SI 엔진에서 배기온도 저감을 위한 열교환기의 열해석

Analysis on the heat exchanger to reduce exhaust gas temperature in a spark-ignition engine

Hamid Raza, Choong Sik Bae, Seokhwan Lee

ABSTRACT

To meet stringent emissions standards, a considerable amount of development is necessary to ensure the suitable efficiency and durability of catalyst systems in SI engines. The close-coupled catalyst performance should satisfy ULEV emission levels after aging at 1050 °C for 24 hours. However, if some malfunctions occurred at engine operation and the catalyst temperature exceeds the 1050°C, the catalytic converter is deactivated and shows the poor conversion efficiency. In that situation, excess fuel is injected intentionally to lower the exhaust temperature. Hence, it resulted in worse fuel economy. In this work, the exhaust cooling system was proposed to lower the exhaust temperature in an SI engine. The cooling systems in exhaust manifold were developed and cooling efficiencies were compared. The heat flux from the exhaust gas into the coolant in the heat exchanger was calculated using the measured coolant temperatures. Exhaust gas temperatures were calculated analytically as a function of engine speed and load. Surface temperature distribution in exhaust manifold was also calculated analytically to investigate the behaviors of cooling systems.

Keywords: exhaust manifold, light-off temperature, thermal deactivation, cooling system, heat exchanger

Nomenclature

\begin{align*}
A & : \text{area, m}^2 \\
C_{pg} & : \text{specific heat of gas} \\
Q & : \text{Heat transfer, watt} \\
T_{cin} & : \text{cooler inlet temperature} \\
T_{cout} & : \text{cooler outlet temp} \\
C_{pg} & : \text{specific heat of gas} \\
M_{g} & : \text{exhaust mass flow rate} \\
T_{gin} & : \text{inlet gas temperature} \\
T_{gout} & : \text{outlet gas temperature}
\end{align*}

1. Introduction

Reduction of exhaust emissions from gasoline engines is largely accomplished by the use of catalysts. However, a conventional catalyst does not function efficiently until its operating temperature is sufficiently high, where the required temperature is generally accepted to be 300°C [1]. Hence, a large portion (up to 80%) of the hydrocarbon emissions occurs during the 1st five minutes in the case of the US FTP (Federal Test Procedure) 75 cycle while the catalyst is not yet light-off. A variety of technologies are under development to reduce cold start hydrocarbon emissions, including close-coupled catalyst, electrically heated catalyst (EHC), hydrocarbon adsorber, by-pass catalyst and
burner [2]. It has been reported that close-coupled catalysts, especially Pd-containing catalysts are very effective at reducing emissions. Most automotive manufactures are considering the adoption of close-coupled catalyst systems to meet stringent LEV and ULEV emission standards [3]. However, the higher thermal loads exerted on the converter system is the disadvantage arising from its position near the engine [4]. In the past, high temperatures were the limiting factor for converter designs. Although it is also related to the substrate material strength, this was mainly caused by the limited temperature resistance of the wash coat. Gas inlet temperatures into the converter above 850°C lead to an increased aging of the coating. As a result of consistent further development of new wash coat formulations, temperatures of 1050°C now can be attained without impairment of the coating [2].

And high temperature coating is capable of withstanding temperature up to 1050°C for 24 hours and still maintains very high conversion efficiency for hydrocarbon (98%). This major step in wash coat development work allows the vehicle manufactures to install the catalytic converter systems closer to the engine. However, if some malfunction occurs at the engine operation and the catalyst has been exposed to high temperature exceeding 1050°C, the catalytic converter is deactivated and found to have degraded performance. It is therefore important to understand the heat transfer modes involved in order to optimize the system by:

- Minimizing the heat loss right after cold start to reach the desired operating temperature as soon as possible
- Maximizing the heat loss at high load to minimize catalyst aging.

This paper introduces a heat exchanger mounted on exhaust manifold surface to reduce exhaust gas temperature and catalytic converter temperature in an SI engine, as the indication of catalytic deactivation. The objective of this study is to find a way to protect precious metal content without losing performance after aging by reducing exhaust gas temperature through a heat exchanger, and to investigate the mechanism of heat transfer in the cooling system. This paper included the methodology to calculate exhaust gas temperature, surface temperature distribution in exhaust manifold, heat lost from manifold to surroundings, coolant and gas heat flux through cooling system by analytical and experimental approaches.

2. Experimental discussions

2.1 Experimental set

The experimental system set up was build to measure exhaust gas temperature, exhaust gas mass flow rate, and the coolant heat flux in heat exchanger. The heat could be estimated by the temperature difference across the heat exchanger. Mass flow rates to the cooling system were determined with a laminar flow meter. Wall temperatures in the test section were measured at the surface of the exhaust manifold, confluence point, and the catalytic converter. All temperatures were measured by using Bendersky-type chromel–alumel thermocouples. Figure 1 shows an exhaust system with a catalytic converter, which is positioned close to the engine. The heat transfer from the exhaust system to the component takes place in the form of conduction, convection, and radiation. The catalytic converter, together with the manifold and exhaust pipes, forms a group of components that emit powerful heat. The consequence of this build-up in the engine compartment is that it becomes harder to remove the heat energy released by the exhaust system for 4 cylinders gasoline engine with compression ratio of 9.8 with specification shown in Table 1.
Table 1 Specification of the test engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>4</td>
</tr>
<tr>
<td>Bore(mm)</td>
<td>66</td>
</tr>
<tr>
<td>Stroke(mm)</td>
<td>73</td>
</tr>
<tr>
<td>Bore Pitch(mm)</td>
<td>72.5</td>
</tr>
<tr>
<td>Displacement(cc)</td>
<td>999</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Fig. 1 Exhaust manifold with catalytic converter

Fig. 2 Cooling system in exhaust manifold

2.2 Cooling system in exhaust manifold

Figures 2 shows the layout of cooling system used in exhaust manifold to reduce the exhaust gas temperatures. A portion of the heat transferred by exhaust gas will be stored in exhaust manifold. This portion will be very small right after the cold start but will become more important as the system reaches high temperatures. The heat lost by the exhaust gas to the wall and surroundings will reduce the catalytic temperature under cold start, which will extend the light-off time. Losing heat will help to minimize catalyst aging. It is therefore important to understand the heat transfer modes involved at each component in order to optimize the system by: Minimizing the heat loss right after cold starts to reach the desired operating temperature as soon as possible and maximizing the heat loss at high load to minimize catalyst aging. In order to improve the efficiency of a heat exchanger, the working fluid should be ethylene glycol which is miscible with water and dispersed into small and uniform droplets, and stay within a heat exchanger for a long time. In addition, it is easy to get dirt so that cleaning is regularly required. Finally the toxicity of ethylene glycol creates problems if it leaks. The most important characteristic of the direct contact heat exchanger is that it can operate with a very small temperature difference unlike an indirect contact heat exchanger [5]. To analyze these heat transfer modes the following methodology was used.

3. Analytical approach

3.1 Exhaust manifold surface

The conservation of energy was applied to satisfy the requirement at the surface of exhaust manifold. In this case the control surface includes no mass or volume and appears as shown in Fig 3. The 1st section is the forced heat convection from the exhaust gas to pipe. The 2nd section is the heat conduction through the pipe between the inner and outer surfaces. The 3rd section is the heat convection and radiation from the pipe to the ambient air acting in parallel. Accordingly, the following generation and storage terms of the conservation expression, are no longer relevant

$$E_{in} + E_{g} - E_{out} = \frac{dE}{dt} = E$$  \hspace{1cm} (1)

And it is only necessary to deal with surface phenomena, for this case the conservation requirement becomes

$$E_{in} - E_{out} = 0$$  \hspace{1cm} (2)

The energy balance then takes the form

$$q''_{\text{cond}} - q''_{\text{conv}} - q''_{\text{rad}} = 0$$  \hspace{1cm} (3)

$$q''_{\text{cond}} = q''_{\text{conv}} + q''_{\text{rad}}$$

$$k \frac{T_{i} - T_{s}}{L} = h(T_{i} - T_{s}) + \sigma \varepsilon (T_{i}^4 - T_{s}^4)$$

$$T_{i} = T_{s} + \frac{L}{k} [h(T_{i} - T_{s}) + \sigma \varepsilon (T_{i}^4 - T_{s}^4)]$$
3.3 Temperature distribution in manifold

Since heat conduction occurs under steady-state, one dimensional condition with no internal heat generation, the heat transfer rate \( q \) is a constant independent of \( x \). Accordingly, Fourier's law may be used to determine the temperature distribution.

For \( x = x_2 \rightarrow T (x_2) = T_2 \)

\[
T_2 = T_1 - \frac{4 q_s}{\pi k} \left( \frac{1}{x_1} - \frac{1}{x_2} \right)
\]

\[
q_s = \pi k (T_1 - T_2)
\]

From the above equation,

\[
T (x) = T_1 + \frac{4 q_s}{\pi k} \left( \frac{1}{x_1} - \frac{1}{x} \right)
\]

where

- \( d_1 \) = inlet diameter of pipe
- \( d_2 \) = outlet diameter of pipe
- \( x \) = length of pipe
- \( A \) = area
- \( T \) = temperature

\[
\begin{align*}
A &= -6.938n + 29.8585b \\
B &= 5.99910.5 + 29.26210.4n + (n+m+4)(27.81 + 29.8585) \\
C &= -3.81610.5n \\
M &= 12n + m + (n+m+4)(27.81 + 29.8585)
\end{align*}
\]

\[
\begin{align*}
B &= 115m + 462.6n \\
C &= 12370n + 13037n + (n+m+4)(237 + 804.96) \\
M &= 12n + m + (n+m+4)(32 + 288)
\end{align*}
\]

Fig. 4 Exhaust manifold pipe

4. Results and discussions

On the basis of analytical and experimental approach and the following results obtained. Figure 6 shows that the temperatures of the exhaust gas and catalytic converter are lowered by using the cooling systems in the exhaust manifold, and thermal deactivation of catalytic converter at higher load can be avoided, which improves fuel economy. Figure 7 shows exhaust gas temperatures and surface temperatures at 2000 rpm and 4000 rpm. They are close to each other, this small difference is due to small thickness of exhaust manifold.
pipe, and indicates that an increase in wall thickness will increase the mass and the external heat transfer.

Fig. 6 Temperatures of exhaust system whp and wohp

Whp = with heat protector  Wohp = without heat protector

Fig. 7 comparison of exhaust and surface temperatures of exhaust manifold whp and wohp

Figure 8 shows the heat lost from manifold to surroundings. There is less heat lost from manifold by using cooling system, which helps in avoiding thermal cracks in manifold at high load. Figure 9 shows coolant heat flux at different speeds of 2000 and 4000 rpm.

Fig. 8 comparison of heat lost from manifold to surroundings using whp and wohp

Fig. 9 Coolant heat flux in heat exchanger at different loads

Fig. 10 Gas heat flux in heat exchanger at different loads.

The coolant heat transfer increases with the increase of load. Figure 10 shows gas heat flux at different speeds of 2000, 4000 rpm. Gas heat transfer increases at low load and decreased as the load is increased. So that heat transfer area should be large to obtain the desired heat transfer rate.
The Figure11 shows the surface temperature distribution of exhaust manifold at 3000 rpm and 4000 rpm. This is due to volumetric heat capacity and this change with specific heat of exhaust gas. Temperatures at confluence points of manifold are high. Heat is hardly transferred to the upstream manifold. Maximum temperature point #8 is decreased by heat transfer to the heat exchanger. Differences in the experimental and theoretical values are due to irregular shape of the exhaust manifold surface.

Fig.11 surface temperatures distribution of exhaust manifold.

5. Conclusions
Heat transfer rate of an indirect contact heat exchanger is low than direct type, so that heat transfer area should be large to obtain desired heat transfer rate
- The exhaust gas temperatures are decreased in range of 50-80°C at high loads by using heat protectors.
- The surface & exhaust gas temperature values are very close to each other. These small differences between values are due to small change in thermal conductivity and thickness of exhaust manifold wall.
- The heat lost from the manifold to surrounding and surface temperatures are reduced by using heat protectors.
- Coolant heat flux in heat exchanger is increased as the load increased.

- The difference in experimental &theoretical values of surface temperature distribution of exhaust manifold is due to irregular shape of the exhaust manifold surface.

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References