Study on the Compatibility between Heat Exchanger used in Automobile Exhaust Thermoelectric Generator and Engine

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\textbf{Keywords:} Automobile exhaust thermoelectric generator, Simulation, Back pressure, Temperature uniformity, Temperature distribution

\textbf{Abstract.} To enhance the compatibility between heat exchanger used in automobile exhaust thermoelectric generator (AETEG) and internal combustion engine, three different kinds of layouts among heat exchanger, muffle and catalytic converter are designed, and the effects on the temperature uniformity and temperature distribution of heat exchanger, the back pressure of engine are also analyzed respectively. The simulated results reveal that the sequential layout of three-way catalytic converter-heat exchanger-automotive exhaust muffle is the best choice, for it ensures the smallest back drops of engine, considerable temperature uniformity and relatively higher temperature distribution of heat exchanger on the same occasion, which improves the performance degradation of engine during the exhaust thermoelectric generation and provides guiding reference for the optimization of AETEG.

\textbf{Introduction}

The utilization efficiency of fossil fuel energy in internal combustion engine of traditional automobiles is below 30\%, while nearly 40\% of the rest one is wasted from exhaust directly \cite{1}, recovering the exhaust heat energy with thermoelectric technology and employing the generated power in the vehicle system is the research focus all over the world \cite{2}. However, the added heat exchanger with certain flow field structure will affect the original performance of engine for it can change the back pressure of exhaust emission, and the worst thing is that the generated power can’t even compensate the degraded performance of engine.

To improve the emission performance and noise characteristic of engine, three-way catalytic converter and automotive exhaust muffle are essential in the development of AETEG. Different AETEGs, different layouts among heat exchanger, automotive exhaust muffle and three-way catalytic converter. In this paper, the compatibility between heat exchanger and internal combustion engine was evaluated.

\textbf{Layout and Schematic of AETEG}

Three Different Kinds of Layouts. According to the distribution sequence, there are three different kinds of layouts among heat exchanger, muffle and catalytic converter. In case one shown in Fig.1, catalytic converter and muffle are connected to the outlet of engine in sequence, heat exchanger is fixed behind muffle. In case two shown in Fig.2, heat exchanger is distributed between catalytic converter and muffle, while in case three shown in Fig.3, heat exchanger is firstly connected to the outlet of engine, then, its outlet is connected with catalytic converter and muffle in sequence.
Structure of Heat Exchanger. The interior flow field structure of heat exchanger designed is made of red copper, as shown in Fig.4, there are several fins with different sizes and shapes inside it, and its dimensions are also provided, all the unit marked is millimeter [3].

Engine. The engine adopted in AETEG designed above is made in CITRON of France (PSA RFN 10LH3X), its capacity is 1997cc, its maximum power is 108 kW when the rotate speed is 6000 r/min, the maximum torque is 200NM when its rotate speed is 4000 r/min [4].

Simulation and Analysis

Fundamental Assumptions and Control Equations. Before the simulation, the fluid is supposed to be steady and impressible, the thermal radiation and thermal contact resistance are ignored. Therefore, the flow and heat transmission are expressed with continuity equation, momentum conservation equation and energy conservation equation which are given in Eq. 1, Eq. 2 and Eq. 3, respectively [5].

The continuity equation is as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

(1)

where $u$, $v$ and $w$ are the $x$, $y$ and $z$ axis vectors of flow velocity, respectively.

The momentum conservation equation is:
\[
\begin{align*}
\rho \left( \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) &= \frac{\partial \rho}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \\
\rho \left( \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) &= \frac{\partial \rho}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \\
\rho \left( \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) &= \frac{\partial \rho}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)
\end{align*}
\]

(2)

where \( \rho \) is the fluid density, \( \mu \) is dynamic viscosity, \( u, v \) and \( w \) are the same meaning as those above.

The energy conservation equation is as follows:

\[
\rho c_p \left( u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]

(3)

where \( c_p \) is the specific heat capacity of fluid, \( T \) is fluid temperature, \( \lambda \) is thermal conductivity.

Boundary Conditions. As to heat exchanger, the velocity inlet boundary is adopted, in the simulation process, when the inlet velocity of heat exchanger is 40m/s, its temperature is 773K, the corresponding fluid density is 0.457 kg/m\(^3\), the thermal conductivity is 0.0656 W/(m·K), the specific heat capacity is 1185 J/(kg·K), the dynamic viscosity is 3.48\times10^{-5} \text{ kg/(m·s)}. While its outlet applies pressure outlet boundary, its outlet pressure is a standard atmospheric pressure. As to red copper heat exchanger, its density is 965 kg/m\(^3\), its thermal conductivity is 388 W/(m·K), its specific heat capacity is 381 J/(kg·K).

Temperature Distribution. Based on the basic thermal transmission equations and boundary conditions above, the Fluent software is applied in this paper, the working condition that the flow velocity of engine is 15m/s, and the inlet temperature of engine is 623K which is the maximum ambient temperature of thermoelectric module is adopted, on this occasion, the temperature distributions of the three different cases of layouts above are given in Fig.5, Fig.6 and Fig.7, respectively.

Figure 5. Temperature distribution of layout in case one.

Figure 6. Temperature distribution of layout in case two.
As shown in Fig.1, in case one, even though the temperature of catalytic converter is above its initiation temperature, muffle can work normally, the average temperature of heat exchanger is only 210°C, and its local temperature is 170°C, it is too low to set up higher temperature difference of each thermoelectric module. As to case two shown in Fig.2, both catalytic converter and heat exchanger can work normally, and the temperature of heat exchanger is above 270°C, which ensures the efficient power generation of thermoelectric modules. While in case three presented in Fig.3, the average temperature of heat exchanger is 280°C which is a little higher than that in case two, the inlet temperature of catalytic converter is only 230°C, its local temperature is only 160°C, for the normal initiation temperature of catalytic converter is about 250°C, it can’t work regularly on this occasion.

Temperature Uniformity. To further analyze the temperature uniformity of heat exchanger with different layouts above, the temperature uniformity coefficient $\gamma$ was put forward, it is described as follows:

$$\gamma = 1 - \frac{1}{\sqrt{n}} \sum_{i=1}^{n} \frac{\sqrt{(T_i - T_{mean})^2}}{T_{mean}}$$

(4)

where $n$ is the number of temperature detecting points, $T_i$ is the average temperature of the $i$th temperature detecting point, $T_{mean}$ is the average surface temperature of heat exchanger, $\gamma$ changes from 0 to 1, when it was equal to 1, it means all the temperature are the same.

For there are 30 thermoelectric modules arranged above the hot surface of heat exchanger, the temperature detecting points are selected to be 30, based on the temperature distribution above, the simulated uniformity parameter of heat exchanger with different layouts are given in Fig.8. The temperature uniformity decreases steadily as the engine speed increases for all the temperature of each detecting point changes obviously, in case two, the temperature uniformity of heat exchanger maintains from 0.78 to 0.71, which is more superior to that in the other two cases.
Back Pressure. Considered the increased back pressure will add load to engine, the working condition that the rotation speed of engine from 1000r/min to 3000r/min is simulated [6], the pressure drops in the three different cases of layouts presented above are given in Fig.9, Fig.10 and Fig.11, respectively. It reveals that the exhaust flows quicker as the rotation speed of engine increases, and its back pressure rises accordingly. In the three different cases of layouts, the pressure drops of both catalytic converter and muffle are almost the same as each other. While in case two, the pressure drops of heat exchanger is much lower than those in the other two cases, even though the rotation speed of engine is 3000r/min, the pressure drop of heat exchanger is only 127Pa, considered the back pressure of engine is from 15KPa to 40KPa when it is at the state of normal operation, the back pressure brought in by heat exchanger in case two can be ignored to some extent.
Compared with the simulated pressure drops cause by different layouts above, it can be concluded that the layout in case two is advantageous, layout in case one takes the second place, while layout in case three is the worst choice for it largely increases the back pressure of heat exchanger.

**Conclusions**

Different layouts of AETEG, different temperature distribution of heat exchanger and pressure drops brought to engine. For the performance of AETEG is affected by temperature difference of each thermoelectric module, catalytic converter has its own proper functioning temperature, and the evidently increased back pressure of engine will degrade its dynamic property and fuel economy, the layout of AETEG is significant. Compared with the layouts in case one that heat exchanger is behind both catalytic converter and muffle as well as in case three that heat exchanger is before both catalytic converter and muffle, the layout that heat exchanger in the middle of catalytic converter and muffle has evident advantages over them, for it not only ensure proper working temperature for catalytic
converter and thermoelectric modules, but also bring negligible back pressure to engine on the same occasion.

Based on the results above, in our practical work, the layout of case two is adopted in both test bench and AETEG applied in vehicle, for the length limitation of paper, the specific experimental results will be provided in further.

**Acknowledgement**

It is a project supported by National Key Basic Research Development Plan (973 Plan) (Grant No. 2013CB632505), National Natural Science Foundation of China (Grant No. 51407063) and Doctor Scientific Research Foundation of Hubei University of Technology (Grant No. BSQD13064).

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