Simulation on Thermoelectric Generator Based on Heat Diversion Control of Automobile Exhaust Gas

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Abstract. In order to make full use of the heat in the internal combustion engine exhaust pipe, based on the typical working condition, the numerical distributions of the pressure and temperature field were carried out. The three-dimensional steady calculation model of the fluid-solid coupling system was established between the exhaust gas and the thermoelectric generator. The structure of the collector was optimized in consideration of the uniformity temperature of the hot end, the continuous operating temperature limit and the back pressure of the exhaust pipe. Simultaneously, a flow diversion control strategy was firstly proposed to divert the exhaust gas. The result showed that, when the length, width and height of the collector box was 400mm 100mm and 110mm, the temperature of the hot side reached 168.80℃, the steady output power was 132W, and the back pressure was 16.8kPa under normal condition. Under extreme condition there were 201.38℃, 186W, and 13.8kPa. Combining with the continuous operating limit of the hot side of TEMs-230℃, this structure can meet the temperature requirements in the hot side and keep in the sustainable range of thermoelectric material through diversion control.

1. Introduction
At present, the engine power conversion efficiency of most internal combustion is only about 40%[1], most of heat energy is dissipated into the air causing huge energy waste and serious environmental pollution, it is necessary to take reasonable measures to reduce the heat loss and improve the heat utilization efficiency of exhaust gas. Because thermoelectric materials has the advantage of pollution-free, reliable, and long service life[2], the application of thermoelectric power generation technology in vehicles had also been paid much more attention. So, it is important to study the design of high temperature tail gas generators, which is not only related to how to maximize the heat recovery of the system, but also to the overall structure of the exhaust pipe.

The Japan nissan automobile research center installed a flat-panel thermoelectric generator in the middle of gasoline engine exhaust pipe, and it produced 84W of electricity in the road test, and the conversion efficiency was up to 11%[3] when the speed is 60km/h. Cummins conducted an experimental study on a cylindrical thermoelectric generator of a 250kW diesel engine, which produced direct current of 30V/1kW with conversion efficiency of 11% [4].
Current analysis advances were only under constant temperature condition, extreme conditions were not considered such as transient high temperature may cause overheating of the thermoelectric power module, as well as the coupling between the thermoelectric material model and the engine type. Therefore, this paper analyzed the structure of thermoelectric generator radiator and fins from the aspects of temperature and pressure field. Two matching design methods under normal engine operating conditions were proposed, a mathematical model of the airflow in the collector was established, and a control strategy was proposed to solve the problem of thermoelectric generation materials caused by high temperature.

2. Calculation model

2.1. Physical model

Fig. 1 showed an overall structural view of a thermoelectric generator installed in exhaust pipe.

![Figure 1. Overall structure of a thermoelectric generator installed in an exhaust pipe](image1)

The flow diversion control strategy was as follows, by simulating and optimizing the collector structure under two typical conditions (normal and extreme working conditions), electronic control valves were installed at all branches in exhaust pipe to maintain high conversion efficiency. In a thermoelectric generator, an electronic control unit controled the state of the valve by receiving a temperature signal from temperature sensor to diversify the exhaust flow. The flow chart of the traffic offload control strategy is shown in Figure 2.

![Figure 2. Flow chart of the diversion control strategy](image2)
Where: S1 S2 S3 was valve 1 valve 2 and valve3; T1 was hot end temperature of heat collector 1 and T2 was that of collector 2; TP1 was constant and TP2 was maximum temperature of thermoelectric material; TS was the safe temperature.

2.2. Mathematical model

For the heat transfer process in the fluid-solid coupling model of the collector, a three-dimensional turbulence model was used for numerical calculation, and the conjugate heat transfer occurred at the junction of the fluid and the solid [5].

2.2.1. Control equation in fluid region. Assuming that exhaust gas is free fluid and density is incompressible, the control equation [12] is:

1) continuous equation:

\[
\frac{\partial}{\partial \mathbf{M} \cdot \mathbf{j} \cdot \mathbf{i}} \left( \rho \mathbf{u}_\mathbf{i} \cdot \mathbf{j} \cdot \mathbf{k} \right) = 0
\]

Where: \( \rho \) is the density of exhaust gas; \( \mathbf{u}_\mathbf{i} \cdot \mathbf{j} \cdot \mathbf{k} \) is the velocity, \( \mathbf{M}_\mathbf{i} \cdot \mathbf{j} \cdot \mathbf{k} \) is the momentum component X, Y, Z axis in each direction.

momentum conservation equation is:

\[
\frac{\partial}{\partial \mathbf{M} \cdot \mathbf{j} \cdot \mathbf{i}} \left( \rho \mathbf{u}_\mathbf{i} \cdot \mathbf{j} \cdot \mathbf{k} \right) = - \frac{\partial P}{\partial \mathbf{M} \cdot \mathbf{j} \cdot \mathbf{i}} + \frac{\partial}{\partial \mathbf{M} \cdot \mathbf{j} \cdot \mathbf{i}} \left( \mu \frac{\partial \mathbf{u}_\mathbf{i} \cdot \mathbf{j} \cdot \mathbf{k}}{\partial \mathbf{M} \cdot \mathbf{j} \cdot \mathbf{i}} \right)
\]

Where: \( P \) is air pressure; \( \mu \) is fluid viscosity; \( t \) is time.

3) Energy conservation equation is:

\[
\frac{\partial (\rho T)}{\partial t} + \frac{\partial}{\partial \mathbf{M} \cdot \mathbf{j} \cdot \mathbf{i}} \left( \rho \mathbf{u}_\mathbf{i} \cdot \mathbf{j} \cdot \mathbf{k} T \right) = \frac{\partial}{\partial \mathbf{M} \cdot \mathbf{j} \cdot \mathbf{i}} \left( \frac{\lambda_1}{C_P} \frac{\partial \mathbf{u}_\mathbf{i} \cdot \mathbf{j} \cdot \mathbf{k}}{\partial \mathbf{M} \cdot \mathbf{j} \cdot \mathbf{i}} \right) + S_f
\]

Where: \( T \) is the temperature of exhaust gas; \( C_P \) is the specific heat at constant pressure; \( \lambda_1 \) is the thermal conductivity; \( S_f \) is the coupling source of the inner surface of the collector.

2.2.2. Heat transfer equation in solid region. Heat transfer calculations can be simplified regardless of the gravity effect inon. The steady state heat transfer model of the thermoelectric generator was calculated in the solid region. Figure 3 showed a cross-sectional view of the thermoelectric generator.

**Figure 3.** Diagram of the cross-section of a thermoelectric generator
The heat flow from exhaust gas to the inner wall of the collector $Q_1$ mainly includes the convective heat flow transmitted to the non-fin part $Q_2$, the fin part $Q_3$ and the heat flux $Q_f$:

$$ Q_1 = Q_2 + Q_3 + Q_f $$

(4)

The convective heat flow transferred to the non-fin part $Q_2$ is:

$$ Q_2 = \alpha_{h1}A_1(T_g - T_1) $$

(5)

Where: $\alpha_{h1}$ is the heat transfer coefficient of inner wall of the collector; $A_1$ is the cross-section area perpendicular to the thermal conductivity direction; $T_g$ is the exhaust gas temperature; $T_1$ is the inner wall temperature.

The convective heat flow transferred to the fin portion $Q_3$ is:

$$ Q_3 = \frac{\alpha_{h2}P_{rib}}{C}(T_g - T_1)\text{th}(CH_{rib}) $$

(6)

$$ C = \sqrt{\alpha_{h2}P_{rib}/\lambda_2A_2} $$

(7)

$$ \text{th}(CH_{rib}) = \frac{e^{CH_{rib}} - e^{-CH_{rib}}}{e^{CH_{rib}} + e^{-CH_{rib}}} $$

(8)

Where: $\alpha_{h2}$ is the heat transfer coefficient between fins and exhaust gas; $P_{rib}$ is the cross-section perimeter of fins; $C$ is the constant related to the heat transfer coefficient; $H_{rib}$ is the height of fins; $\lambda_2$ is thermal conductivity of fins; $A_2$ is the cross-sectional area of fins.

The heat flow transferred from radiation $Q_r$ is:

$$ Q_r = C_sA_1\left[ (T_g/100)^4 - (T_1/100)^4 \right] $$

(9)

Where: $C_s$ is the emissivity of the radiation system.

Heat flow transmitted on the wall of collector $Q_4$ is:

$$ Q_4 = \lambda_3A_1(T_1 - T_2)/\delta_1 $$

(10)

Where: $T_2$ is the temperature of exterior surface; $\lambda_3$ is the thermal conductivity of wall; $\delta_1$ is the thickness of the wall.

The $Q_{HC}$ consists of four parts: the heat $Q_{HC}$ was released from hot to cold end; the heat $Q_t$ transferred from the exterior wall of heat collector to the hot end; the heat $Q_b$ absorbed by the Peltier effect; the Joule heat $Q_j$ generated by the internal resistance of semiconductor which is equivalent to a half flowing to the hot end and another half flowing to the cold end.

$$ Q_{HC} = \frac{A_3}{\varepsilon_1 + \frac{1}{\varepsilon_2} + 1} \left[ (T_1/100)^4 - (T_4/100)^4 \right] $$

(11)
Where: \( A_3 \) is the surface area of radiation; \( \varepsilon_1 \), \( \varepsilon_2 \) is the emissivity of heat end and that of cold end; \( T_3 \) is the temperature of thermoelectric material hot end and \( T_4 \) is that of cold end; \( \sigma \) is a constant.

The heat \( Q_t \) transferred from the exterior wall of heat collector to the hot end is:

\[
Q_t = K_1 A_4 (T_2 - T_3)
\]  

(12)

Where: \( K_1 \) is the heat transfer coefficient; \( A_4 \) is the heat transfer area of hot side; The heat \( Q_b \) absorbed by the Peltier effect is:

\[
Q_b = \pi_{PN} I = \alpha_{PN} T_3 I
\]  

(13)

Where: \( \alpha_{PN} \) is the seebeck coefficient of thermoelectric material; \( I \) represents the current. The Joule heat \( \alpha_j \) generated by the internal resistance of semiconductor is:

\[
Q_j = I^2 R
\]  

(14)

Where: \( R \) is the internal resistance of thermoelectric material. Therefore, the heat \( Q_{H} \) in the hot end of a single thermoelectric sheet is:

\[
Q_{H} = n[\alpha_{PN} T_3 I + I^2 R / 2 + K_1 A_4 (T_2 - T_3)]
\]

\[
- A_4 \times 5.67 \left[ (T_3 / 100)^4 - (T_4 / 100)^4 \right] \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} + 1
\]

(15)

Where: \( n \) is the number of semiconductor galvanic arms in series of each thermoelectric generator; Similarly, the heat \( Q_{C} \) in the cold end of a single thermoelectric sheet is:

\[
Q_{C} = n[\alpha_{PN} T_4 I + I^2 R / 2 + K_2 A_5 (T_4 - T_5)]
\]

\[
- A_5 \times 5.67 \left[ (T_3 / 100)^4 - (T_4 / 100)^4 \right] \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} + 1
\]

(16)

Where: \( K_2 \) is heat transfer coefficient of the cold end; \( A_5 \) is the area of the cold end; \( T_5 \) is the temperature.

3. Results And Analysis of the Simulation

3.1. Boundary conditions

The thermoelectric generator was located between the three-way Catalytic Converter and the exhaust muffler. The total length was 1000mm and heat collector length was 400mm, the branch pipes were both 50mm far away from the main pipe, the inner and outer diameter of the main pipe was 56mm, 46mm respectively.

In order to study the effect of different engine operating conditions on the hot end temperature and exhaust pipe back pressure, two typical engine conditions were selected. A represented that: inlet pressure and temperature of the exhaust gas was 22.2kPa, 280℃, as well as condition B was 15.3 kPa, 340℃ respectively, the density is 0.615kg/m²; the heat capacity was 1047J/(kg · m²); the thermal conductivity was 0.046W/(m · K); the method for discretization was adopted second-order upwind scheme; the turbulence method was defined as intensity and diameter. the inlet was chosen pressure inlet and the outlet was pressure outlet.
The ambilateral walls are used with the standard wall function method to deal with the flow boundary layer and heat transfer boundary layer at the fluid-solid coupling interface, the convective heat transfer coefficient between the inner wall and exhaust gas is $20\,\text{W/(m}^2\cdot\text{K)}$, and the other walls are natural convection heat transfer; the convective heat transfer coefficient between the air and the cooling fin is $10\,\text{W/(m}^2\cdot\text{K)}$, the external temperature is $300\,\text{K}$.

### 3.2. Simulation on structure of heat collector

Figure.4 and figure.5 showed the relationship between the maximum temperature of exterior surface and length, width of collector under normal and maximum engine condition.

![Figure 4](image1.png) **Figure 4.** The relationship diagram between the maximum temperature of exterior surface and length, width of collector under the normal condition

![Figure 5](image2.png) **Figure 5.** The relationship diagram between the maximum temperature of exterior surface and length, width of collector under the maximum condition

Figure.6 and figure.7 showed the relationship between the back pressure of exhaust pipe and length, width of heat collector in the normal and maximum condition.

![Figure 6](image3.png) **Figure 6.** The relationship diagram between the back pressure of exhaust pipe and length, width of heat collector under the normal condition.

![Figure 7](image4.png) **Figure 7.** The relationship diagram between the back pressure of exhaust pipe and length, width of heat collector under the maximum condition.

The results showed that when the structural dimension was $400\,\text{mm}, 100\,\text{mm}$ and $110\,\text{mm}$, the hot end temperature and back pressure reached $215.66\,\text{°C}, 16.8\,\text{kPa}$ respectively under normal condition; Under maximum condition the temperature and back pressure was $247.19\,\text{°C}, 13.8\,\text{kPa}$ Figure.8 and figure.9 showed the temperature distribution in the normal and maximum conditions after being installed in exhaust pipe.
3.3. Temperature distribution in the hot and cold end

When the structural dimension W=100mm, H=110mm, L=400mm, take the cool fins into consideration, simulate and analyze on the temperature distribution of the overall structure under normal and maximum engine conditions, the temperature was shown in Figure 10 and Figure 11.

4. Conclusion

In this paper, the structural model was established and numerical simulations of exhaust emissions were analyzed under normal and maximum conditions which results showed:

(1) The structural dimension W=100mm, H=110mm, L=400mm was verified as the optimal results which the temperature distribution was relatively uniform.

(2) Under normal condition, the output power of optimal structure was stable to 132W, when the boundary condition was 16.8kPa (back pressure), 168.80°C (maximum temperature within hot end) and 56.39°C (minimum temperature within cold end).

(3) Under maximum condition, the output power reached 186W when the boundary condition was 13.8kPa (back pressure), 201.38°C (maximum temperature within hot end) and 64.96°C (minimum temperature within cold end).

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