Abstract

This paper presents a study of a cooled exhaust gas recirculation (EGR) system applied to a turbocharged gasoline engine for improving fuel economy. The use of a higher compression ratio and further engine downsizing have been examined in recent years as ways of improving the fuel efficiency of turbocharged gasoline engines. It is particularly important to improve fuel economy under high load conditions, especially in the turbocharged region. The key points for improving fuel economy in this region are to suppress knocking, reduce the exhaust temperature and increase the specific heat ratio.

There are several varieties of cooled EGR systems such as low-pressure loop EGR (LP-EGR), high-pressure loop EGR (HP-EGR) and other systems. The LP-EGR system was chosen for the following reasons. It is possible to supply sufficient EGR under a comparatively highly turbocharged condition at low engine speed. It is important for knocking suppression to remove nitrogen oxides (NOx) from the EGR gas, which means using EGR gas from the catalyst downstream.

On the other hand, the lower differential pressure and longer EGR route that characterize the LP-EGR system make it necessary to apply more sophisticated EGR rate control. EGR flow is generated by the differential pressure at the EGR valve, which varies according to the air flow rate, so the EGR rate can be maintained with a constant EGR valve opening. Although this principle is usable only in a steady-state condition, we have developed a new compensation control that can maintain the EGR rate even under transient conditions by estimating the pressure delay at the point in the exhaust pipe where the EGR gas is extracted.

Test results showed that fuel economy was improved by as much as 5% with LP-EGR under a turbocharged condition, and the exhaust temperature was also reduced.

Introduction

Gasoline engines have been substantially downsized in recent years to improve fuel economy. There are also demands for further fuel economy improvement in the high-load region in order to increase actual fuel efficiency under real-world driving conditions. Since it is important for downsized turbocharged gasoline engines to improve fuel economy in the turbocharged region, the application of a cooled EGR system to those engines has been studied by several companies [1, 2, 3, 4, 5, 6, 7, 8].

Figure 1 shows the fuel consumption distribution obtained for operation of a 1.6-liter turbocharged engine under the US06 driving cycle. When mated to a CVT, the engine operates more frequently in the turbocharged region, so it is particularly important to enhance fuel economy in this operating region.
Because pumping losses are smaller in the turbocharged region, the following three approaches can be taken to improve fuel economy.

- Advancing the ignition timing by suppressing knocking
- Lowering the exhaust gas temperature
- Increasing the specific heat ratio

Figure 2 shows the effects of cooled EGR on improving fuel economy. Because these effects include the points noted above, an investigation was made of the application of a cooled EGR system to a turbocharged gasoline engine.

**Comparison of EGR Systems**

**Candidate Systems**

There are several types of cooled EGR systems depending on the positions where EGR gas is extracted and introduced. The following three types were investigated in this study as possible candidate systems.

- Low-pressure loop EGR (LP-EGR) system: EGR gas is extracted downstream of the turbine and introduced upstream of the compressor.
- High-pressure loop EGR (HP-EGR) system: EGR gas is extracted upstream of the turbine and introduced downstream of the compressor and/or throttle valve.
- Mixed-pressure loop EGR (mixed EGR) system [8]: EGR gas is extracted upstream of the turbine and introduced upstream of the compressor.

Schematic diagrams of each system are shown in Figure 3.

**System Comparison**

The relative advantages and disadvantages of each system are compared in Table 1 with respect to the width of EGR area, suppression of knocking, and reduction of the exhaust gas temperature. These are key factors for improving fuel economy in the turbocharged region. As a result, the LP-EGR system was chosen because it is superior in terms of all three aspects. Each of these factors is explained in detail below.

1. **Width of EGR Area in Turbocharged Region**

Figure 4 shows contour diagrams of the differential pressure in each type of EGR system when applied to a turbocharged engine. Differential pressure in the EGR system refers to the pressure difference between the EGR gas extraction and supply ports. In the case of the HP-EGR system, the intake air pressure is higher than the exhaust gas pressure in the stripe region, so that fresh air flows into the exhaust pipe when the
Table 1. Comparison of Cooled EGR Systems

<table>
<thead>
<tr>
<th></th>
<th>LP-EGR</th>
<th>HP-EGR</th>
<th>Mixed-EGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of EGR Area in Turbocharged Region</td>
<td>++</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Knocking Suppression</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Exhaust Gas Temperature Reduction</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

EGR valve is opened. In the case of LP-EGR system, it is seen in the same enclosed region that the system provides positive differential pressure. This means that LP-EGR system can introduce EGR gas in larger area than HP-EGR system in the low-speed, high-load region targeted for improvement of fuel economy.

On the other hand, the Mixed-EGR system shows a larger differential pressure than the LP-EGR system in the same enclosed region. The differential pressure, however, is obtained in the EGR valve closed condition, there is the following problem in the EGR valve opened condition. Figure 5 compares simulation results for the quantity of air inducted into the cylinder as a function of the EGR rate in the low-speed region. Because the Mixed-EGR systems is installed upstream of the turbine, the upstream capacity of the turbine becomes larger. That characteristic inhibits the transfer of exhaust gas dynamic pressure to the turbine, causing turbocharging efficiency to decline, whereas no decline occurs with the LP-EGR system. This means that the Mixed-EGR system cannot generate enough torque in the low speed condition while the differential pressure on the EGR system is large.

As indicated in the foregoing discussion, the LP-EGR system was found to be more effective in improving fuel economy than the other two types because it allows introducing EGR gas in larger area in the low-speed, high-load region.

![a. Low Pressure Loop EGR (LP-EGR)](image)

![b. High Pressure Loop EGR (HP-EGR)](image)

![c. Mixed Pressure Loop EGR (Mixed-EGR)](image)

Figure 4. (cont.) Comparison of differential pressures between the EGR gas extraction and supply ports (EGR valve closed)

Figure 5. Charging efficiency of each system as a function of the EGR rate (Simulation, 1600 rpm, Throttle valve and Westgate valve full-open)
2. Effect on Suppressing Knocking

It is well known that the knocking is suppressed by the cooled EGR [1]-[5]. On the other hand, the recirculation of exhaust gas means that various components contained in the gas are introduced into the combustion chamber again. Among exhaust gas species, it has been reported that nitrogen oxides (NOx) in particular tend to promote autoignition of the fuel [9-10]. Accordingly, an investigation was made of the effect of each candidate system on suppressing knocking.

A test was conducted with a single-cylinder gasoline engine to confirm the effect of varying the NOx concentration in the intake pipe on the knocking margin under the application of EGR. The results obtained are shown in Figure 6. The data indicate that with a NOx concentration of zero in the intake pipe, the knocking margin was improved by 3 deg. relative to every 10% increase in the EGR rate. It was also confirmed with an actual engine that the effect on improving the knocking margin decreased as the NOx concentration in the intake pipe was increased. The knocking margin means the difference between MBT and the ignition timing of the knocking intensity criteria.

These results revealed that reducing the NOx concentration in the EGR gas was effective in strengthening the effect of cooled EGR on suppressing knocking. In short, the test results showed that extracting EGR gas downstream of the 3-way catalyst increased the knock suppression effect of EGR.

The foregoing results thus indicated that the LP-EGR system would also be advantageous for suppressing knocking, which is one of the important measures for improving fuel economy in the turbocharged region, because it extracts EGR gas downstream of the catalyst and introduces it upstream of the compressor.

Figure 6. Influence of NOx concentration in the intake air on knocking margin improvement (Single cylinder engine, 1600rpm IMEP 15bar)

The LP-EGR system was then installed in an actual multiple-cylinder engine and a test was conducted to verify its effect on suppressing knocking. The results presented in Figure 7 confirm that the knocking margin was improved by approximately 3 deg. when EGR of 10% was introduced, including under the conditions shown in the figure.

Figure 7. Verification of the knocking suppression effect of the LP-EGR system

3. Effect on Reducing Exhaust Gas Temperature

It is well known that the exhaust gas temperature is reduced by introducing the cooled EGR gas into the fresh air supplied to the cylinder. This is the effects of the dilution by the EGR [1], [2], [3], [4], [5]. Figure 8 shows the relationship between the ignition timing and the exhaust gas temperature when cooled EGR is applied under high-speed, high-load conditions. The data verify that the exhaust gas temperature is reduced in the high-load region by the introduction of cooled EGR. As a result, the region of stoichiometric combustion can be expanded, and improvement of real-world fuel economy can be expected. According to the high-speed, high-load region seen in Figure 4, all three candidate systems can provide sufficient EGR system differential pressure in this region. However, the applied EGR rate is often determined by combustion stability and the limitation on the pressure ratio of the turbocharger. For that reason, even though the same EGR rate can be applied with each candidate system, the LP-EGR system can be expected to reduce the exhaust gas temperature more than the other two systems. The reason is that it allows the ignition timing to be advanced in proportion to the effect on suppressing knocking, as mentioned earlier.

Figure 8. Effect of EGR on reducing the exhaust gas temperature (4000rpm-BMEP9bar)
As explained here, the LP-EGR system was judged to have the greatest effect on improving fuel economy in the turbocharged region, owing to its wider differential pressure area for applying EGR in the low-speed/high-load region, advancing the ignition timing by better suppression of knocking, and reduction of the fuel enrichment area by lowering the exhaust gas temperature.

### Control Technologies for LP-EGR System

The LP-EGR system has several distinct characteristics in comparison with conventional EGR systems (Table 2). It was found that those characteristics made it difficult to supply a suitable EGR rate stably.

One especially distinct characteristic is the lower differential pressure in the EGR system between the exhaust gas extraction and supply ports. This is a factor that impedes the stable supply of EGR gas. Another characteristic is the long length of the EGR passage. There was concern that this characteristic would affect EGR controllability under transient operation. The following sections explain the measures taken to make the LP-EGR system viable with respect to these characteristics.

#### Principle of EGR Rate Control

Figure 9 is a schematic diagram that explains the fundamental operating principle of the LP-EGR system. We consider that the system has three orifices. The first orifice is located upstream of the EGR supply port in the intake system; the second orifice is located downstream of the EGR gas extraction port in the exhaust system; and the third orifice is the EGR valve. In the case of the EGR valve opening is constant, it is regarded as a fixed orifice.

First, changing the intake air flow rate into the engine causes the pressure downstream of the first orifice and the pressure upstream of the second orifice to change. The differential pressure between the two orifices is determined almost unequivocally according to the intake air flow rate. This differential pressure is equal to that between the upstream and downstream sides of the LP-EGR system. Therefore, EGR gas flows according to this differential pressure.

This means that the differential pressure in the EGR system is determined according to the intake air flow rate of the engine. Because the EGR gas flow rate is determined by this differential pressure, the EGR gas flow rate supplied to the engine is proportional to the intake air flow rate. In other words, because the EGR valve opening is fixed, the EGR rate is constant regardless of the volume of air inducted into the engine.

Figure 10 presents the test results obtained for steady-state operation of an engine fitted with the LP-EGR system. The results show that, if the EGR valve opening is fixed, the EGR rate is determined irrespective of the intake air flow rate which is varied by the throttle valve opening angle. Therefore, these results validated the principle that the EGR rate can be controlled by the EGR valve opening.

### Table 2. Characteristics of LP-EGR system

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Concern</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low differential pressure in EGR system</td>
<td>Difficulty of EGR valve control to get stable EGR rate in each condition</td>
<td>Influence on EGR rate by difference pressure based on air flow rate and etc.</td>
</tr>
<tr>
<td>Long length of EGR passage</td>
<td>Difficulty of EGR rate control in transient condition</td>
<td>Influence on EGR rate fluctuation by exhaust pressure delay to intake air flow change</td>
</tr>
</tbody>
</table>

![Figure 9. EGR control principle of LP-EGR system](image-url)
However, it was also found that, because exhaust gas pulsations occur in an actual engine, this relationship cannot be maintained under a condition where the intake air flow rate is exceptionally small. This is a factor that limits the application range of the LP-EGR system on the low-load side.

**EGR Rate Behavior under Transient Conditions**

As explained above, the EGR rate can be controlled stably under steady-state conditions, but the data presented in Figure 11 indicate that it displays different behavior under transient conditions. The results in the figure are for a sharp decrease in the intake air flow rate under the same EGR valve opening. It is observed that the EGR rate increases momentarily.

The increase is caused by a difference in timing between the change in the intake air flow rate and the change in the exhaust gas pressure under a transient condition. When the throttle valve is closed rapidly during deceleration, the intake air flow rate instantaneously decreases, but there is a slight time lag before the exhaust gas pressure drops. Reduction of the EGR flow rate is delayed as a consequence of that time lag. As a result, the EGR rate increases, but when the exhaust pressure drops, the EGR flow rate also decreases, and the EGR rate then becomes stable, as seen in Figure 12.

Attention was focused on the fact that the response delay of the change in the exhaust gas pressure relative to the intake air flow rate can be compensated for by using the intake air flow rate. We developed a control procedure for compensating the EGR valve opening during the duration of the response delay. The amount of compensation for the EGR valve opening is determined by finding the ratio of the exhaust gas pressure calculated for the intake air flow rate at that moment to the exhaust gas pressure calculated for the intake air flow rate at the point going back an amount of time equal to the delay.

Figure 13 compares the results obtained with and without this compensation control. The results indicate that compensating the EGR valve opening area as shown in the figure markedly reduces the amplitude of fluctuation in the EGR rate. As a result, we succeeded in developing a control procedure that facilitates stable introduction of EGR gas. This EGR control procedure is basically configured such that the EGR valve opening is set to obtain the targeted EGR rate under steady-state operation and the response delay is compensated for under transient conditions. In order to implement this control procedure on production vehicles, judgment conditions and additional compensation have been added to enable the control procedure to accommodate a wide range of driving environment conditions.
Experimental Results

A LP-cooled EGR system was constructed based on the results of the foregoing investigations and tests were conducted to confirm its effect on improving fuel economy. Schematic diagram of the system and engine specification are shown in Figure 14 and Table 3.

Exhaust gas, from which NOx has been removed by the catalyst positioned downstream of the turbine, is introduced into the EGR cooler via the EGR pipe and cooled by the engine coolant. The cooled EGR gas flows through the EGR valve and is introduced into the intake pipe upstream of the compressor. The EGR gas mixes with the fresh air and is supercharged by the compressor, after which it is cooled in the charge air cooler (CAC) and introduced into the cylinder.

These results confirm that the LP-cooled EGR system is notably effective in improving the fuel economy of a downsized gasoline engine, especially when mated to a CVT.

Figure 15 shows the fuel economy improvement obtained with the system as a function of the EGR rate under turbocharged operating conditions. The results show that fuel economy is improved by approximately 5% when an EGR rate of 20% is applied.

Figure 16 shows the effect on fuel economy at a constant EGR rate of 10% under steady state. At the same engine speed, a large effect is seen under a high-load condition and an improvement due to the lower engine speed is also seen along the engine speed axis.

Table 3. Engine specifications

<table>
<thead>
<tr>
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<th>Value</th>
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<tbody>
<tr>
<td>Stroke</td>
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<tr>
<td>Bore</td>
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<tr>
<td>Displacement</td>
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</tr>
<tr>
<td>Compression Ratio</td>
<td>10.5</td>
</tr>
<tr>
<td>Cylinder Number</td>
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Summary/Conclusions

This paper has presented a study concerning the use of an EGR system to improve the fuel economy of a turbocharged gasoline engine in the turbocharged region. Through investigating the several EGR systems, developing the EGR rate control technologies, and carrying out the experiments, the following conclusions can be drawn from the results obtained.

1. The LP-EGR system has the best potential to improve fuel economy in the turbocharged region owing to the ease of introducing EGR, better suppression of knocking, and reduction of fuel enrichment area. Especially, reducing NOx concentration in the intake air is an important factor for suppressing knocking, and only the LP-EGR system can realize it because the system extracts EGR gas downstream of the three-way catalyst.

2. The LP-EGR system has the characteristic that the EGR rate is kept constant when the EGR valve opening is fixed,
regardless of the intake air flow rate of the engine under steady state. Moreover, stable control of the EGR rate is achieved by taking into account the delayed change in the exhaust gas pressure under transient operating conditions.

3. Test results show that the LP-cooled EGR system has the remarkable effect of improving fuel economy by as much as 5% in the turbocharged region under steady state. As a larger improvement of fuel economy is seen under a higher-load condition, the LP-EGR system becomes more important for the further downsized gasoline engines.

References


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Definitions/Abbreviations
BMEP - break mean effective pressure
BTDC - before top dead center
CAC - charge air cooler
EGR - exhaust gas recirculation
IMEP - indicated mean effective pressure
MBT - minimum advance for best torque
TDC - top dead center
TVO - throttle valve opening angle
WOT - wide open throttle