CHEMICAL ENGINEERING TRANSACTIONS
VOL. 59, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Zhuo Yang, Junjie Ba, Jing Pan

ISBN 978-88-95608- 49-5; **ISSN** 2283-9216
DOI: 10.3303/CET1759007

Design and Research of Automobile Exhaust Heat Energy Conversion Device

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With the progress of the times, the car has become an indispensable part of people's lives. However, the development of the automobile industry has brought enormous benefits to human beings, while it also consumes a lot of energy and pollutes our living environment. Therefore, this paper intends to use automobile exhaust heat combined with thermoelectric generator to recover part of the energy consumption of automobile. The energy can be converted into electric energy to supply the muffler with purification function, so as to achieve the purpose of energy saving and emission reduction. This paper summarizes the advantages and disadvantages of the first-generation exhaust gas temperature difference generator. In order to improve the power generation, the second-generation exhaust gas temperature difference generator is designed. The utility model has the characteristics of a hexahedron structure and is internally provided with a fin vortex structure. The utility model can increase the airflow disturbance, thereby improving the heat transfer efficiency and the generation power. In addition, using GT-POWER software, a small and medium sized vehicle engine is used as the research object. The simulation results show that the noise value of the engine is between 3500 and 6000r/min. Peak noise is in the 110-124dB interval, and the corresponding frequency of high noise values is in the 180-200HZ, which increases with the speed changes. The simulation results provide the basis for the design of the muffler. Based on the optimized design, the exhaust gas temperature difference generator is processed in real time. The experimental results show that the exhaust gas temperature difference generator designed in this paper has higher power generation efficiency, and it can meet the demand of power supply for the tail gas purification.

1. Introduction

With the sustained and in-depth development of China's social economy, modern industry has created enormous wealth for mankind. Meanwhile, it has brought serious pollution to the ecological environment, especially the air environment. All kinds of poisonous gas, pollution gas and automobile exhaust are the main causes of air pollution (Ibrahim, et al., 2010; Zhao et al., 2016; Arapatsakos et al., 2015; Gattuso et al., 2016; Cannistraro et al., 2016; Lozano et al., 2016). However, the contribution rate of automobile exhaust pollution to the air pollution index of large cities is more than 60%. Data show that 98%-99% NOx generated by automobile exhaust is directly discharged into the atmosphere by the exhaust pipe, and the total amount of NOx emissions within a year can reach 5.21×10^{7}t. This kind of NOx can lead to the formation of photochemical smog and acid rain and other hazards under certain conditions, resulting in serious damage on human health and ecosystems (Liu and Li, 2015). At present, governments often use strict control measures of vehicle exhaust emissions, vehicle management, traffic control, and fuel oil restrictions to curb the production of NO (Rehman, et al., 2016). However, due to the rapid and sustained growth of China's car ownership (nearly 264 million vehicles by the end of 2014), the management is not standardized, resulting in the concentration of NO into the urban atmosphere exceeded two. Therefore, the NO pollution caused by motor vehicle emission has become a thorny problem which has to be faced with.

After entering in the 21st century, with the rapid development of automobile industry in our country, the energy consumption of vehicles is increasing day by day. Unfortunately, the vehicle fuel energy has not been fully utilized (Jeng, et al., 2016). Therefore, in order to effectively achieve the purpose of energy saving and

Please cite this article as: Yuelei Wang, 2017, Design and research of automobile exhaust heat energy conversion device, Chemical Engineering Transactions, 59, 37-42 DOI:10.3303/CET1759007

emission reduction, this paper intends to design a high thermoelectric conversion efficiency of gasoline engine exhaust gas temperature difference generator and exhaust gas purification muffler. The exhaust gas temperature difference power generation device is used to recover the exhaust gas of the automobile, and the automobile exhaust gas is preheated and replaced with a power supply, which is provided with a muffler with exhaust gas purifying function (Li, et al., 2016).

In 1847, Tektronix developed the first thermoelectric generator, but its power generation efficiency was very low. In the following time, new explorations were made. However, with the passage of time, people gradually discovered the value of the recovery of automobile exhaust gas. The thermoelectric generation technology is applied to the automobile, and the exhaust gas is used as the heat source to generate electricity. The thermoelectric generator designed by Nissan Motor Company in Japan is installed in the middle of the gasoline engine exhaust pipe, and the exhaust gas temperature is up to 8000 °C. The design installs 72 modules on the outer wall of the rectangular area on the inner channel (Fang, et al., 2016). A module consists of 8 pairs of thermocouples (Chen, et al., 2015). When the temperature difference reaches 563 K, the output power of a single module is 1.2 W. Under the test condition that the car climbs at 60 km/h speed, the exhaust gas temperature difference power generation device can convert 11% of the energy in the exhaust gas, and its power generation amount is 35.6 W. At home, Wuhan University has also studied the automobile exhaust temperature differential power generation. Their design is to exhaust the exhaust gas from the engine and convert it through a thermoelectric generator. The electric energy is used to charge the battery or to the electrical equipment through the battery management system. The thermoelectric generation section is fitted with the 41.44kw output power when the engine speed is 3000 r/min (Hendricks, et al., 2016; Zhou, 2015).

2. Car muffler

Muffler is a part of the automobile exhaust system, its main role is to effectively reduce engine exhaust noise, and ensure that the smooth exhaust and engine exhaust resistance is small.

2.1 Classification of automobile silencer

(1) Resistance muffler

The basic principle of the resistance muffler: Noise absorbing material is combined with the muffler structure to absorb noise, which is usually good for medium and high frequency noise. Generally speaking, the effect of the muffler is related to the nature of the material used. If the density of the material is large, then the sound absorption effect is better in the initial stage. With the increase of the density of the material, the effect of the noise reduction will be decreased with the increase of the density of the material. Therefore, there is an optimum range for each kind of material. At present, the main sound absorption materials are glass fiber filament, low carbon steel wire mesh and wool chain (Schmidt, et al., 2016).

(2) Reactive muffler

The basic principle of the reactive muffler: The flow of air through a sudden enlargement or reduction of the cross section of the muffler will produce wave reflection and interference, which can reduce the energy of sound waves. In general, the effect of the muffler on the low and middle frequency noise is good, and the effect of the high frequency noise is poor (Wei, et al., 2017).

(3) Impedance compound muffler

The basic principle of the muffler is the superposition of the resistance and the resistance, so as to achieve the purpose of the low, medium and high frequency noise. On the basis of fully understanding for the noise, usually, the resistance muffler is designed at the inlet end of the airflow, and the resistive muffler is designed inside the muffler.

(4) Resonator muffler

The basic principle of resonance resistance muffler is to use resonance system to eliminate noise. The resonance system consists of a pipe with a certain number of small holes and a closed cavity outside the tube. In noise elimination, part of the sound wave is absorbed by the small hole in the pipe and is rubbed against the inner wall, so that the sound energy is converted into heat energy and consumed. The other part will be reflected back by the resonant cavity wall, so that the energy of the acoustic wave is attenuated to achieve the purpose of silencing.

2.2 Evaluation index of muffler

The evaluation of muffler is mainly from two aspects: acoustic performance and aerodynamic performance. The evaluation indexes of acoustic performance mainly include acoustic attenuation, radiation noise, insertion loss, tail pipe noise and transmission loss. The evaluation indexes of aerodynamic performance mainly include pressure loss and resistance coefficient. Acoustic performance evaluation index is to ensure that the muffler can have a sufficient frequency range and the amount of noise elimination (Tao, et al., 2015). However, the

evaluation index of aerodynamic performance is to ensure that the air flow resistance in the process of noise elimination should be small as soon as possible. The following is the main acoustic performance of two mufflers:

Tailpipe noise: Muffler tail pipe noise is one of the key evaluation indexes to evaluate the performance of muffler. Its specific manifestation is the ripple noise, and it is composed of air noise and air friction noise. The proportion of air noise and air friction noise depends on the size and speed of airflow in the muffler. When the engine speed is low, the flow velocity of the muffler is small and the flow rate is low. At this time, the air noise accounts for main proportion. If the engine speed is high, then the flow rate is high and the flow rate is high. At this time, the friction noise accounts for main proportion. Therefore, we should always monitor the engine speed in the design of muffler as far as possible to reduce the friction noise muffler.

Radiated noise: The radiated noise of the muffler is produced by the vibration of the muffler shell and other mechanical components. According to this definition, we can see that when the sound wave is excited, a forced bending vibration wave is generated along the shell and pipe. At a certain frequency, the wavelength of the bending wave is equal to that of the incident wave in the air. The two wave produces resonance, and the shell produces a coincidence effect. At this time, the radiation noise of the muffler reaches the maximum value, then the lowest frequency f_c of the anastomosis effect can be expressed by the Eq (1):

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{\mathrm{M}}{\mathrm{B}}} = \frac{\mathrm{c}^2}{2\pi \mathrm{t}}\sqrt{\frac{12p}{E}} \tag{1}$$

In the Eq (1), C is the sound velocity (m/s). M is the surface density of the shell or pipe (kg/m^2). B is the acoustic stiffness. t is the thickness of the shell or pipe (m). p is the density (kg/m^2). E is the elastic modulus (N/m^2).

3. Engine exhaust noise simulation based on GT-POWER

3.1 Introduction to GT software

GT-power is a simulation module in the GT-suite software package, which is mainly used for engine performance and noise simulation. At the same time, it can also complete the design of the engine electronic control function. GT-suite is also known as the virtual engine, which is widely used in the field of engine performance simulation. It includes GT-power, GT-drive, GT-cool, GT-crank, GT-vtrain. Each module is based on the same operating platform, and the data between modules are compatible with each other.

The detailed model of all the critical conditions of the engine is included in the GT-power software. The software can simulate the actual operation of the engine in different conditions. In GT-power, there are many thermodynamic models that can accurately simulate the operation of an engine, such as chemical models, combustion heat transfer and fluid mechanics models. It is convenient to build engine models by using GT-power. Because there are a lot of off the shelf modules for us in GT-power, such as turbocharger module units and intake and exhaust module units, these are very practical. For some complicated, compressible, nonlinear and unsteady one-dimensional flow models, GT-power is simulated according to the principle of conservation of mass, the principle of finite difference and the principle of conservation of energy. It guarantees the accuracy of the calculation. In addition, GT-power software can also carry out detailed and accurate simulation analysis of different combustion products.

3.2 Calibration of engine model based on GT-POWER

After the completion of the engine model, it is impossible to determine whether the software model can accurately reflect the real engine operation process, so it needs to be verified. By running the model, the power and torque curves of the model can be obtained. Then the load characteristics and speed characteristics of the engine are tested, and the experimental data are compared with the simulation results of the GT-POWER model. The torque error and power error are within 5%, which proves that the model is accurate.

3.3 Analysis of engine exhaust noise based on GT-POWER

As shown in figure 1, the engine exhaust spectrum and 4000r/min noise spectrum can be obtained according to the engine model. It can be seen that the noise value of the engine is between 3500 and 6000r/min when the engine exhaust spectrum is analyzed. The spectrum is about 124 dB, which is an important basis for the design of muffler. At the same time, it can be seen that the noise level of the engine in the 4000r/min band is very high in the 180-200HZ band. The exhaust noise of engine is very obvious, so the noise in the frequency range should be eliminated.

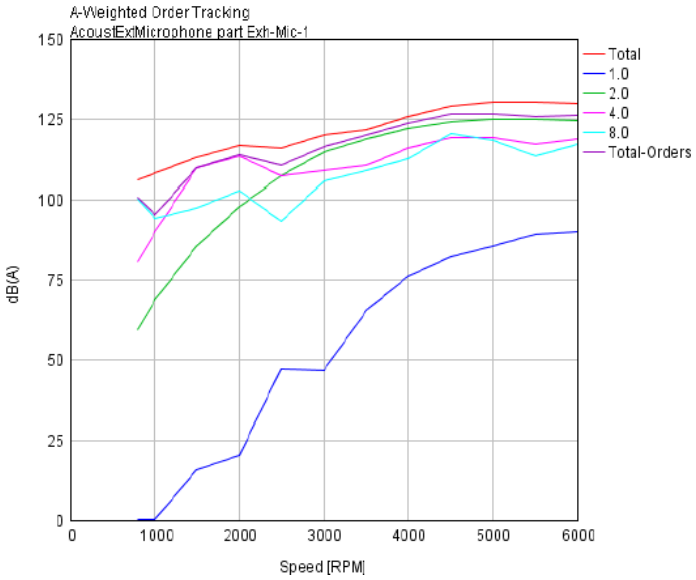

Figure 1: Exhaust spectrum and 4000r/min noise spectrum

The hearing range of the human ear is between 20-20000Hz. In order to study the distribution of noise at different frequencies, the frequency range can be divided into many frequency intervals. It is called the frequency band, frequency range or frequency band. Each frequency range has an upper and lower limit, which is represented by f_u and f_1, respectively.

$$f_u = 2^n f_1 \tag{2}$$

When n=1/3, the band is called the 1/3 octave. In practical engineering applications, the 1/3 octave is often used to study the energy distribution of noise. The center frequency of the 1/3 octave can be calculated by the Eq (3):

$$f_c = \sqrt{f_n f_1} \tag{3}$$

It can be seen that the peak noise of engine exhaust is in the range of 110-124dB. In n=4800r/min, n=5200r/min, the noise has 2 peaks, in addition, the other speed is basically unchanged for the frequency of the peak noise. The corresponding frequency of high noise value is between 180-200HZ. With the increase of the rotation speed, the noise value of the 200HZ frequency also increases. It can be concluded that the main muffler focus in the 180-200HZ frequency band.

3.4 Analysis of stable power supply performance of automobile exhaust gas generator

In order to ensure that the electric energy generated by the electric generator can supply electricity to the plasma of the muffler effectively, the voltage boost control test of the exhaust gas waste heat generator is carried out. In the experiment, the Single Ended Primary Inductor Converter (SEPIC) type DC voltage converter is designed, and the voltage of the generator is boosted and regulated to DC 12V to achieve the same phase boost and voltage. Figure 2 shows the test results of the power generation voltage rise of the exhaust gas generator.

The test results show that the voltage of the 6 thermoelectric power generation components used in the test can be stabilized at about 14V. It is proved that the design of the generator can ensure the power consumption of the muffler. But there is a lack of stability of the voltage. The main reason is: Firstly, in the process of operation, the hydrocarbons and carbon particles in the exhaust gas are deposited on the surface of the tail gas tube, which hinders the heat transfer and reduces the performance of the generator. Secondly, thermoelectric material performance decreased with time, and the temperature of the thermoelectric material increased. It can cause the reduction of the cross-sectional area and the internal resistance of the thermocouple. Meanwhile, excessive temperature rise may also lead to failure of hot end materials. Finally, the thermal expansion rate of the contact interface may lead to insufficient interface contact, which can increase the contact resistance and influence the heat transfer function. The thermal contact resistance of

thermoelectric materials increases with the increase of operating time, which results in the degradation of thermoelectric properties.

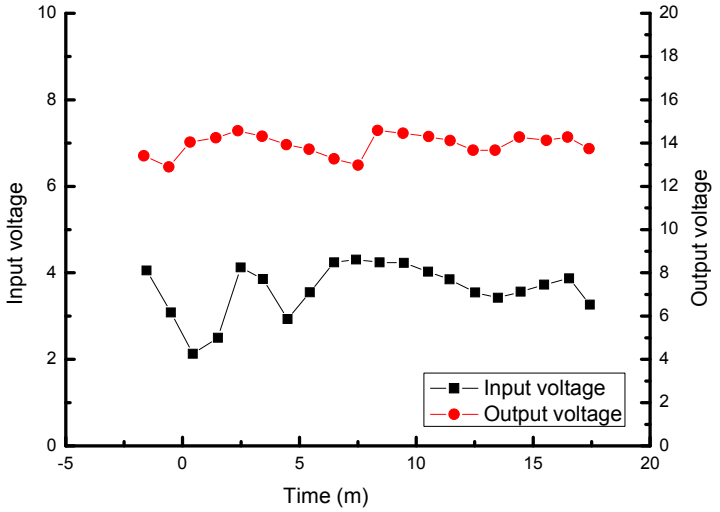

Figure 2: Pressure test results

4. Conclusions

The design principle of the impedance muffler and the technology of plasma cleaning are studied by adding a new vehicle purifier. Through the rational design, the automobile tail gas residual heat generator and muffler with purifying function are produced. Therefore, the utility model can not only recover the residual heat of automobile exhaust, but also purify the automobile emission. The exhaust noise of a small and medium sized vehicle engine was simulated by using the simulation technology and GT-POWER software. The simulation results show that the noise value of the engine is high between 3500 and 6000r/min. Peak noise is in the 110-124dB interval, and the corresponding frequency of high noise values is in the 180-200HZ, which is increasing with speed changes. It can be concluded that the main muffler focus in the 180-200HZ frequency band. After optimization design, the exhaust gas temperature difference generator and the muffler with purification function were processed. The experimental results show that the exhaust gas temperature difference generator designed in this paper has higher power generation efficiency, and which can meet the demand of power supply for the tail gas purification. At the same time, the purification function of the muffler with purification function is mainly affected by the supply voltage and the engine speed. Through this experiment, we summarized some areas which need to be improved:

(1) The temperature of the cold end of the generator needs the control device, and is suitable for the automobile exhaust temperature. The generator needs to keep the constant temperature difference as far as possible, so that the power supply is stable.

(2) The heat transfer efficiency of the inner wall of the generator is low, so it is necessary to design the exhaust gas passage with higher heat transfer efficiency, so as to obtain a higher temperature difference and obtain a larger power generation efficiency.

(3) Due to the addition of plasma generator in the muffler, the structure of the muffler becomes complicated, and the exhaust resistance is increased, thus reducing the power of the vehicle.

(4) Due to the processing precision and the limit of the equipment, the structure and the design dimension of the purified muffler are different. Therefore, we hope to improve the processing technology in the future.

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