Heat exchange analysis of thermoelectric conversion device of automobile exhaust

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Abstract. With the development of economy, people's living standard will be improved and the number of motor vehicles will continue to increase. Among them, automobile exhaust emissions take away a lot of heat, exhaust pollution is also aggravated. This not only accelerates the energy consumption, but also the environmental problems become increasingly prominent. Based on the analysis of thermoelectric effect, the thermoelectric device of engine exhaust is designed and its thermoelectric conversion efficiency is studied in this study, which provides a wide application prospect for saving fuel and reducing the thermal pollution to the environment.

1. Introduction
Economic development improves people's living standards and keeps the number of motor vehicles growing. Among them, automobile exhaust emissions take away a lot of heat, exhaust pollution is also aggravated. This not only accelerates the energy consumption, but also the environmental problems become increasingly prominent. Based on the thermoelectric effect analysis [1-9], the engine exhaust thermoelectric device is designed to study its thermoelectric conversion efficiency. The research shows that the distribution and connection mode of thermoelectric sheet are related to the overall output of the thermoelectric device. The pipe wall should be fully used to convert more heat into electric energy, and the insulation in the non-contact part can reduce the heat loss. The research results can provide a broad application prospect for fuel saving and environmental thermal pollution reduction.

2. Automobile exhaust thermoelectric device
Through the analysis of performance parameters, such as thermal conductivity and high-quality coefficient, the thermoelectric conversion has a certain thermoelectric conversion efficiency by selecting a thermoelectric chip of certain material; the thermoelectric module and connection method are introduced, and the topology structure of thermoelectric chip layout is mainly established. In the connection of thermoelectric chip, different connection methods have certain impact on the power output, so as to establish the topological structure and reasonable distribution of the thermoelectric sheet layout of the thermoelectric device can ensure the stability of power generation output and realize the conversion from heat to electricity, as shown in Figure 1.
3. heat exchange and power calculation of thermoelectric sheet

According to the energy balance equation, the heat exchange between exhaust gas and wall is equal to:

$$\phi = q_m (c_1 t_{f1} - c_2 t_{f2})$$  \hspace{1cm} (1)

Here, $q_m$ is the mass flow, $c$ is the constant pressure specific heat of tail gas, $t_{f1}$, $t_{f2}$ respectively is the temperature of tail gas inlet and outlet. The selected model of the engine YT3800X is a four stroke engine with a rotating speed of 360r/min and a displacement of 0.296l. Then, the volume flow of the exhaust pipe of the engine $q_v = 8.88 \text{L/s}$. The diameter and density of the pipe at the tail gas inlet are shown in the formula: $d = 30 \text{mm}$, $\rho = 0.405 \text{kg/m}^3$. The temperature at the inlet of the pipe is set as 500°C. According to the conservation of mass and the diameter of the inlet pipe, the mass flow is equal to:

$$q_m = \rho q_v = 3.5964 \times 10^{-3} \text{kg/s}$$  \hspace{1cm} (2)

At the same time, in the whole heat transfer process, the convection heat transfer coefficient of the inner wall of the tube $h = 30 \text{W/(m}^2\text{K)}$, the material of the tube is aluminum alloy, the thermal conductivity $\lambda = 200 \text{W/(m} \cdot \text{K)}$, the contact thermal resistance is $r = 1.096 \times 10^{-3} \text{K} \cdot \text{m}^2/\text{W}$, the convection heat transfer coefficient of the fins and the air side $h_2 = 15 \text{W/(m}^2\text{K)}$.

In the following, the single length $L=200\text{mm}$ and double length $2L=400\text{mm}$ are calculated and analyzed respectively, and the generating power of these thermoelectric sheets in theory is obtained.

3.1. generating power of single length thermoelectric sheet

If the tube length is $L = 200\text{mm}$, then each heat exchange area can be determined, and the total heat exchange coefficient and the heat resistance value of each component can be determined.

① Heat resistance of convective heat transfer between exhaust gas and wall

The heat transfer area of the inner wall of the pipe can be determined according to the fin spacing and fin height. The total number of pipes is 104, so the heat transfer area of the inner wall of the pipe $S_{11} = 1.3728\text{m}^2$. According to the convection heat transfer resistance formula, its calculation expression can be expressed as:

$$R_{\text{conv,11}} = \frac{1}{h_{11} S_{11}}$$  \hspace{1cm} (3)

② Heat conduction resistance of pipe wall

The heat is first transferred to the near wall surface by convection, and the heat collected on the wall surface will diffuse outwards, that is, the heat conduction heat transfer will transfer the heat to the outer
wall surface of the pipe, where the heat conduction thickness is 2.8mm, so the heat resistance of the heat conduction part of the pipe can be expressed as:

$$ R_{\text{cond}11} = \frac{\delta}{\lambda_1 S_{12}} $$

(4)

Here $S_{12}$ ($= 0.08976m^2$) represents the total surface area of the outer wall of the pipeline, and the thermal conductivity is $\lambda_1$.

③ Contact thermal resistance

In order to ensure the same heat transfer as the actual heat transfer, the contact thermal resistance is considered here. In the whole heat transfer process, the contact thermal resistance is only discontinuous between two materials, only part of the discrete contact area, the non-contact part is full of air, and the heat passes through the air gap layer in the way of heat conduction, increasing the additional transmission resistance. According to the contact area $S_{13}= 0.048m^2$ of single-layer thermoelectric sheet The contact thermal resistance can be calculated as follows:

$$ R_{\text{touch}11} = \frac{r}{S_{13}} $$

(5)

④ Thermal conductivity and resistance of thermoelectric sheet

According to the selected model of thermoelectric sheet, the thermal conductivity $\lambda_2=1.6W / Km$ , thickness of thermoelectric sheet $\delta=8.0mm$ (thickness of two thermoelectric sheets), the total number of thermoelectric sheets is 42 (the first layer is 12, the second layer is 30), then the average total thermal conductivity area is equal to $S_{13}=0.048m^2$, then the thermal conductivity of thermoelectric sheet can be expressed as:

$$ R_{\text{cond}12} = \frac{\delta}{\lambda_2 S_{13}} $$

(6)

⑤ Convective heat transfer resistance on the air side of the thermoelectric sheet

Since the convective heat transfer on the air side occurs at the cold end of the thermoelectric sheet, assuming that the heat preservation material is used for heat preservation at other places outside the initial contact between the thermoelectric sheet and the pipe wall, which is approximately regarded as heat insulation, the total heat can only be transmitted from the heat conduction of the thermoelectric sheet, where the area of convective heat transfer is also equal to the contact area $S_{13} = (0.048m^2)$, the expression of convective heat transfer resistance is:

$$ R_{\text{conv}12} = \frac{1}{h_2 S_{13}} $$

(7)

Combining the above five thermal resistances, the actual total thermal resistance is equal to:

$$ R_{\text{tot}} = R_{\text{conv}11} + R_{\text{cond}11} + R_{\text{touch}11} + R_{\text{cond}12} + R_{\text{conv}12} $$

(8)

Here, the average temperature of the fluid is expressed by $t_{f1}$, then according to the heat balance equation, we can get:

$$ \frac{\Delta m}{R_{\text{tot}}} = q_m (c_1 t_{f1} - c_2 t_{f2}) $$

(9)

$$ \bar{t}_f = \frac{t_{f1} + t_{f2}}{2} $$

(10)

Because of the temperature function of the specific heat of the gas, equation (9) has only one unknown quantity $t_{f2}$, and $\Delta m$ represents the average heat transfer temperature difference between the
fluid and the environment, \( \overline{t_{f2}} \) can be expressed by the average temperature. Therefore, it is calculated that:

\[
\overline{t_{f2}} = 446 \degree C
\]  

(11)

Then the temperature at the hot end of the thermoelectric sheet is obtained as follows: \( t_h = 462 \degree C \).

The cold end temperature of thermoelectric sheet is about: \( T_C = 443 \degree C \).

According to the thermoelectric effect, the open circuit voltage of the thermoelectric chip is about \( \mu^{' \approx} 0.92v \). Then all the thermoelectric chips are connected in series to increase the output voltage, so the total voltage of the device is about:

\[
U = n \cdot \mu^{' \approx} 42 \times 0.92 = 38.6V
\]  

(12)

Then, in the case of the length of the pipe section, because of the series connection, the current flowing between the power sheets is about \( I \approx 209ma \), then the total power of the power sheets is about:

\[
P = UI \approx 8.1W
\]  

(13)

3.2. generating power of double length thermoelectric sheet

When the length of the pipe is doubled, the corresponding heat exchange area will be changed, the heat transfer effect will be enhanced, and the total heat transfer coefficient of the corresponding flow field will be reduced. The composition of the thermal resistance is the same as that of case 1, but the thermal resistance value will be changed. In the same way, the heat resistance of convection between the exhaust gas and the wall, the heat resistance of the pipe wall, the heat resistance of contact, the heat resistance of the thermoelectric sheet and the heat resistance of convection on the air side of the thermoelectric sheet can be calculated respectively.

Based on the above five thermal resistances, the heat is transferred layer by layer from the tail gas. When the thermoelectric sheet is open, the total heat in the thermoelectric sheet is transferred by heat conduction and heat transfer. The thermal conductivity of the thermoelectric sheet material is generally large, so the heat will be concentrated on both ends of the thermoelectric sheet. For the calculation of the actual total thermal resistance, it can be expressed according to the principle of series thermal resistance superposition:

\[
R_{tot2} = R_{conv21} + R_{cond21} + R_{touch2} + R_{cond22} + R_{conv22}
\]  

(14)

Since the outlet temperature will change, the average temperature of the fluid can be represented by \( \overline{t_{f2}} \). Then, according to the heat balance equation:

\[
\frac{\Delta t_m^{'}}{R_{tot2}} = q_a(c_f, t_f^{'}, t_{f_f})
\]  

(15)

\[
\overline{t_f} = \frac{t_{f_f} + t_{f_2}^{'}}{2}
\]  

(16)

Here, the specific heat is regarded as a function of temperature. For the average heat transfer temperature difference \( \overline{t_{f2}} \), the average temperature of the fluid in the flow field changes due to the change of the outlet temperature of the tail gas, so it is expressed by \( \overline{t_{f21}} \). It can be calculated that:

\[
\overline{t_{f2}} = 398.7 \degree C
\]  

(17)

Then the hot end temperature of the thermoelectric sheet is obtained as follows: \( t_h = 436.3 \degree C \).

The cold end temperature of thermoelectric sheet is about: \( T_C = 411.5 \degree C \).

According to the thermoelectric effect, the open circuit voltage of the thermoelectric sheet is about \( \mu^{' \approx} 1.17v \). According to the length of the pipe section, the number of thermoelectric sheets doubles, and there are 102 thermoelectric sheets. Then all thermoelectric sheets are connected in series to increase the output voltage, so the total voltage of the device is about:
\[ U = n \cdot \mu' = 102 \times 1.17 = 119V \quad (18) \]

Then, in the case of the length of the pipe section, because of the series connection, the current flowing between the generating sheets is about \( I \approx 261\text{ma} \), and the total power of the generating sheets is about:

\[ P = UI \approx 31W \quad (19) \]

The qualitative calculation of the heat transfer of the pipeline under the condition of \( L = 200\text{mm} \) and \( L = 400\text{mm} \). Here, it is assumed that the heat of the pipeline is transferred to the surrounding environment through the thermoelectric sheet at the same time when the pipeline is sealed. In fact, because there is no heat exchange between the contact surface of the thermoelectric sheet and the external fluid, part of the energy cannot be transferred out through the thermoelectric sheet. At the same time, due to the working effect between the thermoelectric sheets and the distribution of the flow field and so on, the output results will be reduced, so the actual overall results are smaller than the calculated results.

### 4. Conclusion

Nowadays, with the improvement of living conditions, the increase of the number of motor vehicles, the tense situation of non-renewable energy and the increasingly prominent environmental problems, people's understanding of energy conservation and environmental protection has been intensified. In this study, through the investigation of automobile exhaust after treatment, combined with the development situation at home and abroad, the waste heat power generation conversion device has been prepared, its thermoelectric conversion efficiency of exhaust waste heat has been studied, and the analysis has been made. The results show that the distribution and connection mode of the thermoelectric sheet are related to the overall output of the thermoelectric device. The pipe wall should be fully used to convert more heat into electrical energy, and the heat loss can be reduced by the insulation in the non-contact part. The improvement of thermoelectric material has a great influence on the output of a single thermoelectric chip. At the same time, the current thermoelectric conversion efficiency is low, many heat is still not recovered, and the power density of the power generation system is low, which is difficult to meet other power supply needs. Therefore, the conversion efficiency of thermoelectric module and thermoelectric device needs to be improved, and the influencing factors need to be further explored.

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