A sandwich-like heat exchanger for low-temperature cogeneration system in factory

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Abstract. Inferior heat power generation can make great profit for factory. As the development of thermoelectric material (TEM), power generation with thermoelectric generators has become a new application area. This paper focuses on applications of low-temperature cogeneration with TEM from Shanghai Institute of Ceramics. A sandwich-like heat exchanger has completed for TEM in this paper. In addition, the system has successfully provided power for illumination in workshops of Baosteel industrial park. In detail, this paper raises a new internal structure of cylinder fins structure and a new external structure of sandwich-like structure for heat exchanger applied on inferior heat power generation in factory. These structures improve the generating efficiency greatly. It is a big step for researches and applications for TEM.

1. Introduction
In steel industry, it is essential to utilize the waste thermal energy in production. The smoke waste heat is superior waste heat, usually over 300°C. The other kinds of waste heat are inferior waste heat mostly, usually about 200~300°C. Superior waste heat’s temperature is high enough, utilized by waste heat boiler and turbine generator. The technology of high-temperature cogeneration is very mature. On the contrary, the low-temperature cogeneration often relies on screw expander technology and other thermoelectric generators (TEG) technology, still in the process of development. Low-temperature cogeneration technology is very promising and has a great application prosperity. Nowadays, there are many researchers working on TEG based on thermoelectric material (TEM). TEM is made of N type and P type semiconducting material. Seeback effect (converting temperature to current) and Peltier effect (converting current to temperature) are two of useful characteristics of TEM. For Seeback effect, TEM can generate power from temperature difference.

TEGs based on TEM started with application on small systems like automobile engine waste heat generation. Historically, Serksnis [1] initially developed a heat exchanger with exhaust pipe structure. However, there is no heat transfer enhancement set in his structure. Birkholz et al. [2] innovated a Hastelloy X rectangular heat exchanger with internal fins structure and aluminum cold side. Bass et al. [3] improved a hexagonal cylinder structure with a center hollow and a discontinuous swirl fins structure for Cummins 14L NTC 350 diesel engine. Thacher [4] et al. proposed a rectangular heat exchanger for 5.3 LV8 gasoline engine, with offset strip fins.

To maximize the thermoelectric efficiency and generation capacity, Crane et al. [5] innovatively integrated numerical cross flow heat exchanger model with TEG model, optimizing the hydraulic
diameters for fins, tubes and cavities. The system with optimal design parameters successfully output a net power of 1000 W. Chad et al. [6] compared five essential structures: single duct, single duct filled with porous metal foams, single duct with fins, multiple parallel counter flow ducts, and multiple serpentine-flow ducts. With analytical method, the compromise programming improved the power density of TEG [7]. Astrain et al. [8] optimized heat exchangers’ thermal resistances.

This paper’s work is based on the researches [9]-[11] of Shanghai Institute of Ceramics, Chinese Academy of Sciences. Their work focuses on inferior waste power generation for automobile engine with their own TEM made of Bi2Te3 and CoSb3. In this paper, we have successfully improved and applied the former work to a new field, inferior waste heat generation in factory. We developed the inner structure of heat exchanger to a cylinder fins structure, and we modify the external structure to a double-decked structure. More importantly, we realized a compact system for TEG in factory, providing power for illumination in workshops. The prototype of our TEG has designed and fabricated by ourselves, considered as an experimental platform for TEM from Shanghai Institute of Ceramics, and a template system for TEG in Baosteel industrial park.

2. Design of heat exchanger
Heat exchanger is the most important part of the system in this paper. It is a device used to transfer heat between different media. In this paper, the heat exchanger transfer heat between two fluid media and a solid medium, specifically the cooling water, the hot air and the TEM. To maximize the generating efficiency, we need to design a fine structure for the heat exchanger to transfer heat quickly and evenly.

2.1. Internal Structure
To determine the internal structure, we take mean temperature, temperature variance, output air speed and air pressure into consideration of internal structure. On temperature, we want the surface heated quickly and evenly. Obviously, we want to maximize the power generating efficiency. One method is to maximize the transfer of heat. For this reason, it is purely good to transmit heat more quickly to TEM on the surface of heat exchanger. In practical use, the output current and voltage of TEM depends on the temperature difference between the cooling water and waste hot air. Approximately, the cooling water keep a constant temperature. So, the output power of TEM nearly only depends on the temperature of the hot side. If the heat of the air transmits to the heat exchanger surface unevenly, the output voltage and current of the TEM will be uneven too. In simple terms, the TEM elements is similar to batteries. The series-parallel connection of batteries with different voltage or current can cause internal friction of power, reducing generating efficiency. As a result, we want to minimize the temperature variance. A least, the surface temperature is symmetry, the output power will be even with appropriate series-parallel connection.
Figure 1. Temperature of five essential internal structure:

On air speed, for our experimental system, the output air speed has a lower limit to circulate in pipeline. Otherwise, hot air will clog in cavity. The pressure will rise and the air is unable to cycle in pipeline. In practical use, the output air speed also has a lower limit in workshops of Baosteel with similar reasons. It is not allowed to set many obstacles in cavity, although it is fine on the angle on maximizing the average surface temperature.

Figure 2. Air speed of five essential internal structure:

On air pressure, the air pressure has an upper limit, which depends on structure and material of heat exchanger. The material of heat exchanger is stainless steel and copper. In detail, the cavities are steel and the obstacles set in cavities are copper. If air pressure in cavity is over than the upper limit, heat exchanger will not withstand the pressure and it will break. We must carefully test the structure on air pressure. Each part of the structure should withstand the air pressure with margin of safety to ensure durability of the system.
(a) Empty cavity, (b) Parallel plate, (c) Serial plate,
(d) Inclined plate, (e) Cylinder fins

Figure 3. Air pressure of five essential internal structure:

Finally, for all reasons above, we choose an improved cylinder fins structure as our internal structure. There are some copper cylinder fins with different distances set as obstacles in cavity. With different distances, it can transmit heat to surface more evenly than structure with equal distances. This structure has tested to be better than essential cylinder fins structure on surface temperature simulation, and almost equal on-air pressure, air speed simulation.

2.2. External Structure
The external structure transmit heat between cooling water, hot air and TEM, including series-parallel of TEM elements. Firstly, we tried a single-cavity external structure. The heat exchanger has one cavity, some water boxes and some TEM. Many TEM fixes on surface of the cavity with hot side sticking to the surface, transferring heat with hot air going through the inner cavity. On the other side, there are some water boxes, providing constant low temperature for the cold side of TEM elements.

(a) TEM elements on cavity surface, (b) a water box, (c) the overall structure

Figure 4. Single-cavity external structure

To transmit heat more quickly and evenly, we design a double-layer external structure for the heat exchanger. The upside, downside and middle part of the external structure are water boxes, circulating cooling water. There are two cavities circulating hot air, circulating hot air. Between the water boxes and cavities, there lies a lot of TEM, generating power from the temperature difference between the cold side and the hot side.
3. Experimental Data of System
After some experiments, we got data of characteristics on TEM network, particularly, the I-P and I-U graph. I-P graph is similar to a quadratic curve.

![Figure 5. Final overall external structure](image)

![Figure 6. I-P and I-U graph with different temperature](image)

The I-U graph is similar to a straight line, which is the characteristic of most batteries. There is a difference between the I-U graph of a piece of TEM and series-plate connection of TEMs. For a piece of TEM, the researches by Shanghai Institute show that its I-U graph has a constant gradient. For series-parallel connection of TEM elements, the more temperature difference is, the larger the absolute value of gradient is. The absolute value of gradient in a battery’s I-U graph represents its internal resistance. After series-parallel connection, the internal resistance is variable as the temperature difference changes. The reasons are many. Logically, when the temperature difference gets larger, the difference of different TEMs gets larger too. There will be more inner friction as a result. So the equivalent inner resistance of the battery system gets larger.

After we studied the characteristics of the TEM network, we did experiment on different series under different temperature circumstances. In detail, we researched on the output current, voltage, power, generating efficiency of Series1, Series2, Series3, Series4, Series5, Series6, when the temperature of the hot side is 230℃, 180℃, 150℃ and 150℃.
Figure 7. Experimental Data of different TEM series

From these data, the maximal voltage, current, power difference of six TEM series is under 1%. There is not large inner electronic friction of six TEM series, they are quite similar to each other. The main inner friction happens in these series, because the temperature of air will drop through the heat exchanger. Maximizing the generating efficiency is often incompatible with maximizing generating capacity.

4. Conclusion

In conclusion, we have successfully designed a sandwich-like heat exchanger for an experimental system for TEM. We have designed a new internal and external structure of heat exchanger. For application, we have successfully provided power for illumination in workshops in Baosteel industrial park. It is very instructive for researches and applications of TEM in practical use. It will be the footstone of low-temperature cogeneration in factory with TEM in the future, saving great amount of energy and making promising profit for Baosteel co. ltd.

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