2002-01-1677

# Effects of Engine Operating Conditions on Catalytic Converter Temperature in an SI Engine

**Seokhwan Lee and Choongsik Bae**
Korea Advanced Institute of Science and Technology

**Yongpyo Lee and Taesik Han**
Hyundai-Motor Company

## ABSTRACT

To meet stringent emission standards, a considerable amount of development work is necessary to ensure suitable efficiency and durability of catalyst systems. The main challenge is to reduce the engine cold-start emissions. Close-coupled catalyst (CCC) provides fast light-off time by utilizing the energy in the exhaust gas. However, if some malfunction occurred during engine operation and the catalyst temperature exceeds 1050°C, the catalytic converter becomes deactivated and shows poor conversion efficiency.

Close-coupled catalyst temperature was investigated under various engine operating conditions. All of the experiments were conducted with a 1.0L SI engine at 1500-4000 rpm. The engine was operated at no load to full load conditions. Exhaust gas temperature and catalyst temperature were measured as a function of lambda value (0.8-1.2), ignition timing (BTDC 30°-ATDC 30°) and misfire rates (0-28%). It was found that ignition retard and misfire can result in the deactivation of the catalytic converter, which eventually leads the drastic thermal aging of the converter. Significant reduction in light-off time can be achieved with proper control of ignition retard and misfire, which can reduce cold-start HC emissions as well. Exhaust gas temperature was also predicted according to engine speed, air/fuel ratio and ignition timing to complement the experimental results.

## INTRODUCTION

With increasingly stringent environmental regulations such as LEV and ULEV emission standards, much attention has been paid to global environmental destruction and energy conservation. Emission regulations for automobiles are also being strengthened in recent years. 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 occur during the first 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 manufacturers 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 addition, the Environmental Protection Agency (EPA) has proposed testing cycles for emissions with the air conditioner turned on, which lead to additional 10% loads. In order to meet the proposed emission standards on the SFTP, catalyst washcoats and precious metals must be improved to endure short term exposure to temperatures of up to 950°C [5]. Hence, the catalyst design must have the necessary thermal durability.

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 washcoat. Gas inlet temperatures into the converter above 850°C lead to an increased aging of the coating [6]. As a result of consistent further development of new washcoat formulations, temperatures of 1050°C now can be attained without impairment of the coating [2]. And the 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%) [7]. This major step in washcoat development work allows the vehicle manufacturers to install the catalytic converter systems closer to engine.

However, if some malfunction occurs at 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. The catalyst has suffered from a significant reduction in BET surface area or, in some cases, a catastrophic substrate melt due to high catalyst temperature [8]. Table 1 demonstrates the thermal deactivation phenomena as a function of catalyst operating temperature [9].

Table 1 Thermal deactivation phenomena as a function of catalyst operating temperature [9]

| Temp(°C) | Thermal Deactivation |
|---|---|
| 1900 | Pellet Melting |
| 1800 | |
| 1700 | High temperature ceramic melts (50% Mulite, 50% Titanate) |
| 1600 | |
| | Metal monolith melts |
| 1500 | Ceramic monolith melts |
| 1400 | |
| | Ceramic monolith softens |
| 1300 | Cordierite phase change to mulite |
| 1200 | **θ-Alumina phase change to α-Alumina** |
| 1100 | |
| | Pt-Rh alloy forms in oxidation A/F |
| | **δ-Alumina phase change to θ-Alumina** |
| 1000 | |
| 900 | Pt-Pd alloy forms in oxidation A/F |
| | **Alumina sinters(γ-Alumina to δ-Alumina)** |
| 800 | |
| | Pt-Pd and Pt-Rh alloy forms in reducing A/F |
| 700 | Pt sinters |
| | Rh-Alumina reaction in oxidation A/F |
| 600 | |
| 500 | Optimum converter operating temperature |

Engine misfire and ignition retard are the significant parameters affecting exhaust gas temperature. The effect of ignition-induced misfire on exhaust catalyst temperature has been investigated using an engine bench and a computer model by O'Sullivan et al. [8]. Chan et al. [10] proposed the high value of ignition retard control to reduce catalyst light-off time. They showed that the exhaust gas temperature increased by 150°C with a retard value of 26°CA relative to the normal timing setting. Also, Ueno et al. [11] demonstrates the effect of ignition timing on exhaust gas temperature.

This paper presents the effects of engine operating conditions on catalytic converter temperature in an SI engine, as the indication of catalytic deactivation. Exhaust gas temperature and catalyst temperature were measured as a function of air/fuel ratio, ignition timing and misfire rates. Additionally, light-off time was measured to investigate the effects of operating conditions. Exhaust gas temperature was also predicted under various engine-operating conditions by utilizing a commercial simulation program (Ricardo Wave) to complement the experimental findings [12].

## EXPERIMENTS

All of the engine bench experiments were performed on a 1.0L SI engine fitted with a programmable electronic control unit. Six thermocouples were used to monitor the exhaust system thermally as a function of mixture strength, engine speed, load, ignition timing and misfire rate. A Misfire generator was used to induce the misfire through interruption of ignition signal.

TEST ENGINE - All of the experiments were conducted with 1.0L gasoline engine. It was equipped with a close-coupled catalyst to meet Euro-3 mode legislation. Concept feasibility and validation were conducted with the engine coupled to an eddy-current dynamometer (Maximum brake power = 176Ps/3200rpm, Maximum brake torque = 39.0kg·m). To change the air/fuel ratio and ignition timing arbitrarily, the programmable EMS (Engine Management System ; Motec) was used. A summary of the engine features is shown in Table 2.

Table 2 Engine Specifications

| Specifications | Resources |
|---|---|
| Cylinder | 4 |
| Valves / Cylinder | 3 |
| Bore (mm) | 66 |
| Stroke (mm) | 73 |
| Displacement (cc) | 999 |
| Compression Ratio | 9.8 |

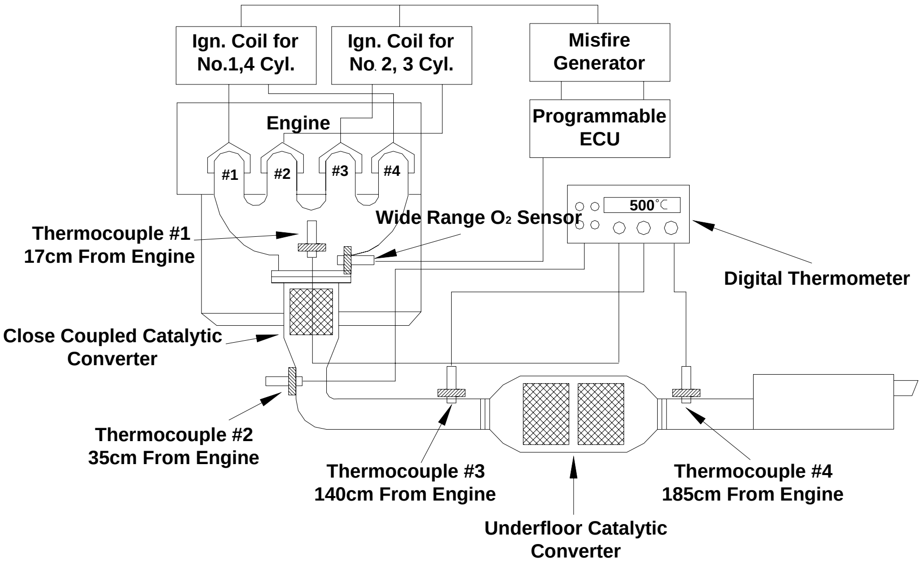

Fig. 1 Schematic diagram of the experimental set-up

TEMPERATURE MEASUREMENT – Thermal mapping of the exhaust system was done through the temperature measurements at various locations in the exhaust system as shown in Fig. 1. K-type thermocouples were used to characterize exhaust gas temperature, catalyst temperature and catalyst light-off time/temperatures according to various engine operating conditions. To measure the temperature of CCC and under-floor catalytic converter, thermocouples were installed at 50mm from the front face of the catalyst bed along the central axis which is 40mm from the upper face. This mid-position is believed to be most active in catalytic reaction.

MISFIRE GENERATOR – Misfire generator (Bosch Y280 V02 078) was adopted to generate misfire for each cylinder at any required conditions through interruption of ignition signal from the engine control unit (ECU) to ignition coils.

TEST PROCEDURES – In this study, 1050°C was defined as catalyst damage threshold temperature as it can be used without any damage to the washcoat coating [2]. For over 1050°C of the catalyst temperature, the catalyst was regarded in deactivated condition. Exhaust gas temperatures and catalysts temperatures were measured for various loads and engine speeds at normal state with MBT timing and stoichiometric condition. A series of tests were carried out to see the effects of air/fuel ratio, ignition timing retard, misfire rates. Excess air ratio(lambda value) was varied at 0.8~1.2 and ignition timing was varied at BTDC 30°CA~ATDC30°CA. In the misfire test, misfire was generated for the different engine loads. Light-off time was also measured according to these operating conditions at a cold-start state. Lastly, engine simulation was carried out to complement the experimental data.

## NUMERICAL SIMULATION

Engine simulation packages such as WAVE are widely used in industry to aid engine design and development, having the advantage of being able to capture engine flow through intake and exhaust systems, with user input of the system geometry and flow data for valves and ports [13]. Exhaust gas temperature was predicted using the simulation code, WAVE, according to engine speed, air/fuel ratio and ignition timing.

SIMULATION CODE – WAVE is a one-dimensional engineering code developed by Ricardo. For every element, it solves mass conservation equation, energy conservation equation and momentum equation. Calculations of variations in pressure and velocities with crank-angle are possible with finite difference formulations of the equations. It handles pressure reflections at area changes and at open ends as well as closed ends. Flow coefficients of restrictions, e. g. valves, are determined experimentally under steady-state conditions, and the flow rate through each restriction is computed using steady one-dimensional flow equations. Ducts are characterized by given wall friction factors. Additional pressure losses can be added for bends in order to make up for the difficulty in dealing with one-dimensional simulations.

The WAVE code incorporates a perfect mix concept, which means that for every volume element and cylinder there is always an instant mixing between the entering gases and the gases remaining from previous timestep. During the overlap between these gases, the perfect mix supposes that the fresh gas entering the cylinder is not displacing the exhaust gas. The fresh gas is mixed with the exhaust gas and part of the mixture exits through the exhaust valve.

The in-cylinder calculations incorporate a thermodynamic model, assuming a homogeneous mixture with the input defining combustion characteristics. The combustion model used is a Wiebe correlation [14] for the heat release. This is controlled by three parameters, crank angle when 50% of the charge is burned, burn duration (10-90%) and a Wiebe exponent. An empirical correlation, by Woschni [15], is used for heat transfer to the cylinder walls. This model utilizes the parameters such as cylinder bore, cylinder pressure, cylinder temperature and a characteristic velocity. It is possible to tune volumetric efficiency, inlet manifold pressure, IMEP(Indicated Mean Effective Pressure) and peak pressure independently. This was realized by considering two periods separately, one for the period when the intake valves are open and one for the remaining cycle. Engine friction is modeled with a polynomial, which is based on maximum cylinder pressure and piston speed, called as the Chen-Flynn correlation [16].

TUNING OF ENGINE MODEL – Engine friction characteristics were determined using data from a full-load test run on the engine. Discharge coefficients for the intake and exhaust valves and ports were taken from flow bench measurements. The cylinder wall temperatures were set with guidance from measurements done at low speed and low load. Cylinder peak pressure and IMEP were tuned by adjusting in-cylinder heat transfer coefficients, one for the period when the intake valves are closed.

## RESULTS AND DISCUSSION

### 1. EXHAUST GAS TEMPERATURE AND CATALYST TEMPERATURE AT NORMAL STATE.

Figure 2 describes the relationship between catalyst inlet gas temperature and catalyst temperature. Exhaust gas temperatures were measured at the entrance of CCC and UCC (Under-floor catalytic converter), and catalyst temperatures were also measured at CCC and UCC beds at 2500 rpm under various engine loads. Results show that catalyst temperature is higher than the exhaust gas temperature of catalyst inlet by 100~110°C. Hence, 950°C of catalyst inlet gas temperature was considered as the threshold temperature of catalyst damage, corresponding 1050°C of catalyst temperature. The reason why the catalyst temperature is higher than the catalyst inlet gas, is that exothermic reactions take place in the catalyst when CO gas is changed into $CO_2$ gas. The CCC temperature is approximately 200°C higher than UCC temperature. This means that most catalytic deactivation caused by high temperature is generated at the close-coupled catalyst. Figure 3 shows exhaust gas temperature for different measuring positions at various engine loads. Engine speed was fixed at 3000rpm and testing was performed at no load to full load condition. Exhaust gas temperatures were linearly increased by up to approximately 300°C at full load condition.

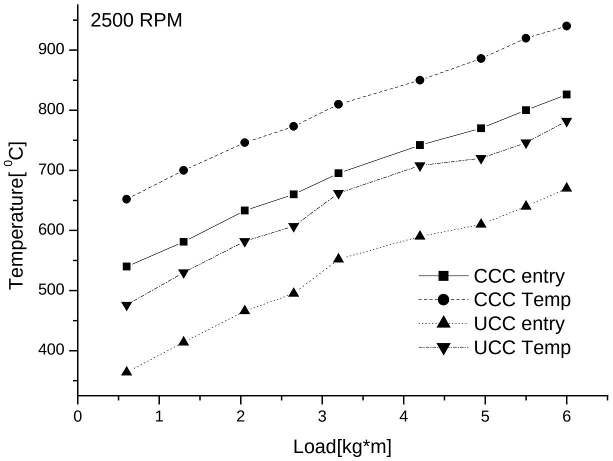

Fig. 2 Relationship between catalyst inlet gas temperature and catalyst temperature at 2500rpm

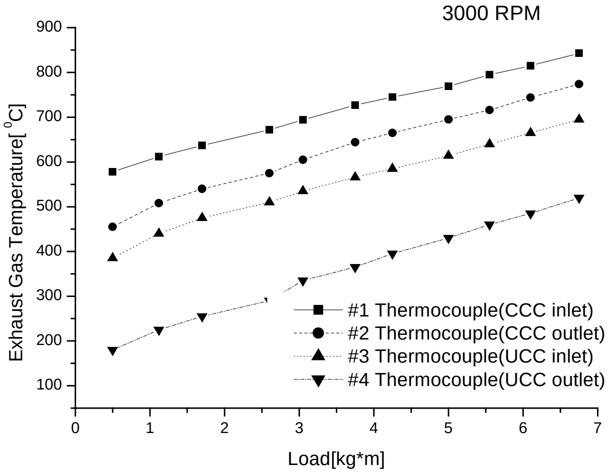

Fig. 3 The effect of engine load on exhaust gas temperature under different measuring positions at 3000rpm

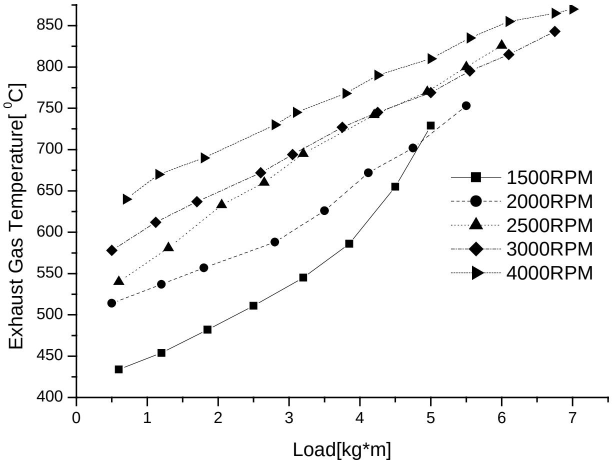

Fig. 4 The effect of engine load on exhaust gas temperature at the entrance of CCC under different engine speeds

At normal state conditions (MBT ignition timing and Stoichiometric condition), catalyst inlet gas temperature was below 950°C, hence catalyst may not be affected by any thermal shock. Figure 4 describes the exhaust gas temperature increasing for higher engine speeds at the entrance of close-coupled catalyst. When the engine is operated at higher load and speed, the fuel supply (chemical energy) to the engine is increased, resulting in an increased output of mechanical and thermal energy and hence increased exhaust gas temperatures. Additionally, as the load is increased there is a corresponding increase in spark retard, which also results in increased temperatures.

## 2. EXHAUST GAS TEMPERATURE AND CCC TEMPERATURE AT VARIOUS EXCESS AIR RATIO.

To investigate effect of excess air ratio(lambda value) on exhaust gas temperature and CCC temperature, tests were performed for different engine speeds at half load condition (3.6kg·m). Figure 5 demonstrates temperature variation as a function of lambda value with engine speed (2000, 2500, 3000 rpm). Exhaust gas temperature was measured at the entrance of CCC and catalyst temperature was measured at CCC bed. The exhaust gas temperature and CCC temperature were maximum at the excess air ratio of 1.0 as shown in Fig. 5. There are two reasons for this phenomena. Firstly, the exothermic reaction heat as CO gas changes into $CO_2$ gas is at maximum under stoichiometric condition(at the excess air ratio of 1.0), and secondly, combustion temperature is maximum at the excess air ratio of 1.0. In general, an SI engine operates at the excess air ratio of 0.85~0.95 to obtain its maximum torque, but the requirement of much heat of vaporization to evaporate the excess fuel and increasing of combustion rate results in lower exhaust gas temperature at rich area. There is some engine control strategy that excess fuel is injected intentionally for lowering the exhaust temperature at high speed and load.

In this study, excess air ratio did not give any serious effect to thermal deactivation of the catalyst. However, air/fuel ratio can be still the dominant factor driving exhaust gas temperature in addition to some operation conditions.

It is known that high temperature lean aging is detrimental to TWC catalyst performance [17,18]. Deactivation was found to be greatest with lean air/fuel ratio. Carol et al. [19] also reported that loss of three way conversion efficiency occurred readily under oxidizing conditions, but not under reducing or neutral conditions. Increasing the amount of fuel supplied to the engine with secondary air injection during cold-start idling was also investigated as a method of increasing exothermic reaction in the exhaust manifold [20].

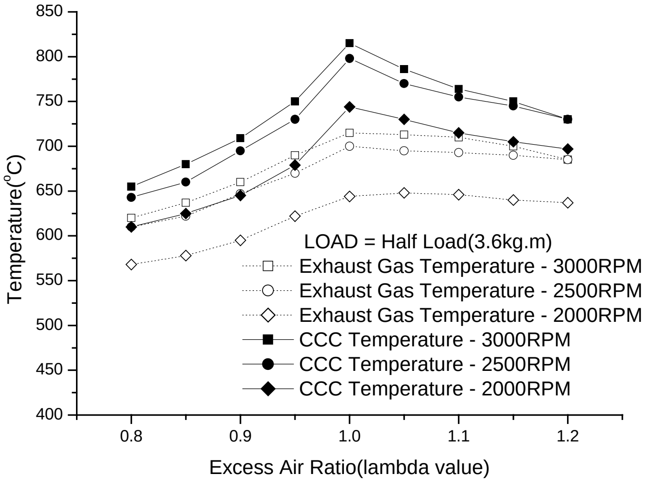

Fig. 5 The effect of excess air ratio on catalyst inlet gas and CCC temperature at different engine speeds

## 3. EXHAUST GAS TEMPERATURE AT VARIOUS IGNITION TIMINGS.

Figure 6 demonstrates the temperature variation with ignition timing retard at half load condition. Retarding the ignition timing induced rapid increase in catalyst inlet gas temperature. The catalyst inlet gas temperature has been increased by about 300°C with a retard value of 30°CA relative to TDC (top dead center) when the engine is running at 3000 rpm under half load condition. Ignition timing retarded at 20°CA relative to TDC can cause thermal deactivation of the catalyst. Excessive retardation would lead to engine afterburn in the exhaust and rapid increase of the exhaust gas temperature, and in the worst case, engine stalling which results in serious emission problems. However, proper retardation of the ignition timing for a short period can provide sufficient exhaust energy to warm up the catalytic converter fast enough [10,11,21].

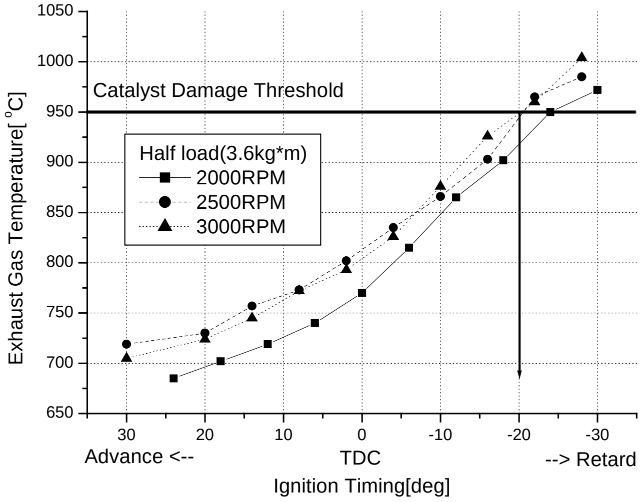

Fig. 6 The effect of ignition timing on catalyst inlet gas temperature under different engine speeds at half load condition

## 4. CATALYST TEMPERATURE WITH ENGINE MISFIRE.

The variation of catalyst temperature by misfire was tested. The purpose of this experiment is to explore how misfires, as a result of ignition faults, affect catalyst temperature. Test was performed with misfire generator so that misfire occurred at 4 cylinders randomly. Figure 7 shows linear relationship between the catalyst temperature and misfire rate under various engine loads. The catalyst temperature was increased by about 250°C with a misfire rate of 20% when the engine is running at 3000 rpm under 4kg·m load condition (a little higher than half load). Misfiring in SI engines can cause immediate damage to the catalyst and increase emissions since it brings unburned fuel and oxygen into the catalyst, resulting in an increase in temperature due to subsequent combustion.

Figure 8 describes the relationship between catalyst temperature and catalyst inlet gas temperature. As misfire rate was increased, the catalyst temperature was linearly increased, while catalyst inlet temperature decreased. When misfire occurs, unburnt hydrocarbon is produced at the exhaust gas, which gives a slight cooling effect on the inlet gas.

It was found that the melting of a ceramic substrate catalyst is usually associated with ignition-induced misfire. This might also cause the low BET surface areas measured on a catalyst, resulting from high hydrocarbon and oxygen levels entering the catalyst during normal transient engine operation [7]. Therefore, misfiring must be detected, as specified in the on-board diagnostics (OBD) regulations.

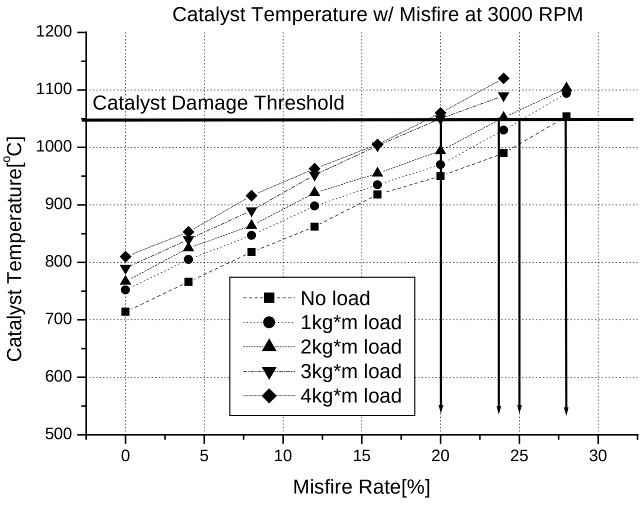

Fig. 7 The effect of misfire rate on catalyst temperature for different loads at 3000 RPM

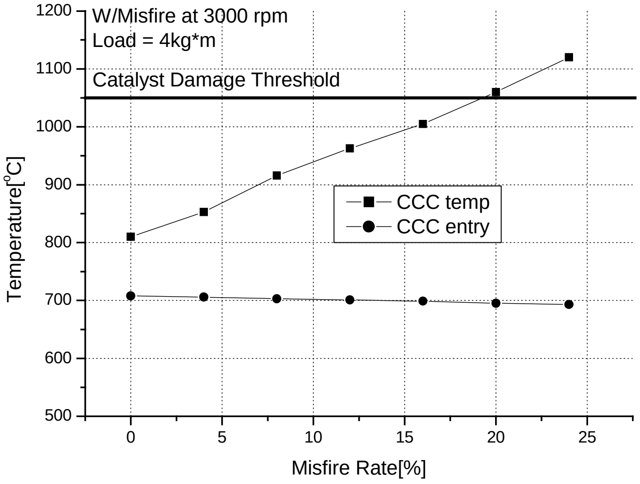

Fig. 8 The effect of misfire rate on catalyst temperature and catalyst inlet gas temperature

## 5. INFLUENCE OF IGNITION TIMING AND MISFIRE RATES ON CATALYST LIGHT-OFF.

Previous experimental results showed that ignition timing retard and misfiring were a major factors affecting catalyst temperature. To examine the light-off characteristics, catalyst light-off time was measured under various ignition timing and misfire rates at cold start conditions. Light-off temperature was defined as 300°C adopted in this study[1].

Figure 9 demonstrates the characteristics of catalyst light-off at various ignition timing under idling condition. Retard of the ignition timing provides higher exhaust thermal energy, which induced shorter light-off time. The catalyst light-off time has been shortened by about 34s with a 30°CA retard of ignition timing (from BTDC 20°CA to ATDC 10°CA) under idle state. The curve shows a steep slope until it meets light-off temperature and thereafter it shows a shallower gradient.

Figure 10 shows the behavior of the catalyst temperature under various misfire rates. The temperature curve has similar trend compared with the case of ignition timing shown in Fig. 9. The catalyst light-off time has been shortened by about 26s with misfire under idle state. It is noticeable that increasing misfire rates resulted in higher catalyst temperature though light-off time is nearly same for all misfiring conditions.

The results can suggest that significant reduction in light-off time can be achieved with proper control of the ignition timing and misfire for a short period. In addition, reduction of the light-off time could decrease the exhaust emission at cold start condition.

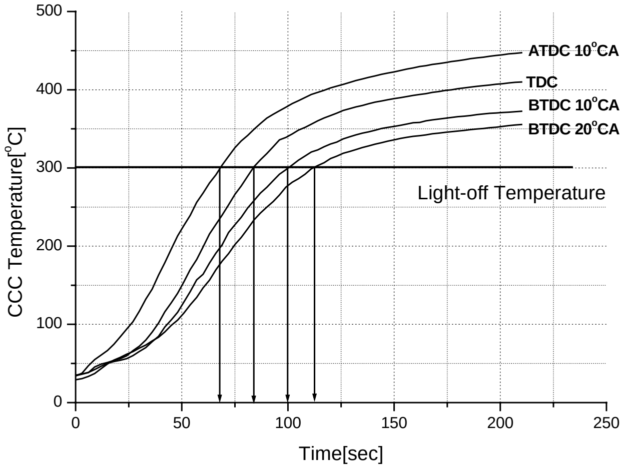

Fig. 9 Influence of ignition timing on catalyst light-off time under idling condition

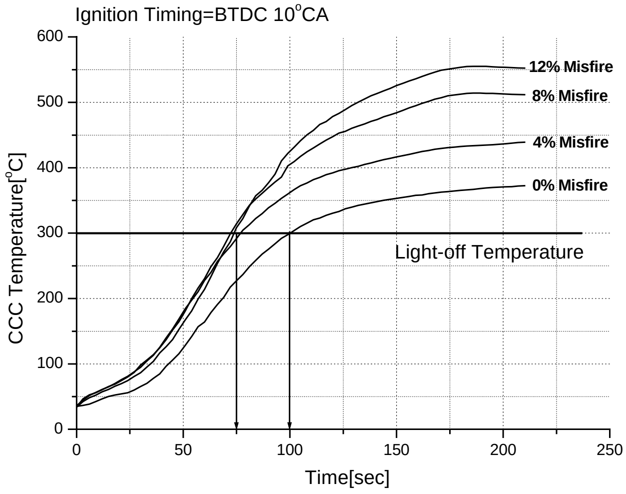

Fig. 10 Influence of misfire rate on catalyst light-off time under idling condition

## 6. NUMERICAL SIMULATION RESULTS.

Figure 11 shows the WAVEBUILD representation of the engine model used in this study. The basic configuration of the engine is a 4 cylinder, with 3 valves per cylinder. The vehicle intake system includes an intake plenum, injectors, and an intake manifold. The exhaust system includes an exhaust manifold and a close-coupled catalyst. The air cleaner and resonator were omitted to simplify the model. Exhaust gas temperature was predicted at the confluence point. The confluence point (5004 junction) matches the position of the thermocouple #1(CCC inlet) in the experiment.

The predicted catalyst inlet gas temperature according to engine speed, ignition timing, and air/fuel ratio is shown in Fig. 12 to Fig. 14. Results were predicted with crank angle based resolution at full load condition.

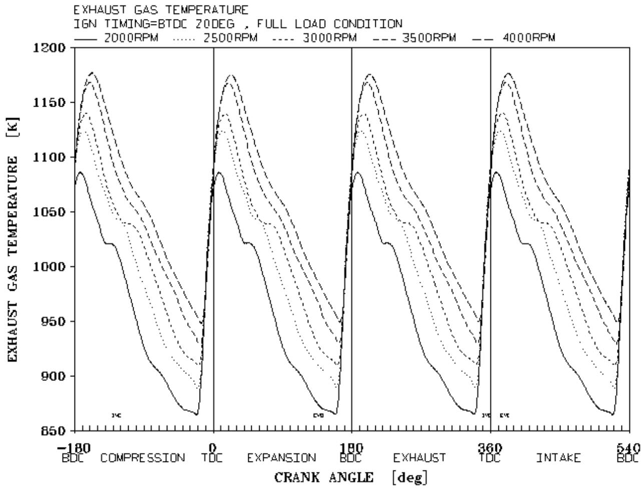

Fig. 12 Predicted catalyst inlet gas temperature under various engine speeds

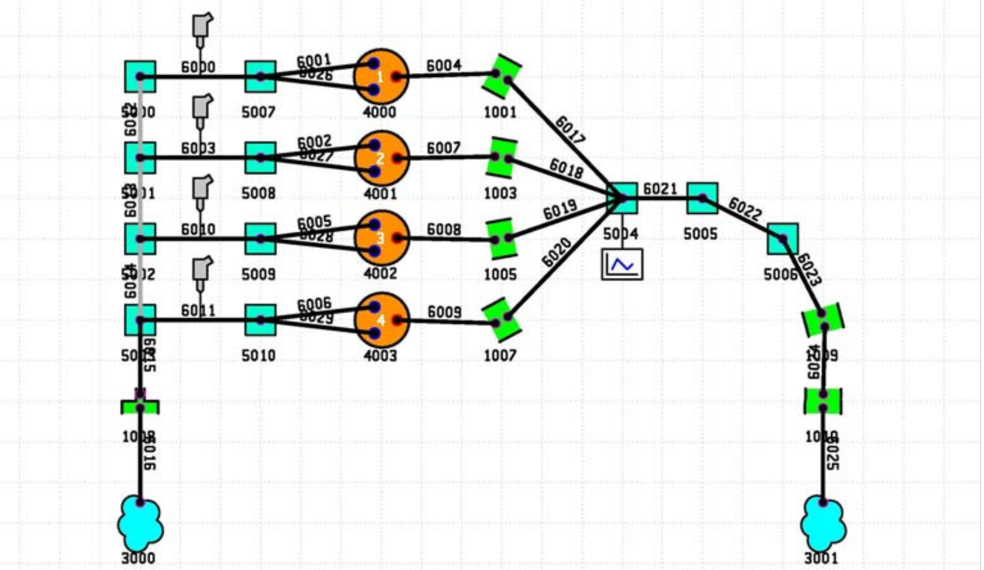

Fig. 11 WAVEBUILD representation of engine model

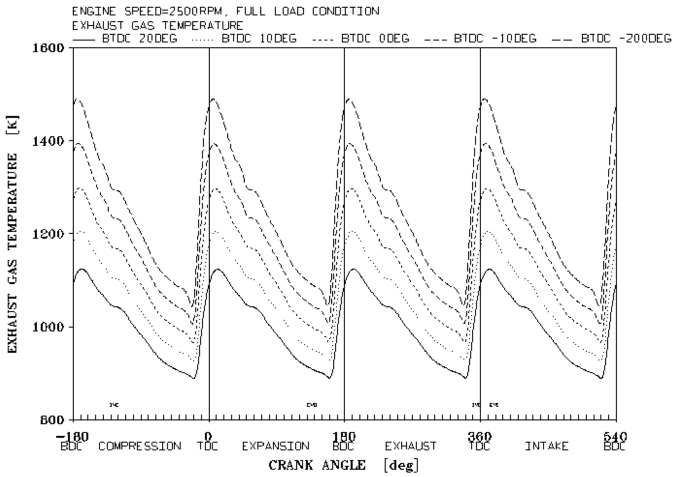

Fig. 13 Predicted catalyst inlet gas temperature at various ignition timing

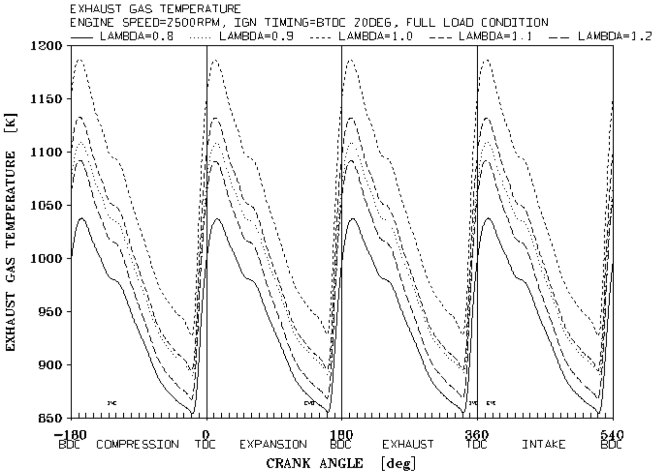

Fig. 14 Predicted catalyst inlet gas temperature under various excess air ratio

Simulation results compared well with measured data. Katsuki et al. [22] in 1987 measured the fluctuating temperatures in flames with the thermocouple under the sinusoidal 30 Hz mode of vibration. Results showed that time constants of the thermocouple with 25μm wire diameter was over 100ms. In this test, the thermocouple with 3.2mm wire diameter, which had definitely larger time constants than 100ms was used to measure the fluctuating temperatures. The thermocouple signal was not able to follow the vibration and display the mean temperature to thermometer. Mean temperature of the simulation results and measuring data were compared in this case.

Figures 15-17 show the comparisons between the computation and the experiment under various operating conditions with regard to engine speed, ignition timing and excess air ratio, respectively. The results show the relevance of simulation through the similar trend between the computation and the experiment with the error less than 5%.

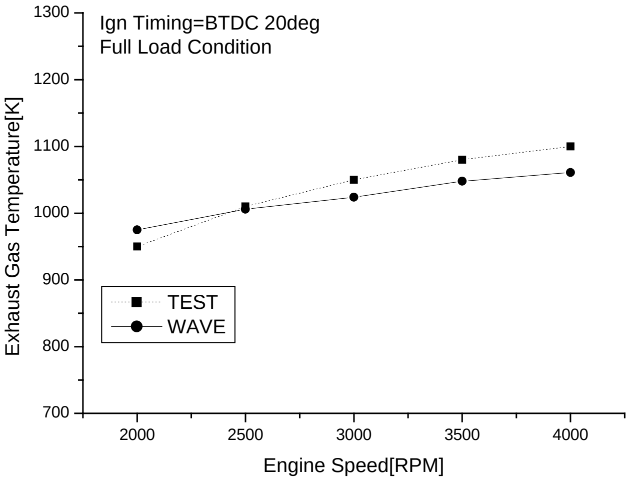

Fig. 15 Predicted and measured catalyst inlet gas temperature under various engine speeds

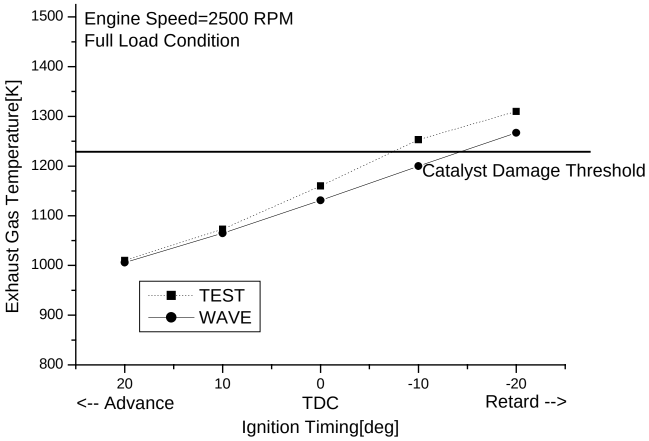

Fig. 16 Predicted and measured catalyst inlet gas temperature under various ignition timing

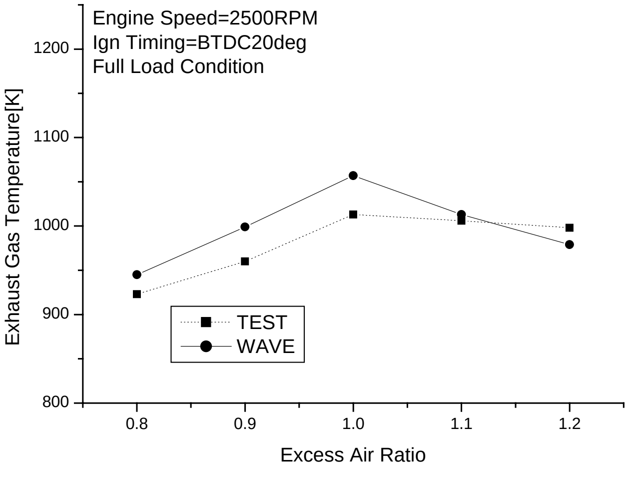

Fig. 17 Predicted and measured catalyst inlet gas temperature under various excess air ratio

## CONCLUSION

Parametric study of engine operating conditions affecting catalyst temperature was presented. Additionally, based on experimental data, engine simulation was conducted to complement the experiment. The major findings are as follows ;

1. Exhaust gas temperatures were linearly increased by up to approximately 300°C at full load condition. When the engine is operated at higher load and speed, the fuel supply (chemical energy) to the engine is increased, resulting in an increased output of mechanical and thermal energy, and hence increased exhaust gas temperatures. Additionally, as the load is increased there is a corresponding increase in spark retard, which also results in increased temperatures.

2. When the engine operated at the excess air ratio of 1.0, the CCC temperature was higher than 150°C in the case of excess air ratio of 0.8 condition. The exothermic reaction, that CO gas changes into $CO_2$ gas is maximum at the excess air ratio near 1.0 and combustion temperature is maximum at the excess air ratio of 1.0, which induces maximum temperature gradient.

3. Retardation of ignition timing over 20°CA after TDC led a rise in catalyst temperature higher than 1050°C, which can cause thermal deactivation of the catalyst. Excessively retarded ignition timing would lead to afterburn in the exhaust, resulting in rapid increase of the exhaust gas temperature, and in the worst case, engine stalling with serious emission problems.

4. The catalyst temperature has been increased by about 250°C with a misfire rate of 20%. The misfire can cause immediate damage to the catalyst since it brings unburned fuel and oxygen into the catalyst.

5. Light-off time was significantly shortened with proper control of the ignition timing and misfire for short period. Increase of the misfire rates induced higher catalyst temperature though light-off time is nearly same for all misfiring conditions.

6. Catalyst inlet gas temperature was predicted according to engine speed, ignition timing, and air/fuel ratio by utilizing a commercial simulation program (Ricardo Wave) to complement the experimental findings. The error between calculated data and experimental data is within 5% range, so that the simulation technique was proved reasonable.

## ACKNOWLEGEMENTS

The authors would like to acknowledge the support of Hyundai-Motor Company and National Research Laboratory scheme, Ministry of Science & Technology, Korea.

## REFERENCES

1. Crane, M. E., Thring, R. H., Podnar, D. J., and Dodge, L. G., “Reduced Cold-Start Emissions Using Rapid Exhaust Port Oxidation (REPO) in a Spark Engine”, SAE 970264, 1997.
2. Hu, Z., and Heck, R. M., “High Temperature Ultra Stable Close-Coupled Catalysts”, SAE 950254, 1995.
3. Brisley, R. J., O’Sullivan, R. D., and Willkins, A. J. J., “The Effect of High Temperature Ageing on Platinum-Rhodium and Palladium-Rhodium Three Way Catalysts”, SAE 910175, 1991.
4. Nagel, T., Maus, W., and Breuer, J., “Development of Increased Test Conditions for Close-Coupled Catalyst Applications”, SAE 962079, 1996.
5. Duleep, K. G., and Meszler, D., “Emission Control Technology to Comply with FTP Revisions”, SAE 961115, 1996.
6. Lui, Y. K., and Dettling, J. C., “Evolution of Pd/Rh TWC Catalyst Technology”, SAE930249, 1993.
7. Heck, R. M., Hu, Z. Smaling, R., and Amundsen, A., “Close Coupled Catalyst System Design and ULEV Performance After 1050°C Aging”, SAE 952415, 1995.
8. O’Sullivan, R. D., and Will, N. S, “The Effect of Intermittent Misfire and Air to Fuel Ratio Excursions on Exhaust Catalyst Temperature”, SAE 940927, 1994.
9. Johnson Matthey and HMC Technical Seminar, “Deactivation of Catalyst”, pp.25, 1985.
10. Chan, S. H., and Zhu, J., “The Significance of High Value of Ignition Retard Control on the Catalyst Lightoff”, SAE 962077, 1996.
11. Ueno, M., Akazaki, S., Yasui, Y., and Iwaki, Y., “A Quick Warm-Up System During Engine Start-Up Period Using Adaptive Control of Intake Air and Ignition Timing”, SAE 2000-01-0551, 2000.
12. Hetherington P., et al., “Simulating Odd Fire V-10 Exhaust Noise for Sound Quality Evaluation”, SAE 1999-01-1652, 1999.
13. Ricardo North America, Inc., WAVE Basic Manual, Documentation/User’s Manual Version 3.6, 2001.
14. Watson, N., Pilley, A. D., and Marzouk, M., “A Combustion Correlation for Diesel Engine Simulation”, SAE 800029, 1980.
15. Woschni, G., “A Universally Applicable Equation for the Instantaneous Heat Transfer Coefficients in the Internal Combustion Engine”, SAE 670931, 1967.
16. Chen S. K., and Flynn, P. F., “Development of Single Cylinder Compression Ignition Research Engine”, SAE 650733, 1965.
17. Burkholder, S. P., and Cooper, B. J., “Effect of Aging and Testing Conditions on Catalyst Performance”, SAE 911734, 1991.
18. Heck, R. M., Hochmuth, J. K., and Dettling, J. C., “Effect of Oxygen Concentration on Aging of TWC Catalysts”, SAE 920098, 1992.
19. Carol, L. A., Newman, N. E., and Mann, G. S., “High Temperature DeactiFvation of Three-Way Catalyst”, SAE 892040, 1989.

20. Nishizawa, K., Yamada, T., Ishizuka, Y., and Inoue, T., "Technologies for Reducing Cold-Start Emission of V6 ULEVs", SAE 971022, 1997.
21. Choi, M. S., Sun, H. Y., Lee, C. H., Myung , C. L., Kim, W. T., and Choi, J. K., "The study of HC Emission Characteristics and Combustion Stability with Spark Timing Retard at Cold Start in Gasoline Engine Vehicle", SAE 2000-01-1082, 2000.
22. Katsuki, M., Mizutans, Y., and Matsumoto, Y., "An Improved Thermocouple Technique for Measurement of Fluctuating Temperatures in Flames", Combustion and flame, vol. 67, pp. 27~36, 1987.
23. Sandquist, H., Wallesten, J., Enward, K., and Stromberg, S., "Influence of Valve Overlap Strategies on Residual Gas Fraction and Combustion in a Spark-Ignition Engine at Idle", SAE 972936, 1997.
24. Matsunaga, S., Yokota, K., Hyodo, S., Suzuki, T., and Sobukawa, H., "Thermal Deterioration Mechanism of Pt/Rh Three-way Catalysts", SAE 982706, 1998.

## DEFINITION, ACRONYMS, ABBREVIATIONS

| | |
|---|---|
| ATDC | After Top Dead Center |
| BET | Brunauer Emmett Teller |
| BTDC | Before Top Dead Center |
| CA | Crank angle |
| CCC | Close-Coupled Catalyst |
| ECU | Engine Control Unit |
| EHC | Electrically Heated Catalyst |
| EMS | Engine Management System |
| EPA | Environmental Protection Agency |
| FTP | Federal Test Procedure |
| IMEP | Indicated Mean Effective Pressure |
| LEV | Low Emission Vehicle |
| MBT | Maximum Brake Torque |
| OBD | On Board Diagnostics |
| RPM | Revolution Per Minute |
| THC | Total Hydrocarbon |
| TWC | Three Way Catalyst |
| UCC | Under-floor Catalytic Converter |
| ULEV | Ultra Low Emission Vehicle |
| $\lambda$ | Excess air ratio ; $(A/F) / (A/F)_{\text{stoichiometric}}$ |