A Study on Flow Analysis of the Exhaust Manifold for Automobile

Jae Ung Cho

Division of Mechanical & Automotive Engineering, Kongju National University, 1223-24, Cheonan Dae-ro, Seobuk-gu, Cheonan-si, Chungnam, 31080, Republic of Korea.
E-mail: jucho@kongju.ac.kr

Abstract
In the exhaust manifold, which emits the exhaust gas, the thermal deformation occurs due to periodically recurring thermal conditions of overheat and overcooling time. Therefore, it is properly necessary to understand the thermal deformation and the flow with high temperature at the exhaust gas occurring in the manifold. In this study, two forms of exhaust manifolds used in turbo diesel engines are analyzed to find out which form shows more efficiency. ANSYS program is used for the analysis of this study. If these analysis results are applied to turbo diesel engine manifolds which will be designed later, we expect to develop products with improved thermal characteristics, durability, structure, and engine performance.

Keywords: Exhaust manifold, Thermal stress analysis, Thermal deformation, Flow analysis, Flow velocity, Pressure drop

Introduction
Exhaust manifold, which is connected to the cylinder head, emits the exhaust gas in the cylinder. In these exhaust manifolds, high temperature conditions (when the engine starts) and low temperature conditions (when the engine stops) are repeated, leading to thermal deformation. This deformation is caused by the heat fatigue crack phenomenon. Recently, to increase engine power, improve fuel efficiency, and alleviate environmental problems, the temperature of exhaust gas is on an increasing trend and the possibility of thermal fatigue is rising due to the excessive thermal deformation of the exhaust manifold. To reduce deformation and cracks due to heat, we need to properly understand the heat deformation phenomenon occurring in the exhaust manifold. Recently, the developed exhaust manifolds for turbo diesel engines are equipped with EGR(Exhaust gas recirculation system) to improve the performance of the engine. EGR is a method to reduce NOx in exhaust gas. EGR recirculates some of inactive exhaust gas into suction system, and the exhaust gas is mixed with a gas mixture inhaled by the engine, thereby decreasing the maximum temperature during combustion. This leads to reduction of NOx production and improves fuel efficiency and engine power, so this system is widely used in diesel engines. By the increase of engine power, however, the temperature has risen by comparing with the previous exhaust manifolds for diesel engines. And the runner is short because the engine room is small, thus complicated design is necessary. Therefore, this kind of model is known to be deficient in thermal fatigue and flow. To satisfy the requirements mentioned above during the design process, the analyses of structure, thermal stress, thermal deformation, and flow are needed. Model 1 in this research is manifold used in D2848T, and model 2 is modeled as the manifold, which is often found in heavy equipment vehicles such as an excavator. We conducted and compared with the analyses of the two models and by using the ANSYS program, tried to investigate which one is more efficient. If this analysis result is applied in later designs of manifolds for turbo diesel engines, we expect to develop an exhaust manifold with improved thermal characteristics, durability, and engine performance[1-13].

Model and Analysis
Dimension and Material Property of Model
To study about thermal stress and the characteristics of turbo diesel engine exhaust manifolds, the restriction effect occurring from the thermal expansion of cylinder head must be considered. The analysis model of exhaust manifold is made by simplifying the actual model. Exhaust manifold models were made by using CATIA program[13]. Figs. 1 (a) and (b) are each the configuration of model 1 and model 2. Also, the meshes of model 1 and model 2 are Figs. 2 (a) and (b). Table 1 shows the number of finite elements' nodes and elements necessary for the analysis. Material properties of the models are AISI 5000 series steel among gray cast iron, and their properties are presented in Table 2.

![Figure 1: Configurations of models](a) Model 1  (b) Model 2)
Figure 2: Mesh configurations

Table 1: Meshes of models

<table>
<thead>
<tr>
<th></th>
<th>Node</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>38397</td>
<td>19239</td>
</tr>
<tr>
<td>Model 2</td>
<td>43030</td>
<td>21571</td>
</tr>
</tbody>
</table>

Table 2: Material property

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus</td>
<td>110 GPa</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.28</td>
</tr>
<tr>
<td>Density</td>
<td>7200 kg/m³</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient</td>
<td>$1.1 \times 10^{-5}$ /°C</td>
</tr>
<tr>
<td>Compressive Ultimate Strength</td>
<td>820 MPa</td>
</tr>
<tr>
<td>Tensile Ultimate Strength</td>
<td>240 MPa</td>
</tr>
</tbody>
</table>

Analysis of Thermal Stress

When the vehicle runs at the speed of 60km/h, the entrance pressure of the manifold is 5MPa. The exit pressure is 0.65MPa and the pressure ratio is 10. In this experiment, the convection coefficient as the heat transfer is set at $5 \times 10^{-2} W/mm^2 ^{\circ}C$ and the manifold is exposed to 22°C of air. We conducted the analysis by assuming that the average inner temperature of manifold is 139.5°C. For the boundary condition of the model's thermal conduction, 139.5°C is given as the average temperature of inside the manifold, as can be seen in Fig. 3.

In Fig. 4, the temperature distribution of the manifold due to the thermal conduction is provided when the vehicle runs at the speed of 60km/h at the normal state. The constraint conditions of the model's thermal stress analysis are as follows; the surfaces of the manifold's entrance and exit are fixed, the entrance pressure is 5MPa, and the exit pressure is 0.65MPa as shown by Fig. 5. Each model's amount of the total deformation and the equivalent stress caused by heat is shown by Figs. 6 and 7.

In Fig. 6, model 1 shows the largest deformation of 4.5067mm at the curved part of the entrance where the exhaust gas of cylinder enters. Model 2 shows the largest deformation of 12.985mm, at the same part. Manifolds of cars are especially connected to engines and catalysis, which may cause the final damage of weak components when the vehicle is operated harshly, and the complicated forms of irregular loads are accumulated. At the same time, with the high temperature of exhaust gas emission from the engine and the environmental factors changing at every moment, the additional damages may occur. In this research, the thermal stress of engine joint parts were analyzed, which were found to affect the durability of these manifolds. In Fig. 7, the inner entrance of flange which is jointed with the manifold and the entrance of engine's cylinder through which the exhaust gas enters, showed the highest stress level of 1369.1MPa in model 1 and 2520.7MPa in model 2 at the same part.
Flow Analysis

When the vehicles run normally, the average fuel consumption is 0.10 liter/km and air-fuel ratio is 15 generally. In this research, we are dealing with exhaust manifolds under the vehicle's normal driving condition. The flow analysis is carried out by assuming the speed of the vehicle is 60km/h.

Flow constraint conditions of models 1 and 2 are shown by Fig. 8. Meshes of flow models also are indicated as Table 3. The entrance of the model is shown by the inlet and set as the amount of mass flow. The exit part is also shown by the outlet under the static pressure. Boundary conditions of flow analysis are shown in detail as shown by Table 4. The study model used in this research is the manifold connected to the turbo diesel engine with a four-cylinder. Each cylinder's mass flux is 9.15*10^-2 kg.

Fig. 9 with the streamlined shape, is shown as the intensity and direction of each model's exhaust flow velocity. As shown in Fig. 9, model 1 showed the highest speed of 16.17m/s at the manifold exit, and of 16.50m/s in model 2 at the manifold exit. At the curved part, the inner velocity and outer velocity differ greatly.

Fig. 10 shows the pressures of model 1 and 2's exhaust flows. The pressure drops(the difference between the highest pressure and the lowest pressure) became 500Pa in model 1 and 700Pa in model 2. Hence, the difference of velocity between the entrance and the exit was 14.993m/s in model 1, and 16.361m/s in model 2, so the flow velocity is faster in model 2 than model 1. It is thought that the faster the flow velocity, the larger the pressure drop.
Conclusion
In this study, the following results are obtained through the analyses of the thermal stress and the flow in cases of two forms of turbo diesel engine exhaust manifolds.
1) Model 1 shows the largest deformation of 4.5067mm at the curved part of the entrance where the exhaust gas of cylinder enters. Model 2 shows the largest deformation of 12.9855mm, at the same part.
2) At the equivalent thermal stress levels of model 1 and model 2, at the inner entrance of flange, jointed with the manifold and the entrance through which the exhaust gas of each engine's cylinder enters, the highest stress levels of 1369.1MPa in model 1 and 2520.7MPa in model 2 at the same part was shown.
3) The difference of velocity at the entrance and the exit are 14.993m/s in model 1 and 16.361m/s in model 2. The pressure drops of model 1 was 500Pa and of model 2 was 700Pa.
4) By the analysis result of thermal stress, model 1 showed smaller deformation, less thermal stress, and less pressure difference than model 2, the manifold of model 1 has more superior performance than that of model 2.
5) If these analysis results are applied to the manifolds with the turbo diesel engine to be designed later, it is thought that the products with the improved thermal characteristics, structural durability and engine performance can be developed.

References