeck effect. The discovery of Seebeck effect lays a very important theoretical foundation for thermoelectric technology[3].

As figure 1, Seebeck effect refers to the temperature \((T_1 - T_2)\) difference between the joints of conductor A and conductor B in the circuit formed by the connection of conductor A and conductor B. Then, a voltage difference is generated between conductor A and conductor B, and a current is formed in the circuit to convert the heat energy of the joints at both ends into electric energy.

\[\Delta U = \alpha_{AB} (T_1 - T_2)\]  

\(\Delta U\) is the voltage difference in the loop, \(\alpha_{AB}\) is the relative Seebeck coefficient of conductor A and conductor B materials, \(T_1\) is the temperature of connection point 1, \(T_2\) is the temperature of connection point 2.

2.2. The basic structure of thermoelectric generator

As figure 2, in the system of thermoelectric power generation, thermoelectric generator is the basic module of thermoelectric power generation. The basic unit of thermoelectric generator is composed of p-type couple arm, n-type couple arm and electrode[5].
When one end of the junction of p-type and n-type semiconductors contacts the heat source and the other end contacts the cold source, due to Seebeck effect, the carrier holes of p-type couple arm will diffuse from the heat source to the cold source and accumulate positive charges in the cold source to form the positive electrode. Because of the high concentration of carrier electrons in the n-type couple arm, they will diffuse from the heat source to the cold source and accumulate negative charges in the cold source to form the negative electrode. When the diffusion reaches equilibrium, the excess carrier holes gather in the cold source of p-type arm and the electrons gather in the cold source of n-type arm. Thus, the electromotive force is generated between the cold source of p-type arm and n-type arm. After the load resistance is connected, the current loop is formed and the stable current I output is formed.

2.3. Main function parameters of thermoelectric

Generally, the main function parameters of thermoelectric include generation efficiency and output power. In order to qualitatively analyze the output performance of thermoelectric units, the following assumptions are proposed: (1) the temperature of cold end and hot end is constant. (2) The contact resistance and thermal resistance of the junction between p-type and n-type semiconductors and metal guide plate can be neglected. (3) The resistance of metal deflector can be neglected. (4) The cross-sectional area of the thermocouple arm composed of p-type and n-type semiconductors is constant. (5) The properties of the material do not change with temperature.

2.3.1. Generation efficiency

The generation efficiency of thermoelectric generator, namely energy conversion efficiency, refers to the ratio of the electric energy output to the external load and the heat energy input at the hot end of thermoelectric generator:

$$\eta = \frac{P}{Q_h}$$

(2)

$\eta$ for power generation efficiency, $P$ for the electrical energy output to the external load, $Q_h$ is the heat absorption of the hot end.

If the current generated in the circuit is I, the output power of the thermoelectric generator is:

$$P = I^2 R_L$$

(3)

$R_L$ is the external load resistor.

According to the principle of heat balance, the heat absorbed by the hot end of thermoelectric generator is the sum of heat conduction, Peltier heat and Joule heat:

$$Q_h = Q_p + Q_F - Q_J = \alpha_{NP} T_1 I + k(T_1 - T_2) - \frac{1}{2} I^2 R$$

(4)

$Q_p$, $Q_F$ and $Q_J$ are the Patel heat, conduction heat and Joule heat, $\alpha_{NP}$ is the Seebeck coefficient, $k$ is the thermal conductivity of semiconductor materials, $T_1$ and $T_2$ are the temperature of hot end and cold end respectively, $R$ is the internal resistance of thermoelectric device.

Equation (3) and equation (4) into equation (2) get:

$$\eta = \frac{I^2 R_L}{\alpha_{NP} T_1 I + k(T_1 - T_2) - \frac{1}{2} I^2 R}$$

(5)

$$S = \frac{R_L}{R}, \text{ the coefficient of merit is introduced } Z = \frac{\alpha_{NP}^2}{kR}, \text{ we get:}$$
\[ \eta = \left( \frac{T_1 - T_2}{T_1} \right) \left[ \frac{S}{(1 + S) \frac{T_1 - T_2}{2T_1} + \frac{1 + S}{ZT_1}} \right] \]  

(6)

Obviously, for the thermoelectric generator with given material and temperature difference, its power generation efficiency \( \eta \) varies with the ratio of internal resistance to external load resistance \( S \).

When \( \frac{d\eta}{dS} = 0 \), we get:

\[ S = \frac{R_1}{R} = \sqrt{(1 + Z \cdot \bar{T})} \]  

(7)

\[ \bar{T} = \frac{(T_1 + T_2)}{2} \]  

is the average temperature of the hot and cold end.

The maximum power generation efficiency of thermoelectric generator is:

\[ \eta_{\text{max}} = \left( \frac{T_1 - T_2}{T_1} \right) \left[ \frac{\sqrt{(1 + Z \cdot \bar{T})} - 1}{\sqrt{(1 + Z \cdot \bar{T})} + \frac{T_2}{T_1}} \right] \]  

(8)

As in equation (8), the first term on the right is Carnot effect, and the second term is related to the material properties of thermoelectric generator, and the value is less than 1. Therefore, the generation efficiency of thermoelectric generator is less than the cycle efficiency of ideal Carnot engine.

2.3.2. Output power

According to the basic principle of Seebeck effect, when there is a temperature difference at both ends of the thermoelectric generator, the voltage generated by the semiconductor thermocouple in the loop is:

\[ V = \alpha_{NP} \cdot (T_1 - T_2) \]  

(9)

If a load is connected to the thermoelectric element, the voltage generated will be divided into two parts, one in the internal resistance of the thermoelectric generator, the other part is applied to the external load resistor. The output voltage applied to both ends of the external load resistor is:

\[ V = \alpha_{NP} \cdot (T_1 - T_2) \cdot \frac{R_L}{R_L + R} \]  

(10)

\( \alpha_{NP} \) is seebeck coefficient, \( T_1 \) and \( T_2 \) are the temperature of the hot end and the cold end of the element, \( R_L \) is the external load resistance, \( R \) is the internal resistance of thermoelectric generator.

The current generated in the closed circuit is:

\[ I = \frac{\alpha_{NP} \cdot (T_1 - T_2)}{R_L + R} \]  

(11)

So the output power of the thermoelectric generator is obtained as follows:

\[ P_0 = I^2 R = \frac{\alpha_{NP}^2 \cdot (T_1 - T_2)^2}{(R_L + R)^2} \cdot R_L \]  

(12)

For \( S = \frac{R_L}{R} \), final get:
When $R_L$ is the same as $R$, we can get the maximum output power:

$$P_{\text{max}} = \frac{\alpha_{NP}^2 \cdot (T_1 - T_2)^2}{4R}$$  \hspace{1cm} (14)$$

And the generation efficiency is:

$$\eta = \left[ \frac{T_1 - T_2}{T_1} \right] \cdot \left[ 2 - \frac{1}{2} \left( \frac{T_1 - T_2}{T_1} \right) \right] + \frac{4}{ZT_1}$$  \hspace{1cm} (15)$$

3. Layout scheme design of the thermoelectric generation system

3.1. Overview of the direct air cooling system

As figure 3, the exhaust steam generated by the steam turbine after working enters the exhaust device, which distributes the steam evenly, and the steam enters into 8 rows of steam distribution pipes. Each row of steam pipe is composed of 7 to 8 air cooling units (the unit looks like a letter ‘A’). After entering the pipe, the steam flows into the finned tube bundles on both sides of air cooling unit. The lower air cooling fan is forced to ventilate upward to cool the finned tubes of each unit, after the steam condenses into water, it returns to the condensate tank through the condensate recovery pipe at the lower part of each A-type tube fin, and then it is sent to the steam turbine thermal system by the condensate make-up water system for recycling.

![Fig. 3. The whole picture of the air cooling units.](image)

In the air cooling system, each row of air cooling units includes fair current unit and counter current unit. In the fair current unit, the condensed water flows into the condensate pipe and into the water tank. In the counter current unit, the non-condensable steam is extracted by the negative pressure system. About 80% of the steam in the whole air cooling system is condensed into water for recycling, because the steam in the counter current condenser is pumped away in the opposite direction of condensation, it also ensures the formation of individual steam pipe dead zone and the adjacent unit tube bundle will not be frozen[7].

3.2. Structure design of the thermoelectric generator

As figure 4 and 5, the overall structure length is 134mm, width is 85mm and height is 126.2mm. Because both sides of the finned tube of the condenser of the direct air cooling unit are fin structure, and the transverse length of the fin is long, the slot type installation structure can be designed. The structure size of the pin at the hot end of the thermoelectric system is 9mm long, 2mm wide and 60mm
high. When installing, the pin at the hot end is directly inserted into the gap between the fins. This structure design is convenient for installation and disassembly, and can also play a certain role in heat conduction. The cold end of the thermoelectric generator is designed as pin fin, and in this paper, the pin type heat dissipation structure can increase the heat dissipation area. The size of the pin fin is 9mm in length, 2mm in width and 50mm in height.

![Thermoelectric generator mechanical structure design diagram](image1)

**Fig. 4.** The mechanical structure design diagram of the thermoelectric generator.

![Thermoelectric generator installation mode diagram](image2)

**Fig. 5.** Installation mode diagram of the thermoelectric generator.

3.3. *The whole layout scheme of the thermoelectric generation system*

The radiator area of the air cooling island is huge and the temperature distribution is uneven. According to the characteristics of the temperature field of the whole air cooling units, a reasonable layout scheme of the thermoelectric power generation system is needed. Taking the 660MW air cooling unit of Guohua Jinjie Power Plant as an example, the air cooling system of the unit is divided into 8 lines and 8 rows, with 64 air cooling units in total, that is, the lower part of each line of steam distribution pipe is composed of 8 cooling units, of which 6 are downstream units and 2 are mixed flow units. According to the previous temperature field analysis, the temperature distribution of the down stream unit and the counter current unit is gradually rising from top to bottom along the condenser tube bundle. Because the upper temperature of the counter current unit is significantly lower than that of the down stream unit, and the average temperature of the counter current unit is lower than that of the down stream unit, the number of the lower side of the counter current unit is
more than that of the upper side, the thermoelectric system is mainly arranged in the down stream unit. According to the temperature characteristics of condenser tube bundle of down stream unit and counter current unit and the layout experience of monitoring points, the layout of thermoelectric power generation system is designed as shown in figure 6. Three rows of thermoelectric generation system are arranged on each cooling surface, and 12 counter current units and external parallel units are arranged. The counter current units are arranged from bottom to top, and the amount is 5, 4 and 3. There are 15 thermoelectric generators arranged in each internal down stream unit.

![Fig. 6. Layout of thermoelectric power generation system.](image)

**3.4. Design of thermoelectric energy harvesting circuit**

Using the output voltage of thermoelectric power generation as DC voltage, the thermoelectric collection module adopted in this paper adopts BQ25504 chip, as shown in figure 7. This chip is a leading new intelligent integrated energy collection nanowatt power consumption component, which can meet the special needs of ultra-low power consumption applications, and can efficiently collect and manage the microwatt to nanowatt power generated by various DC sources such as thermoelectric generators. The DC boost converter designed by BQ25504 only needs micro watt power. The boost converter can be started by VIN as low as 600mV. After starting, it can continue to collect energy for VIN as low as 130mV. BQ25504 also implements a programmable maximum power point tracking network (MPPT) to optimize power transmission to devices. The VIN-DC open circuit voltage is programmed through an external resistor and maintained by an external capacitor (CREF).

![Fig. 7. Thermoelectric energy collection circuit.](image)

**4. Conclusion**

Based on the theory of thermoelectric power generation, combined with the working characteristics of direct air cooling system in thermal power plant, this paper studies and analyzes the structure design, installation and overall layout of thermoelectric generator, and forms a closed loop for thermoelectric power generation system through electric energy collection circuit:

1. By analyzing the basic principle and formula derivation of thermoelectric effect, this paper analyzes the variation of power generation efficiency and output power with external temperature difference and external load resistance parameters, which provides a research basis for the structure design and layout of thermoelectric generator.

2. According to the working environment analysis of direct air cooling system of thermal power unit, the overall structure of slot type thermoelectric power generation system is designed. According to the characteristics that the temperature field of air cooling unit increases gradually from top to bottom, the layout scheme of thermoelectric power generation system in air cooling unit is designed.
(3) Finally, the energy collection circuit of the thermoelectric system is designed to lay the foundation for the industrial application of the thermoelectric system

References
[1] Jin, XZ., Xu, Y., Zhang, JH. (2013) Design of air cooling island temperature monitoring system for 300MW units. J. Computer Simulation., 30 (11): 112-114.
[2] Bao, LL., Han, YH., Zhang, YZ., Meng, QS. (2015) Research on thermoelectric technology and industrial waste heat thermoelectric system design. J. Ordnance Materials Science and Engineering., 38 (02): 110-114.
[3] Yan, LQ., Cheng, J., Liu, MY. (2015) On thermoelectric power generation. J. Solar Energy., (1): 11-15.
[4] Gao, M., Zhang, JS., Rowe, D.M. (1996) Thermoelectric Conversion and its Application. Ordnance Industry Press, Beijing.
[5] Chen, W., Liang, Y., Hu, CJ., Zhai, JG. (2016) Structural design of new thermoelectric device. J. Thermal Power Engineering., 31 (03): 125-128 + 146.
[6] Zhang, N., Li, P., Xiao, JS. (2008) Analytical model of output power and efficiency of thermoelectric power generation devices. J. Journal of Wuhan University of Technology., 30 (1): 9-12.
[7] Chen, LJ., Mi, LJ., Xu, C., Lei, Y. (2010) Development analysis of direct air cooling and indirect air cooling under new situation. J. Power Station System Engineering., 26 (06): 5-6 + 9.