Design of diesel exhaust waste heat power generation device

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Abstract. Based on the study of the basic knowledge of thermoelectric effect, the selection of thermoelectric materials, the layout of thermoelectric sheets and thermoelectric modules, this paper uses thermoelectric technology to select thermoelectric sheets suitable for the corresponding conditions, selects high, medium and low temperature sheets for different temperature environments, studies the corresponding pipe sizes, and designs diesel engine thermoelectric devices.

1. Introduction
At present, China's energy shortage and low energy utilization rate are only 33%, which is more than 20 years behind the developed countries. The intensity of energy consumption is far higher than the world average, about three times that of the United States and 7.2 times that of Japan [1]. The automotive sector needs to consume a lot of energy every year. With the increase of global car ownership year by year, it is estimated that the automotive oil consumption will account for more than 62% of the total global oil consumption by 2020. With the rapid development of automobile industry, the energy consumption of vehicles is increasing day by day, which makes the energy situation in China more severe. The investigation shows that only 34%～38% (diesel engine) or 25%～28% (gasoline engine) of the energy generated by the fuel combustion of automobile engine is fully utilized. Other energy is discharged outside the engine. The heat taken by exhaust alone accounts for 30%～45% of the heat generated by the fuel entering the engine. The rest energy is consumed in the form of engine cooling water 30%, vehicle exhaust and friction loss 5%. This not only causes a great waste of energy, but also causes serious pollution of the surrounding air environment. Therefore, energy conservation and emission reduction is the only way to maintain sustainable development, reduce energy consumption and make full use of waste heat to improve energy efficiency. In this study, the thermoelectric technology [2-7] is used to select high, medium and low temperature power generation chips for different temperature environment, study the corresponding pipe size, and design the diesel engine thermoelectric device.

2. Thermal power plant model establishment
According to the relevant knowledge of heat transfer, the heat transferred by the high-temperature tail gas is transferred to the surrounding environment through convection and heat conduction. Therefore, all the heat resistance in the middle can be regarded as a total heat resistance. Then, the heat exchange model between the pipeline and the outside can be simplified as shown in Figure 1.
Therefore, according to the thermal resistance analysis, it is necessary to know the length \( L \) of the pipeline from the designed pipeline. At the same time, considering the practicability, the pipeline in the heat exchange section should not be too long. Therefore, the enhancement of heat transfer has practical significance. From heat exchange between exhaust gas and wall to heat exchange with environment, the heat transfer process can be analyzed as follows through figure 2 heat transfer process thermal resistance:

![Figure 2. Resistance analysis of heat transfer process](image)

3. Design of tail gas thermoelectric device

3.1. selection of thermoelectric sheet

At present, the optimal coefficient of thermoelectric power conversion is generally used to describe the performance of thermoelectric power generation. The development of thermoelectric materials with high optimal value can greatly improve the performance of thermoelectric devices. For thermoelectric materials, they can be divided into low, medium and high temperature thermoelectric materials according to the working temperature. Most of the electrical refrigeration devices are made of low-temperature thermoelectric materials. The thermoelectric sheets selected here Sp1848-27145 is used to connect the thermoelectric sheets in series.

3.2. pipeline design of thermal power plant

In order to realize the conversion between thermal energy and electric energy, it needs enough pipe wall as the heat source, so it can stick with the thermoelectric sheet of the pipe wall as the hot end. The outlet temperature of diesel vehicle exhaust gas is generally very high, and the maximum temperature of thermoelectric device is not more than 750°C. At the same time, in the actual situation, the diameter of exhaust gas flowing through the thermoelectric device pipeline becomes larger, and the gas expands. According to the gas isentropic constant flow and state equation:

\[ P = \rho RT \]  

\[ \frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{(\gamma-1)/\gamma} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma} \]  

Therefore, under a certain mass flow rate, the temperature is reduced due to volume expansion, and some energy losses are ignored in theory. Under the same inlet and outlet conditions, the calculation results will be higher, and the catalyst used in tail gas treatment is suitable for the temperature range of 200 ~ 600°C. The temperature should not be too high. We can arrange the thermoelectric device
before catalytic treatment. Considering the heat loss caused by gas expansion, two different shapes of pipes are designed as the main body of the thermoelectric device.

3.2.1. 3D design of pipeline. (1) hexagon pipe

At the beginning of the design, in order to strengthen the heat exchange, because of the large relative heat exchange area of hexagon, and more thermoelectric sheets are attached to the long wall of unit tube. The inner side of the pipe is 132mm long and 3mm thick. The material can be aluminum with light weight. At the same time, the bolt model $\varnothing = 5\text{mm}$ is used here to connect and fix the pipe. The main body of the pipe is divided into 6 flow channels by the splitter plate, which is 5mm thick. In this way, the flow condition in each sub pipe is roughly the same, and the uneven heat distribution on the wall affects the work of the thermoelectric sheet.

The collector is designed with different rib heights. Considering the obstruction of the splitter plate, the collector can be taken as low on both sides and high in the middle. At the same time, the heat exchange in the middle of the heat exchange wall in the pipeline is more intense than that on both sides. Here, the thickness of the collector rib is 3mm, the spacing is 3.2mm, the rib height is 70mm and 30mm, and there are 14 ribs (including 8 long ribs and 6 short ribs). The specific distance between thermoelectric sheets in the general diagram of thermoelectric sheet installation also needs to be adjusted with the cold end radiator of thermoelectric sheet, including the fixing of the cold end radiator, etc.

In order to ensure the reasonable combination of the engine outlet and the pipeline, a transition section pipeline is required. Here, three $\varnothing = 5\text{mm}$ bolt holes are arranged on each side of the hexagon pipeline. Considering the air tightness, aluminum foil can be used to seal the gap between the transition section and the hexagon pipeline in the middle of the bolt connection. The length of the transition section is 200mm in the preliminary design. Similarly, for hexagon pipes, in order to be able to connect with transition pipes, they can also be connected by bolts. On each side of hexagon, there is a rectangular strip with the size of 110mm $\times$ 15mm $\times$ 5mm. At the contact gap, sealant and aluminum foil can be used for double sealing to ensure good sealing effect. In this case, theoretical calculation shall be carried out according to the pipe length first. The effective cross-sectional area of the pipeline can be calculated as 0.0285m$^2$. The heat exchange area in the pipeline is about 2.316m$^2$.

![Figure 3. Distribution diagram of thermoelectric sheet (hexagon pipe)](image)

According to the design of hexagonal pipeline, the layout of thermoelectric sheet on the wall of the pipeline needs to make full use of the surroundings of the pipeline and arrange reasonably. According to the selected model of thermoelectric sheet, its size is 40mm $\times$ 40mm $\times$ 4mm. Therefore, according to the plan, six thermoelectric sheets can be attached to a single surface. It is estimated that a total of 36 thermoelectric sheets (one layer) can be installed here. Since the distribution of each hexagon surface is the same, the distribution topology of the thermoelectric sheets on a single surface is shown in Figure 3.

(2) Quadrilateral pipeline

Quadrilateral pipes are processed by multi rib fins. Because the ribs of the pipes are evenly distributed, the heat can be fully exchanged with the pipes. There are relatively few gaps in the pipes. The processing can be made of ready-made materials, so there are not many sealing sections at the same time with the processing, which is convenient for sealing.
The pipeline part of the thermoelectric device is mainly composed of four parts, the internal small pipe size is 1.5mm×31.5mm×200mm, the wall thickness between the pipes is 1.1mm, there are four screw holes (M3 rivet holes) on the back for riveting and fixation, the preliminary design takes the length of 200mm, and the four main parts of the pipes are two-to-two, the smooth external surface can be used to attach the thermoelectric sheet, and the engine exhaust gas passes through the middle, which is effective in the pipeline. The cross-sectional area can be calculated as \(9.828 \times 10^{-4} \text{m}^2\), and the heat exchange area in the pipeline is about 1.3728 m².

The splint is used to fix the pipeline. In order to prevent the pipeline from moving along the direction perpendicular to the flow channel, the splint is added with small teeth with a height of 2mm. At the same time, the design plywood thickness is 15mm, and the length is 200mm as the pipe length. The fixed flange and transition section pipe are convenient for fixing the thermoelectric device pipe and connecting with the engine exhaust gas outlet. Considering the tail gas purification pipe at the back, the inner diameters of the transition section pipe inlet and outlet are 30mm and 50mm respectively, and all gaps are sealed with fire-proof sealant and aluminum foil. The bolt hole size is \(\varnothing = 5\text{mm}\).

According to the quadrilateral pipeline design, the thermoelectric sheet is arranged on the smooth four walls of the pipeline by using the quadrilateral wall surface. Because the size of the thermoelectric sheet is 40mm×40mm×4mm and the length and width of the quadrilateral are different, the unworthy topological structure of the thermoelectric sheet is shown in Figure 4. It is estimated that 30 thermoelectric sheets (one layer) can be installed here.

![Schematic diagram of thermoelectric sheet layout (quadrilateral pipeline)](image)

**Figure 4.** Schematic diagram of thermoelectric sheet layout (quadrilateral pipeline)

3.2.2. **Pipeline selection.** For hexagon and quadrilateral pipes, considering the different design advantages of the two pipes, the quadrilateral pipes are selected based on the following factors:

1. Considering that the exhaust gas outlet of diesel vehicles has a great impact on environmental pollution, the requirements for sealing are very high. For hexagon pipes, because there are more gaps, it is easier to leak. At the same time, the concave part of the joint at both ends of the pipe is not easy to seal due to the uneven between the collector and the wall surface; while for quadrilateral pipes, because the wall surface is flush, the overall pipe gap wants to be less, Reduce the risk of leakage.

2. The heat exchange area of hexagon pipe is large, but the processing difficulty is increased. From the pipe to the collector to the joint, the processing difficulty is high; the main body of quadrilateral pipe can directly use the existing fins, so the processing is simple and time-saving.
(3) compare the distribution of flow field under the same inlet condition, as shown in Figure 5. The flow velocity of the fluid near the fins of the hexagonal pipe is very low, but the flow in the center of the pipe is fast, and the flow field distribution is uneven, so that the heat of the tail gas in the center cannot be fully exchanged with the wall; while the flow field in each channel of the quadrilateral pipe is evenly distributed and roughly the same, which not only avoids the uneven heat distribution, but also makes the heat exchange between the tail gas and the wall, reducing the heat waste.

(4) According to the comparison of cross-sectional area in the pipe, it can be found that the cross-sectional area of hexagon pipe is large, and when the tail gas flows out from small caliber, it will expand. According to formula (1) ~ (2), it can be found that the gas expansion will reduce the temperature, resulting in more energy loss.

According to the theory of heat transfer, strengthening heat transfer can increase the heat exchange area, which is convenient for heat diffusion. However, other factors need to be taken into account in the specific consideration. Here, the quadrilateral pipe is selected and the theoretical calculation is carried out.

![Figure 5. Velocity field distribution of the longitudinal section in the center of the pipeline](image)

4. Conclusion
Energy conservation and emission reduction is the only way to maintain sustainable development, reduce energy consumption and make full use of waste heat to improve energy efficiency. In this study, through the basic knowledge of thermoelectric effect, the selection of thermoelectric materials, the arrangement of thermoelectric sheets and the understanding and research of thermoelectric modules, the working mechanism of thermoelectric device is consulted and studied, the thermoelectric sheets suitable for the corresponding conditions are selected, the high, medium and low temperature sheets are selected for different temperature environments, the corresponding pipe sizes are studied, and the diesel engine thermoelectric device is designed.

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