The application of an exhaust heat exchanger to protect the catalyst and improve the fuel economy in a spark-ignition engine

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Abstract: A close-coupled catalyst (CCC) can reduce engine cold-start emissions by utilizing the energy in the exhaust gas. However, in case the engine is operated at high engine speed and load condition, the catalytic converter may be damaged and eventually deactivated by thermal ageing. Excess fuel is sometimes supplied intentionally to lower the exhaust gas temperature, avoiding thermal ageing. This sacrifices fuel economy and exhaust emissions.

This paper describes the results of an exhaust heat exchanger to lower the exhaust gas temperature, mainly under high load conditions. The heat exchanger was installed between the exhaust manifold and the inlet of the CCC to avoid thermal ageing. The exhaust heat exchanger successfully decreased the exhaust gas temperature, which eliminated the requirement of fuel enrichment under high-load conditions. A reduction of fuel consumption by approximately 7.7 per cent at high vehicle speed was achieved due to no fuel enrichment. Although the amount of hydrocarbon during the cold start increases due to the increment of the catalyst light-off time, it still meets the EURO-IV regulations. This problem could be resolved by adopting the solenoid valve to cut off the coolant at the inlet of the coolant passage of the heat exchanger.

Keywords: close-coupled catalyst, heat exchanger, thermal ageing, fuel economy, fuel enrichment

1 INTRODUCTION

With increasingly stringent environmental regulations such as EURO-IV and ULEV (ultra low emission vehicle) emission standards, much attention has been paid to environmental hazards and energy conservation. Reduction of exhaust emissions from spark-ignition (SI) engines is largely accomplished with the use of catalysts. However, a conventional catalyst does not function efficiently until its operating temperature reaches the light-off temperature, which is generally about 300 °C [1]. Hence, a large portion (up to 80 per cent) of the hydrocarbon emissions occurs in the engine cold start during the first 5 min

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in the case of the US FTP (federal test procedure) 75 cycles before the catalyst is activated. On the other hand, at high engine loads, the exhaust gas temperature is greatly increased and could cause fast ageing of the catalyst coating [2]. The higher thermal loads exerted on the converter system during the high-load condition became more serious after most automotive manufacturers adopted the Pd-containing close-coupled catalyst systems to meet stringent concurrent emission standards [3–5]. Previous studies showed that the current catalytic converter could be damaged and eventually deactivated through thermal ageing with higher exhaust gas temperatures exceeding 850 °C, resulting in poor conversion efficiency. The catalyst suffers from a significant reduction in BET (Brunauer Emett Teller) surface area or, in some cases, a catastrophic substrate meltdown owing to the high catalyst temperature [6]. Some recent studies introduced new washcoat formulations
that can stand up to a temperature $1050^\circ C$ without impairment of the coating, while maintaining very high conversion efficiency for hydrocarbon (98 per cent) [7, 8]. However, the exhaust gas temperature should not exceed $850^\circ C$ for the current commercial catalyst. In order to reduce the exhaust gas temperature without power loss, additional fuel is usually injected to formulate a richer mixture. This approach not only wastes fuel but also increases the emission of carbon monoxide (CO) and hydrocarbon (HC). This is not so far considered to be a problem owing to the relatively short period when the engine is running at full power. However, the new legislation is expected to regulate full load emissions. Consequently, fuel enrichment during full load has to be reduced in order to meet the new legislation [9].

In this study, the exhaust gas temperature was reduced during high-load conditions by using a small water-cooled heat exchanger, which, in principle, acts like an exhaust gas recirculation (EGR) cooler [10]. This heat exchanger was installed between the exhaust manifold and the inlet of the close-coupled catalytic converter to transfer the exhaust thermal load from the exhaust gases to the engine coolant, and it provided an alternative way to reduce the exhaust gas temperature at higher engine load without wasting fuel. However, special attention has to be paid in order not to increase the engine back-pressure and the catalyst light-off time.

The design of the heat exchanger affects the exhaust gas inlet temperature into the close-coupled catalytic converter and, consequently, the temperature levels attainable inside the ceramic washcoat. To maximize the convective effect between the exhaust gas and coolant, fins were implemented at the inner surface of the heat exchanger [11]. During the last few years, computational models are employed for the attainment of low heat rejection from exhaust systems of large cars, thereby avoiding undesirable temperature increases in the encapsulated engine compartment [12]. This study also used the computational analysis and design of experiments (DOE) technique to design an optimal exhaust heat exchanger to reduce the exhaust gas temperature under high-load conditions [11].

2 EXPERIMENTAL SET-UP AND OPERATING CONDITION

2.1 Vehicle tests

Vehicle tests have been performed according to the European driving cycle (EDC) [13]. A vehicle was equipped with a 1.01, 12-valve gasoline engine and the actual mileage of the engine was 12 000 km. The engine was fitted with a programmable electronic control unit as shown in Fig. 1. A close-coupled catalyst (CCC) and under-floor catalytic converter (UCC) were equipped with the engine to meet the Euro-III emission legislation. To monitor the engine operating parameters (relative load, mass of intake air, coolant temperature, and lambda value, etc.) and to change the fuel mapping data, both a programmable engine management system (EMS; NTK) and a data acquisition system (ETAS MAC2) were used. Thermocouples and thermo-scan were installed to monitor the exhaust system thermally. A wide-band $O_2$ sensor and a lambda meter were also employed to control the air–fuel ratio of the engine. A summary
of the engine features is shown in Table 1. The water pump inside the engine was used to circulate the coolant to the heat exchanger. This study used a mixture of 50 per cent water and 50 per cent ethylene glycol as a coolant. Figure 1 also shows a scheme of the coolant circulation between the engine and the heat exchanger. The coolant running to the heat core was a source of the coolant through the heat exchanger, and the coolant supply increased with the engine speed because of the water pump. The water pump was connected directly to the engine, and the work of the pump increased with engine speed.

2.2 Temperature measurement
K-type thermocouples were used to monitor the exhaust gas temperature before the catalyst, the catalyst temperature, and the coolant temperatures at the inside of the heat exchanger. To measure the catalyst temperature, a thermocouple was installed at 50 mm from the front face of the catalyst bed along the central axis, which is 40 mm from the upper face. It was assumed that this mid-position was the most active in the catalytic reaction. Another thermocouple was installed at 170 mm from the engine to measure the catalyst inlet exhaust temperature. The diameter of the thermocouple bead was 3.2 mm; therefore, the catalyst temperature could be considered a bulk temperature of the catalyst.

2.3 Heat exchanger
To lower the exhaust gas temperature, a heat exchanger was developed. The heat exchanger was installed between the exhaust manifold and the close-coupled catalyst, which could acquire a cooling effect by circulating the engine coolant to the passage of the heat exchanger. The heat transfer from the exhaust system to the heat exchanger takes place in the form of conduction and convection. To maximize the convective effect between the exhaust gas and coolant, fins were implemented at the inner surface of the heat exchanger [11]. Figure 2 shows the heat exchange phenomena between the exhaust system and the heat exchanger.

3 RESULTS AND DISCUSSION

3.1 Exhaust gas and catalyst temperatures at European driving cycle (EDC) mode
To examine the cooling performance of the heat exchanger, it was necessary to conduct a test in an actual vehicle. The vehicle was tested during a
Table 2  Temperature reductions by adopting the heat exchanger

<table>
<thead>
<tr>
<th>Test mode</th>
<th>Average exhaust gas temperature (°C)</th>
<th>Maximum exhaust gas temperature (°C)</th>
<th>Average catalyst temperature (°C)</th>
<th>Maximum catalyst temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>482</td>
<td>770</td>
<td>574</td>
<td>900</td>
</tr>
<tr>
<td>With heat exchanger (ΔT)</td>
<td>443 (39)</td>
<td>760 (10)</td>
<td>482 (92)</td>
<td>830 (70)</td>
</tr>
</tbody>
</table>

European driving cycle. Testing was conducted at first on the base engine (without heat exchanger) and on the engine with the heat exchanger installed. Figures 4 and 5 show the temperature reduction in the exhaust gas and catalyst during EDC mode owing to the heat exchanger. The average and maximum temperature reductions due to the heat exchanger are listed in Table 2. Although, the reduction in the exhaust gas temperature due to the heat exchanger was 39°C on average, the reduction in catalyst temperature reached up to 92°C. In conclusion, the exhaust heat exchanger successfully decreased the exhaust gas temperature, and therefore eliminated the requirement of fuel enrichment under high-load conditions and protected the catalytic converter from exposure to high temperature.

3.2 Fuel economy

In the case of BASE (without using a heat exchanger and with fuel enrichment), the lambda value was fixed at 0.805 under maximum speed and load conditions. This worsens the fuel economy. The exhaust gas temperature and catalyst temperature were reduced when the optimum heat exchanger was applied, so that fuel enrichment was no longer required. To remove the component protection (fuel enrichment) mode at the ECU (engine control unit), the lambda value was set at 1.0 for the entire operating region. Table 3 shows the results of fuel consumption rates using a chassis dynamometer for the two-vehicle speeds (115 kph, maximum speed) with and without the heat exchanger. The experiments were performed five times to minimize the experimental error. The results showed a slight reduction in fuel consumption rate by 2.1 per cent in the case of the 115 kph vehicle speed; it reaches up to 7.6 per cent at maximum vehicle speed. A comparison of the results of exhaust gas temperature, catalyst temperature, and lambda value is shown in Table 4. At maximum speed, the lambda value of the BASE case was indicated as 0.869 to protect the catalyst, while with the heat exchanger lambda was 0.928 at maximum power (WOT range). This difference of lambda value brings the benefit of fuel economy when the heat exchanger was installed. Comparing the temperatures of the exhaust gas, heat exchanger case without fuel enrichment showed a value of 895°C, while BASE case showed 885°C with fuel enrichment. Accordingly, when the heat exchanger was installed, similar levels of exhaust gas temperature and catalyst temperature could be obtained without fuel enrichment.

Table 3  Chassis dynamometer results of the fuel consumption rate (km/l)

<table>
<thead>
<tr>
<th>Vehicle speed</th>
<th>BASE</th>
<th>With heat exchanger (improvement (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>115 k/h</td>
<td>11.97</td>
<td>12.13 (2.1%)</td>
</tr>
<tr>
<td>135 k/h (maximum)</td>
<td>7.05</td>
<td>7.59 (7.6%)</td>
</tr>
</tbody>
</table>
Table 4  Comparison of exhaust gas temperature, catalyst temperature, and lambda value

<table>
<thead>
<tr>
<th></th>
<th>115 k/h</th>
<th>Maximum speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BASE</td>
<td>Heat exchanger</td>
</tr>
<tr>
<td>r/min</td>
<td>3400</td>
<td>3400</td>
</tr>
<tr>
<td>Throttle angle (%)</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Measured exhaust gas temperature (°C)</td>
<td>760</td>
<td>740</td>
</tr>
<tr>
<td>Measured catalyst temperature (°C)</td>
<td>875</td>
<td>805</td>
</tr>
<tr>
<td>Lambda value</td>
<td>0.990</td>
<td>1.000</td>
</tr>
</tbody>
</table>

3.3 Main drawbacks after installing the heat exchanger

In spite of the benefits in fuel economy and the associated emissions reduction, two main drawbacks could be raised. The first is the possible increment of exhaust backpressure caused by the existence of fins. The second is the increase in the catalyst light-off time.

Excessive exhaust backpressure can impair engine performance by lowering horsepower and decreasing fuel economy [14]. Hence, it was required to estimate how much backpressure and power loss would be caused by the heat exchanger. Experiments were performed in an engine dynamometer while engine power and back pressure were measured at 2500–5000 r/min with WOT condition. Pressure was measured with a piezoelectric-type pressure transducer (Kistler, 4045A; maximum range = 10 bar) at confluence point. Figure 6 shows the measured back pressure and engine torque with heat exchanger (H/E) and without heat exchanger (BASE). The back pressure fluctuated severely in the time domain; hence after an acquired 10 000 of pressure data, the time-averaging method was used to acquire a representative value. The maximum deviation in engine torque with a heat exchanger was 1.1 per cent, and the back pressure was increased by only 0.4 per cent. Therefore, installing the heat exchanger has almost no influence on back pressure and engine torque.

To investigate the effect of the exhaust heat exchanger on the catalyst light-off time, three engine test cases were conducted (engine test without heat exchanger, with heat exchanger, without cooling water, and with cooling water). The aim was to identify the increment of light-off time assuming the catalyst light-off temperature is 300 °C [1]. Figure 7 showed that the existence of the heat exchanger with coolant induced an increment of 18 s of catalyst light-off time and a possible increase of unburned hydrocarbon at cold start. The results also showed that a longer exhaust system due to the additional heat exchanger could be disadvantageous to the catalyst light-off characteristics. Therefore, it was necessary to reduce the light-off time to meet the more stringent emission regulations in the future.

Table 5 lists the results of the EDC mode emission test, which measured the total hydrocarbon (THC), CO, and nitrogen oxide (NOx), together with the corresponding light-off time. The results were
collected for the vehicle that was equipped with a CCC and UCC with and without heat exchanger and also with coolant. Hydrocarbon emission was increased by 0.021 g/km owing to the heat exchanger, though it still meets the Euro-IV regulation. The table also lists the results of the fuel economy at EDC mode. Fuel economy was improved by 8 per cent due to the elimination of the fuel enrichment region.

In addition to the above-mentioned drawbacks, special attention has to be paid to the sufficient coolant supply to the exhaust exchanger; otherwise the heat flux from exhaust gas causes local boiling to the coolant. The existence of very small vapour bubbles, which may be formed during nucleate boiling (and which quickly collapse as they move away from the solid surface) leads to an increase in the heat transfer; and it soon increases in size and energy to the point where they begin to coalesce, and form a blanket above the solid surface. Therefore, monitoring the coolant supply and coolant temperature is necessary. Figure 8 shows the coolant temperature behaviour at the EDC mode test. The coolant temperature starts to rise up during the early stage of engine operation and then fluctuates between 105 °C and 120 °C at higher loads. Considering that the coolant is a mixture of 50 per cent water and 50 per cent ethylene glycol, the boiling temperature of which is about 108 °C, nucleate boiling is then expected that could increase the heat flux at high-load conditions. This problem must be addressed in case the heat exchanger is to be implemented practically.

### Table 5  Vehicle test results at EDC mode

<table>
<thead>
<tr>
<th>Case</th>
<th>Exhaust emission (g/km)</th>
<th>Fuel economy (km/l)</th>
<th>Light-off time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
<td>CO</td>
<td>NOx</td>
</tr>
<tr>
<td>BASE</td>
<td>0.055</td>
<td>0.380</td>
<td>0.012</td>
</tr>
<tr>
<td>Heat exchanger (with coolant)</td>
<td>0.076</td>
<td>0.444</td>
<td>0.030</td>
</tr>
<tr>
<td>Heat exchanger (no coolant)</td>
<td>0.062</td>
<td>0.400</td>
<td>0.012</td>
</tr>
<tr>
<td>EURO-IV legislation</td>
<td>0.10</td>
<td>1.00</td>
<td>0.08</td>
</tr>
</tbody>
</table>

#### 3.4 Reduction of the light-off time during cold start

Although the exhaust gas temperature and catalyst temperature were decreased with the heat exchanger, the amount of hydrocarbon during the cold start increases due to the increment of the catalyst light-off time. Considering the increasingly stringent emission regulations, it will be difficult to use the heat exchanger as described above. A simple strategy was proposed to resolve this problem. By adopting a solenoid valve at the inlet of the coolant passage, the coolant could not circulate through the heat exchanger at the cold start condition. The coolant could circulate after the catalyst temperature exceeds 400 °C. This solenoid valve control strategy can compensate the increment of light-off time.

Figure 9 shows the reduction in the CCC temperature due to the heat exchanger during EDC mode with and without the solenoid valve. The heat exchanger successfully decreased the CCC temperature, regardless of the solenoid valve. The light-off time was decreased with the solenoid valve control.
strategy. The average and maximum CCC temperature reductions with and without the solenoid valve are listed in Table 6. The reduction in the CCC temperature due to the heat exchanger without the solenoid valve was 65 °C on average; the reduction in the CCC temperature with the solenoid valve was 53 °C. The cooling performance of the heat exchanger without the solenoid valve was slightly better than the case of adopting the solenoid valve.

Two engine test cases were conducted (with and without the solenoid valve) to investigate the effects of the solenoid valve control strategy on the catalyst light-off time. Figure 10 showed that cutting off the coolant that circulated through the heat exchanger at the cold start only induced an increment of 3.7 s of catalyst light-off time. The solenoid valve control strategy decreased the light-off time by 9.7 s and it was expected that unburned hydrocarbon would decrease, compared with no solenoid valve control strategy.

Table 7 lists the results of the EDC mode emission test. Hydrocarbon emission was increased by 0.006 g/km due to the heat exchanger with solenoid valve control strategy, though it still perfectly meets the Euro-IV regulation.

### 4 CONCLUSIONS

A heat exchanger was applied to decrease the exhaust gas temperature to eliminate the fuel enrichment during the high-load-and-speed engine operations and, eventually, in order to avoid the thermal ageing of close-coupled catalysts and improve fuel economy. From the vehicle tests with the heat exchanger, the following conclusions are obtained.

1. During the EDC mode test, the average exhaust gas temperature reduction by the heat exchanger was around 39 °C, and the average catalyst temperature reduction was no less than 92 °C. The exhaust heat exchanger successfully decreased the exhaust gas temperature, which could eliminate the requirement of fuel enrichment under high-load conditions.
2. The fuel economy was improved by 7.6 per cent at maximum speed conditions owing to the elimination of the fuel enrichment.
3. Cooling the exhaust gas through the heat exchanger may cause the increase in catalyst light-off time at cold start and, accordingly, the hydrocarbon emission was increased by 0.021 g/km, though it still meets the Euro-IV regulation.
4. The experimental result showed that the presence of the heat exchanger causes only a slight decrease in engine torque and a slight increase in back pressure.
5. The problem of the increment of the catalyst light-off time was resolved by adopting a solenoid valve at the inlet of the coolant passage to cut off

![Fig. 10 Effects of the solenoid valve control strategy on the light-off time](image)

### Table 6 CCC temperature reductions by adopting the heat exchanger and the solenoid valve control strategy

<table>
<thead>
<tr>
<th>Test mode</th>
<th>Average CCC temperature (°C)</th>
<th>Maximum CCC temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>614</td>
<td>901</td>
</tr>
<tr>
<td>Heat exchanger without coolant control (AT)</td>
<td>549 (65)</td>
<td>825 (76)</td>
</tr>
<tr>
<td>Heat exchanger with solenoid valve control (AT)</td>
<td>561 (53)</td>
<td>833 (68)</td>
</tr>
</tbody>
</table>

### Table 7 EDC mode emission results with the solenoid valve control strategy

<table>
<thead>
<tr>
<th>Case</th>
<th>Exhaust emission (g/km)</th>
<th>Light-off time (increment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>0.057</td>
<td>0.310</td>
</tr>
<tr>
<td>Heat exchanger (+ no control)</td>
<td>0.080</td>
<td>0.420</td>
</tr>
<tr>
<td>Heat exchanger (+ solenoid valve control)</td>
<td>0.063</td>
<td>0.340</td>
</tr>
</tbody>
</table>
the coolant. The solenoid valve control strategy decreased the light-off time by 9.7 s, compared to the basic heat exchanger without solenoid valve control, so that unburned hydrocarbon was decreased.

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REFERENCES


4 Nagel, T., Maus, W., and Breuer, J. Development of increased test conditions for close-coupled catalyst applications. SAE paper 962079, 1996.


APPENDIX

Notation

BET  Brunauer Emett Teller
CC  close-coupled catalyst
CO  carbon monoxide
ECU  engine control unit
EDC  European driving cycle
EGR  exhaust gas recirculation
EMS  engine management system
FTP  federal test procedure
HC  hydrocarbon
H/E  heat exchanger
NOx  nitrogen oxide
WOT  wide open throttle
UCC  under-floor catalytic converter
ULEV  ultra low emission vehicle