Investigations on an oriented cooling design for thermoelectric cogenerations

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Abstract. In thermoelectric application, it is widely known that the material limitation has still been the chief barrier of lifting its application to a higher level. Continuous efforts are extensively being made in developing novel material structures and constructions for thermoelectric modules with higher conversion efficiency. However, the overall system efficiency, which is one of the major parameters that most of the engineer and users care about, is not only ruled by the properties of applied thermoelectric materials, but also decided by the design of heat exchangers used on both sides of thermoelectric modules. Focusing on the cooling capacity and hydraulic characteristics of heat exchanger, this paper introduces an oriented cooling method for the domestic thermoelectric cogeneration, which delivers system efficiency up to 80%. This purpose-oriented cooling plate is designed for thermoelectric cogeneration for the residential houses installed with boiler or other heating facilities with a considerable amount of unused heat. The design enables Thermoelectric Cogeneration System (TCS) to be flexibly integrated into the existing hydraulic system. The mathematical model for the cooling plate has been established for a well understanding at the theoretical level. The performance of cooling plate has been investigated in a series of experimental studies which have been conducted under different coolant inlet velocity and temperature. The economic operating zone in which a good system performance could be achieved has been discussed and identified for the current configuration.

Key words: Cooling plate, thermoelectric application, system efficiency

1. Introduction

In thermoelectric applications, the design of heat exchangers has found the important position in creating optimum thermal conditions for the great performance of thermoelectric applications. The cold side heat exchanger, which shoulders the responsibility of cooling the cold side of thermoelectric module, decides where and at what rate the heat is dissipated into the environment or managed for other purposes. The cooling methods that have been used in thermoelectric power generations normally include fan cooling, heat pipe and water cooling. They can be classified into active cooling (fan/water cooling) and passive cooling (heat pipe). In previous researches [1], [2], [3], fan cooling is the most used one which dissipates heat to the environment. A typical installation is shown in Figure 1.

![Figure 1 Typical cooling fan for thermoelectric power generation](image-url)
Fan cooling is effective due to its forced convection. The disadvantage lies in extra electricity consumption, short lifespan, existence of moving parts which causes noisy operation and waste of unconverted heat. Methods such as heat pipe combined heat sink keep cold side temperature at a low level by extracting the heat from module surface and dissipating it into the environment. It uses phase change process to transmit heat without consuming energy. Figure 2 shows two typical examples.

![Figure 2 Passive heat dissipating method: heat pipe sink (a heat pipe; b thermosyphonic heat sink [4])](image)

The advantages of this method is energy saving and quiet due to its zero energy consumption and none moving parts compared to other methods that are related to the use of cooling fan. However, both of them dissipate the unconverted heat into local environment, which optimistically helps improve the local thermal condition if heat is required by the local environment such as in winter, or it deteriorate the thermal condition if the heat is not required such as in summer. It delivers low system efficiency, takes up a large space and increases the system weight, not practical for compact systems.

An oriented cooling method involves the optimum match of hydraulic characteristic and heat exchange capacity. The pressure drop caused by utilising heat exchanger is directly related to the hydraulic characteristic. The capacity of a heat exchanger needs to match with the system. If it is smaller than that required by the system, the conversion efficiency would be decreased because of the lowered temperature difference across the generators. If it is bigger, it would consume more energy. Therefore, an oriented cooling design needs to take these two factors into account.

2. Structure and construction

Reviewing all the recent thermoelectric applications, there are two ways of assembling thermoelectric modules, which include individual assembly and whole assembly. In practical applications, when the system uses multiple modules, the typical assembly method is sandwiching all the modules together between two surfaces of heat exchangers. This assembling method is called whole assembly, shown in Figure 3b.

![Figure 3 Schematic diagram of individual assembly (a) and whole assembly (b)](image)
In the whole assembly, the pressure is loaded on each module ceramic substrate from the same surface. Uneven pressure load could be caused by two major factors: module thickness difference and distance to the fastening screws. The module thickness difference makes each module take the pressure at different level. The more different the thickness, the more uneven the pressure load on each module will be. Consequently, the system performance is farther from the optimum performance because the pressure load is one of the factors that determine the system performance by affecting the heat transfer. It can even damage the modules due to the concentrated pressure load at the corner or edge. The distance to the screw affects the pressure load because the torque value is related to it. The torque deforms the surface and the degree is decided by the material and thickness of the mounted surface.

Figure 4 Thickness of 20 random thermoelectric modules

Figure 4 shows the thickness of 20 thermoelectric modules which are randomly chosen from new modules. They are measured by a digitronic calliper. It lies in the range of 3.84mm-3.96mm with 0.12mm maximum thickness difference. This creates a pressure load difference on the modules which consequently degrades the module performance proved by a pair of comparison tests, the result is shown in Figure 5. At temperature difference 130K, the power output of individual assembly is 54% more than the average power output of single module in whole assembly. This difference is bigger when the temperature difference is higher.

Figure 5 Single module performance in whole assembly (WA) and individual assembly (IA)

The whole assembly, despite the possibility of degrading thermoelectric performance, shows a large module density. It is suitable for the facilities with limited space. However, restrictions on the thickness difference can be adapted in the module selection to make sure the thickness difference is not in the performance-degrading range.

Individual assembly means each thermoelectric module is individually assembled with a set of assembling configurations, shown in Figure 3a. Due to being sandwiched between individual pair of surfaces, the pressure load on each module can be equally set at the optimum level. In this study, a cooling plate oriented for domestic thermoelectric cogeneration is presented. The plate structure is shown in Figure 6 with a looped flow channel. This design enables the flow to “sweep” the whole plate simultaneously, which gets a good uniformity of temperature distribution on the surface by
reducing the temperature accumulating effect. In the real application, the cooling plates are integrated into existing hydraulic system between the feed water and boiler. The tap water is preheated in the cooling plates before goes to the boiler. The cooling plate plays two roles: establishing thermal condition for generation and preheating tap water for the boiler.

![Cooling plate](image)

**Figure 6** Cooling plate for thermoelectric cogeneration

The test block consists of a cooling plate, an oil tank and a thermoelectric generator. The thermoelectric module is sandwiched between the cooling plate and oil tank by four stainless screws. A flat metal washer, a crinkle washer and a fibre washer are placed between the screws and the cooling plate. The crinkle washer and fibre washer accommodate thermal expansion and eliminate thermal bridge, respectively.

### 3. Modelling

The design of heat exchangers in this system combines the configurations of Figure 7 (a) and (d). On the hot side, it uses an oil reservoir as the heat source which stores the absorbed heat. Heat transfer oil is used to absorb waste heat and solar power. Due to the thermal properties of heat transfer oil, an even temperature distribution can be obtained on the surface attached with the modules. On the cooling side, the cooling plate uses water to take the heat away from the cold side. The design of cooling plate aims at creating an isothermal surface for the module.

![Heat exchange types](image)

**Figure 7** Heat exchange types in thermoelectric applications

Figure 8 shows the thermal cycle in the block. When the heat is supplied on the hot side, the total heat input is split into three directions, $Q_{te}$, $Q_{tb}$ and $Q_{loss}$. Among which, $Q_{te}$ is the heat that flows through thermoelectric module (part is for power generation and the other part is absorbed by heat
sink). $Q_{tb}$ is the part that is transferred to the cooling plate via thermal bridge formed by the screws and $Q_{loss}$ is heat loss from the heat source to ambient environment. $Q_{output}$ is the unconverted heat consisted and taken away by the cooling water. The equation showing the distribution of heat flux is,

$$Q_{input} = Q_{te} + Q_{tb} + Q_{loss}$$

(1)

Among them, $Q_{te}$ and $Q_{tb}$ are used by the system for energy conversion and preheating the water. The sum of them is denoted by $Q_{sys}$. Conversion efficiency and system efficiency are used to characterize the system performance. The former is defined as the ratio of power output to the heat flux that passes through the module, denoted by $\eta$.

$$\eta = \frac{P}{Q_{te}}$$

(2)

The latter is defined as the ratio of the sum of power output and heat output to the overall external heat input, denoted by $\eta_s$.

$$\eta_s = \frac{(P + Q_{output})}{Q_{input}}$$

(3)

![Figure 8 Schematic of heat flow in the test rig](image)

4. Performance

An experimental study has been carried out to investigate its performance. The hydraulic characteristic is investigated by a manometer. It measures the pressure drop at different velocity, shown in Figure 9. The cooling plate is assembled with each module using an experimentally verified assembling method to ensure both sides are well attached with the surface of oil tank and cooling plate.

For the cooling plate, the correlation between pressure drop and the inlet velocity is unknown and here is described by Eq.(4).

$$\Delta P = av^2 + bv + c$$

(4)

According to the test result, a, b and c can be obtained and the correlation is expressed by Eq.(5).

$$\Delta P = 26.3v^2 + 6.0v \quad (R^2=0.9987)$$

(5)
The thermal performance has been investigated on a thermoelectric block test rig. The real time cooling capacity has been tested under different inlet water velocity together with the pressure drop.

![Figure 9 Hydraulic performance of the cooling plate](image)

The conventional thermoelectric generation system only uses the converted energy which is less than 5% in most cases. The unconverted part, which represents over 95% of the absorbed heat, is dissipated to the environment through the heat sink without being actively used. The system introduced in this paper is designed to harvest the absorbed energy to the maximum by utilising both the converted and unconverted energy. This goal has been achieved by using the cooling plate designed specifically for TCS. It enables the system to use up to 80% of absorbed energy by converting it to electrical power and recovering the unconverted energy for heat use, shown in Figure 10. Two cartridge heaters are used to heat the oil in the tank. In an initial test, it takes approximately 4800 seconds for the system to reach the stable operation. In the experiments, each set is tested for 5400 seconds (1.5 hours) to guarantee the data accuracy with 600 seconds for identification of pre-test thermal condition.

![Figure 10 System efficiency with the heat inputs at 47W and 93W](image)

The cooling capacity is defined as the rate at which the heat is extracted from the thermoelectric module by the cooling plate. As previously mentioned, the cooling plate is expected to deliver a required cooling capacity with the lowest pressure drop. In this case, the cooling plate gives the expected capacity by consuming the least energy. The test has been done at different inlet velocity. For each velocity change, the test was run until its output stabilized, which took between 1-2 minutes counting from the beginning. In order to obtain the reasonably accurate result, the time length for each velocity range is set at 10 minutes. The accuracy of the results shown below has been further proved by another set of experiment which delivers the same system performance.

The results show that the power output has hardly changed when the flow velocity changes in the range of 0.12m/s-0.59m/s and the cold side temperature rises up when the inlet velocity decreases. The decrease of inlet velocity increases its thermal resistance, shown in Figure 11. The temperature rise at
the cold side of thermoelectric module leads to an increase of heat output, namely the cooling capacity. It can be described by Eq.(6).

\[ \Delta T = RQ \]  

(6)

Where, \( \Delta T \) is the temperature difference between the cooling water and cold side of the module; \( R \) is the thermal resistance of the cooling plate on the module side; \( Q \) is the cooling capacity.

As shown in Figure 11, \( R \) increases with the decrease of inlet velocity. According to Eq.(6), the temperature difference of cooling plate \( \Delta T \) increases when the inlet water velocity goes down.

The system efficiency defined as the ratio of the sum of power output and heat output to the absorbed energy, increases with the decreasing inlet velocity, shown in Figure 13. However, the conversion efficiency, defined as the ratio of power output to the sum of power output and heat output, shows the opposite trend.

Therefore, provided the heat input doesn't change, we can conclude that the inlet velocity doesn't significantly impact the system’s power output although the conversion efficiency slightly goes down but the heat output is increased by the inlet velocity. The reason can be explained by Eq.(7)

\[ Q_{op} = cA\nu(T_{outlet} - T_{inlet}) \]  

(7)

Where \( c \) is the water specific heat capacity, \( A \) is the cross section area of inlet, \( \nu \) is the inlet velocity, \( T_{outlet} \) and \( T_{inlet} \) are the water temperature at outlet and inlet. When \( \nu \) decreases, \( T_{outlet} \) increases. However, the heat output increases because the weight of temperature rise \((T_{outlet} - T_{inlet})\) outweighs the velocity decrease.
As shown in Figure 13, the system efficiency goes up more significantly when it operates in the range of 0.12-0.27m/s, in which the pressure drop lies in the range of 0-2.9mbar. Based on the discussion, the economic operating zone lies in 0.12-0.27m/s where the system gives higher system efficiency whilst the power output stays at the same level in the higher range of flow rate. The optimum inlet velocity is eventually determined by the combination of the system architecture and the hydraulic conditions in the real applications. Considerations must be taken in the requirement of flow rate of the hydraulic system which the thermoelectric application is integrated in. Taking the domestic boiler as an example, the boiler needs a nominal flow rate of water feed when it supplies hot water to the heating system and hot water user ends. The designed cooling block needs to be tuned to the required flow rate to make sure the normal operation of the boiler while delivering the designed performance.

5. Conclusion
This paper presents a cooling design oriented for thermoelectric cogeneration concept. Different from the traditional cooling method, it enables the system to utilise the absorbed energy from a traditional low level (less than 5%) to over 70%. The cooling plate, which adapts the looped flow channel, delivers the required cooling capacity by showing lower pressure drop compared to the traditional cooling methods. An even temperature distribution, which is beneficial for the performance of thermoelectric generators, has been obtained by employing this cooling design. The system performance has been discussed at different water flow rate and temperature. The economic operating zone has been initially identified for this particular type of system. The impact of cooling water temperature upon the system performance has been analyzed experimentally, which shows a beneficial contribution to the system performance from a lower water temperature although the hot source is not significantly affected. The advantage of the cooling plate also lies in the flexibility of constructing the cooling system and the compatibility of being applied in different on-site conditions. Based on the current structure, further modifications have been made to optimize the geometry. This novel cooling design endows thermoelectric application with the ability of using the absorbed heat to produce electrical power and preheated water by consuming less pump power compared to the traditional cooling methods.

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