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ABSTRACT

Wall wetting of injected fuel onto the intake manifold and cylinder wall causes unpredictable transient behavior of air-fuel mixing which results in a significant emission of unburned hydrocarbon (HC) emission during cold start operation. Heated exhaust gas oxygen (HEGO) sensors cannot measure the air-fuel ratio (A/F) of exhaust gas during cold start condition. Precise and fast estimation of air/fuel ratio of the exhaust gas is required to elucidate the wall wetting phenomena and subsequent HC formation. Refined A/F estimation can enable the control of fuel injection minimizing HC emissions during cold start conditions so that HC emissions can be minimized.

A new estimator for A/F of the exhaust gas has been developed. The A/F estimator described in this study utilizes measured exhaust gas temperature and general engine parameters such as engine speed, airflow, coolant temperature, etc. A fast response, fine-wire thermocouple was used to measure exhaust gas temperatures and a fast response flame ionization detector was used to measure HC emissions during the cold start period. A Generalized Regression Neural Network Function Approximation (GRNN) was used to estimate the A/F of exhaust gas. The A/F traces generated by the GRNN algorithm agree very well with measurements.

INTRODUCTION

'Cold Start' is defined as the engine operation period before the coolant temperature of the engine reaches about 80ºC. During the early stage of cold start, due to the low temperature of the intake system, the injected fuel does not evaporate easily and is partially in the state of fuel film. The fuel film in the intake manifold and cylinder wall is emitted as a combustion product or unburned hydrocarbon. This is why the A/F of the exhaust gas is lean at the beginning, and it gradually approachs stoichiometric. The cold start duration is divided into two modes. The first mode is the cranking and the second is the warming-up. During the cranking mode, the operation stresses engine startability. Very rich air/fuel mixture is required during this period to compensate for the liquid fuel fraction, which is not easily vaporized for mixture preparation. During the warming-up mode, the commercial lambda sensor (HEGO; Heated Exhaust Gas Oxygen Sensor) is inactive yet due to its own thermal inertia in the cold environment. This forces production control strategies to run in the open-loop mode and to use look-up tables for A/F control during cold start.

The fuel injectors deliver a spray of atomized fuel into the intake port and, under cold running conditions, a significant part of the spray is deposited on the intake port surfaces and valve backs forming a thin film. Fuel is subsequently evaporated from fuel film in the intake system. Fuel is emitted as a form of a unburned fuel or a fuel-originated product, and strongly influence emissions of HC [1-3]. Very rich fuel injection is required because of a discrepancy between fuel injected and fuel induced into the cylinder. This fuel is becoming the main source of automobile hydrocarbon emissions.

In the early stage of a cold start, the HEGO sensor is inactive due to the low temperature of exhaust gas. Even when the HEGO sensors are active, they still only yield information of the A/F mixture being rich or lean of stoichiometry. This switch-like behavior does not enable closed-loop operation at conditions other than stoichiometry. Thus, commercial engines adopt open loop control to calculate fuel injection quantity. Control of A/F is an important factor in reducing exhaust emissions, especially HC. Catalytic efficiency could be secured within a very narrow range of A/F during cold start, where the commercial oxygen sensors are inactive [4]. This requires a new control strategy to replace the open-loop mode using look-up tables for A/F control during cold start. These open-loop systems are unable to compensate for disturbances such as fuel quality, aging over time, and manufacturing tolerances. All of these disturbances can degrade the performance of open-loop strategies [5]. The A/F estimation model during cold start by measuring the torque fluctuation of the engine was attempted by Asik et al. [6].

The mixture is usually set very rich at low coolant temperature. A large amount of hydrocarbon emission is produced under cold start condition, where startability and stability are more important than exhaust emissions. The exhaust gas temperature reaches a maximum value near stoichiometry. This can be used to develop a tool to estimate the A/F in cold start condition utilizing fast response thermocouples.

In this research, by measuring exhaust gas temperature and other engine parameters, A/F is estimated during a cold start. The A/F estimation from exhaust gas temperature measured by fast response thermocouple, was performed to replace the function of the HEGO sensor during a cold start. A mechanism for A/F estimation was established using Generalized Regression Neural Network (GRNN) algorithm which utilizes exhaust gas temperature, coolant temperature, oil temperature and HC concentration as well as wide range lambda sensor (UEGO) data.

ESTIMATION OF AIR FUEL RATIO USING A NEURAL NETWORK

Exhaust gas temperature rises gradually with engine coolant temperature and eventually reaches stationary state after warming up period. Exhaust gas temperature is determined by each engine driving condition such as engine rpm and load. Exhaust gas temperature reaches a maximum at a slightly rich A/F ratio [7]. By measuring the exhaust gas temperature, HC concentration, and coolant temperature simultaneously, an attempt has been made to find an estimation method for A/F. An A/F estimation model could be utilized for exact engine control, consequently to reduce HC in cold start condition. A/F was estimated by GRNN (Generalized Regression Neural Network), which is available in the Matlab Neural Network Toolbox. GRNN is a feedforward neural network for system modeling and estimation. GRNN is a kind of radial basis network that is often used for function approximation. It is composed of 4 layers, where the 1st layer is the input layer. The 2nd layer is the pattern layer having one neuron for each input pattern. The 3rd layer is composed of 2 kinds of neurons, S-Neurons, and D-Neurons. S-Neurons calculate the sum of the weighted output, while D-Neurons calculate the sum of the output not weighted. Each output neuron has one S-Neuron and one D-Neuron. The last layer of the GRNN is the output layer, dividing each S-Neuron output with the D-Neuron output. A neural network algorithm is generally used when the system modeling is exceedingly difficult. Input and output parameters of the system are used to identify the system as a form of neural network.

Figure 1 shows the architecture of GRNN used in this study for A/F estimation. As shown in Fig. 1, input parameters are engine rpm (N), air flow rate, exhaust HC concentration, exhaust gas temperature, coolant temperature, oil temperature, and atmospheric temperature. The real exhaust A/F was measured by a wide range oxygen sensor.

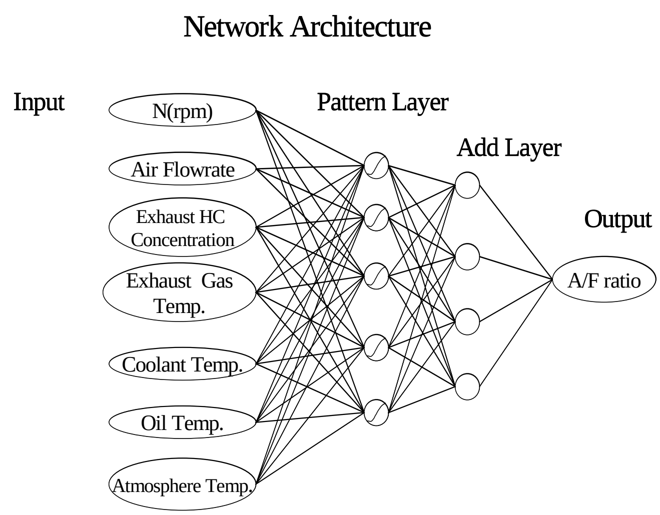

Figure 1. GRNN (Generalized Regression Neural Network) architecture for A/F estimation.

EXPERIMENTAL APPARATUS

ENGINE CONFIGURATION

All the engine experiments were performed at the Walter E. Lay Automotive Laboratory in the University of Michigan, with a 2.5L DOHC engine. It is a 60° V6 engine with aluminum head and block with DOHC and four valves per cylinder. It uses sequential port fuel injection and has two unequally-long intake runners per cylinder. At speeds below 3500 rpm (which accounts for all tests performed in this study) the short runner is closed at the intake manifold, which greatly increases in-cylinder turbulence and burning rate. Two fast light-off catalysts integrated into the double-wall stainless steel manifolds are positioned very close to the engine. Table 1 describes detailed specifications of the engine, and Fig. 2 shows the engine in the test cell.

Table 1: Specifications of 2.5L DOHC engine.

Bore	82.4 mm
Stroke	79.5 mm
Connecting rod length	138 mm
Piston pin offset	1.4 mm
Compression ratio	9.7
Combustion chamber	pent roof
Piston	flat
Intake valve IVS dia. (each)	27.9 mm
Exhaust valve IVS dia. (each)	22.2 mm
EVO @ 1 mm valve lift	43º BBDC
EVC @ 1 mm valve lift	14º BTDC
IVO @ 1mm valve lift	6º ATDC
IVC @ 1mm valve lift	21º ABDC primary 28º ABDC secondary
Maximum torque @ speed	165 lb-ft @ 4250 rpm (advertised)
Maximum power @ speed	170 bhp @ 6250 rpm (advertised)
Minimum BSFC @ speed, load	253 g/kWhr @ 2000 rpm, WOT

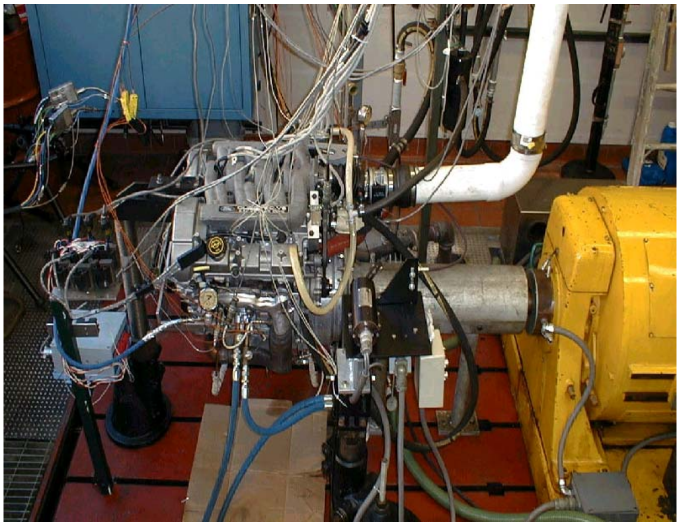

Figure 2. Research engine on the dynamometer.

The block assembly and catalysts were new and the heads came from a vehicle with 30,000 miles. Testing began after a break-in procedure for the engine and an ageing procedure for the catalysts. The engine was mounted to a DC dynamometer (Westinghouse) controlled by a Dyn-Loc IV controller (Dyne Systems). Fuel injection and spark timing were set with a Cosworth/Intelligent Controls IC 5460. The IC 5460 modulated injector pulse width so that the desired exhaust lambda value was achieved. Ignition timing at zero load was set to 30º BTDC.

SENSOR POSITIONS

The locations of the sensors in the exhaust manifold are depicted in Fig. 3. Data such as coolant temperature have been acquired via Labtech data acquisition software. Fine wire thermocouples were used for the measurement of exhaust gas temperature while a fast FID and a wide range oxygen sensor were used for the measurement of exhaust gas concentration. Figure 4 shows the exhaust gas temperature sensor and the Fast FID analyzer probe.

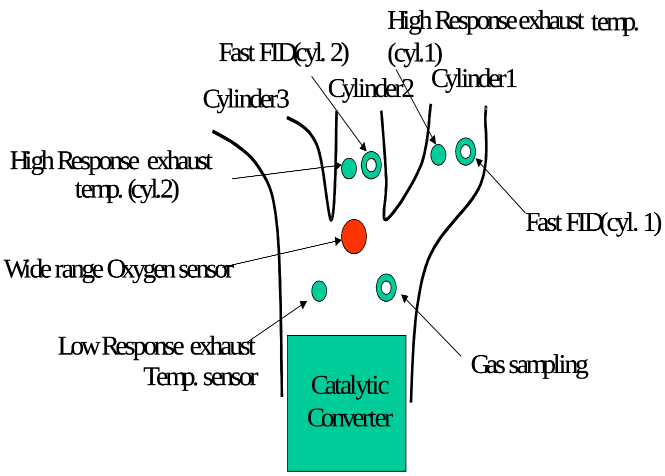

Figure 3. Position of sensors at the exhaust manifold.

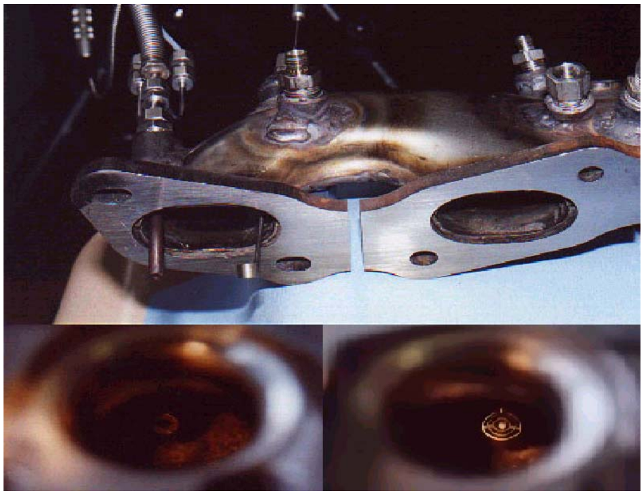

Figure 4. Installation of the fast FID probe and fast temperature sensor located 40mm from the exhaust valve seat.

A/F MEASUREMENT WITH WIDE RANGE LAMBDA SENSOR (UEGO)

During a cold start, A/F of the exhaust gas was measured using a Bosch wide range lambda sensor (UEGO) at several engine speed and load conditions. A/F could be measured during cold start condition since the lambda sensor was preheated well before the start of engine. As shown in Fig. 3, the UEGO sensor is located at the junction of the exhaust manifold.

THC MEASUREMENTS WITH FAST FID ANALYSER

The steady-state emission analyzers provide time-averaged emissions data for locations farther away from the cylinder where the flow is more steady. A fast response analyzer is needed to monitor the realistic fluctuation of the exhaust gas motion, temperature and HC concentration, which may vary significantly through an engine cycle. For this reason, two fast FID (Flame Ionization Detector; Cambustion HFR 500 system) probes are mounted in the exhaust system. Exhaust gas is taken from a point in the exhaust system and passes through a 360 mm heated sample probe to a miniature flame ionization detector. The analyzed data were acquired by a data acquisition system (Labtech). The attached position is at the outlet of the exhaust valve.

The sample probe opens into a constant pressure chamber and also feeds a connecting tube to the FID flame. The constant pressure chamber ensures that a constant flow of exhaust is brought to the flame. A thorough review of the fast FID was given by Cheng et al. [8]. The exhaust gas spends 5.2 ms in the sample probe (transit time) and the FID has a response time of 1.4 ms. The output signal is shifted by the transit time. The response time causes a slight smearing of the signal (17 crank angle degrees at 2000 rpm), which is considered small enough to be neglected.

CYCLE-RESOLVED EXHAUST GAS TEMPERATURES MEASURED BY A FAST-RESPONSE THERMO-COUPLE

A type K fast response thermocouple (Medtherm) was used to measure the exhaust gas temperature (Fig. 5), which has a diameter of 25 μm and is surrounded by a triple radiation shield [9]. During the transient cold start condition, it can measure the instantaneous exhaust gas temperature. It cannot withstand the thermal load at high engine speeds or loads but lasts long enough to acquire temperature at low engine speed and load. The fast response thermocouple signals are amplified with 10kHz isolated amplifiers. In these experiments, the signals are recorded with the time based data acquisition system. Response time of the thermocouple was found to be less than 10ms at typical exhaust gas velocities [9].

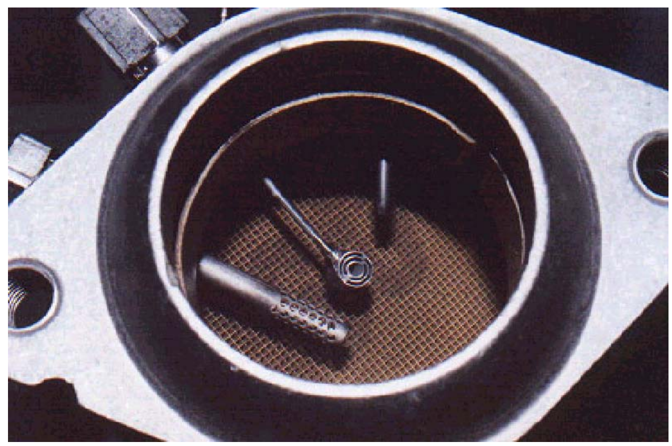

Figure 5. Fast FID and exhaust gas temperature sensor.

AIR AND FUEL FLOW MEASUREMENT

Airflow into the engine was measured with a laminar flow element (400 cfm, Meriam) and a differential pressure transducer (Sentra). The signal passes through an RC filter and is recorded by a time based data acquisition system installed in a PC (CIO-EXP16 & CIO SAS08 supported by NI Labtech). Airflow was also measured by a production mass airflow sensor (Hitachi). Airflow measurements were corrected for temperature, pressure and humidity. Fuel flow is measured by a positive displacement flow meter (Pierburg 103A-150). The fuel is temperature conditioned and supplied to the engine at 42 psi. The time based data acquisition system converts volume to mass flow and records mass flow versus time.

TEST RESULTS AND DISCUSSIONS

The engine was motored by a DC dynamometer until the coolant temperature reached 25° C. After the coolant temperature reached 25° C, fuel injection was started. Data acquisition takes place at the same time.

AIR-FUEL RATIO

A/F of the exhaust gas was measured in several conditions using the UEGO sensor. The measured exhaust A/F trends are illustrated in Fig. 6 during a cold start at 2000 rpm, 12% throttle opening with supplied air/fuel ratio 13 based on the measured air flow and injected fuel amount. It can be noticed that A/F is very lean at the beginning and gradually converges to A/F 13. The area between the A/F 13 line and the measured A/F line is considered to be the contribution of the fuel film (wall wetting) in the intake manifold and the cylinder and unburned hydrocarbons above and beyond what are generated at steady-state operation. As the engine warms-up gradually, the "wall wetting" amount in intake system and combustion chamber wall is decreased. The amount of fuel supplied to engine is not changed. The A/F of the exhaust gas has been changed gradually from lean to stoichiometric operation.

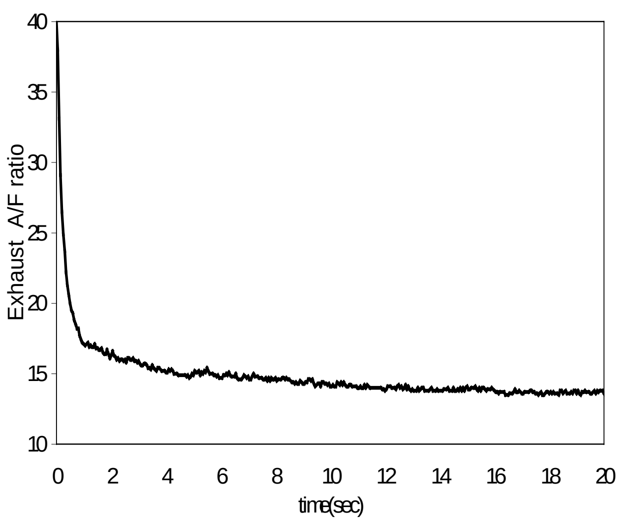

Figure 6. Measured A/F of exhaust gas (2000rpm, throttle 12% open, Supplied A/F=13)

Figure 7 shows measured exhaust A/F at 1000 engine rpm with the supplied A/F=11. Sudden change was made in throttle opening position from 6% to 10% at 50 seconds. Again A/F is very lean at the beginning, and gradually reaches to supplied A/F. At 50 seconds, due to the abrupt change of the throttle opening position, the A/F changes sharply, and gradually reaches normal condition (A/F 11) again.

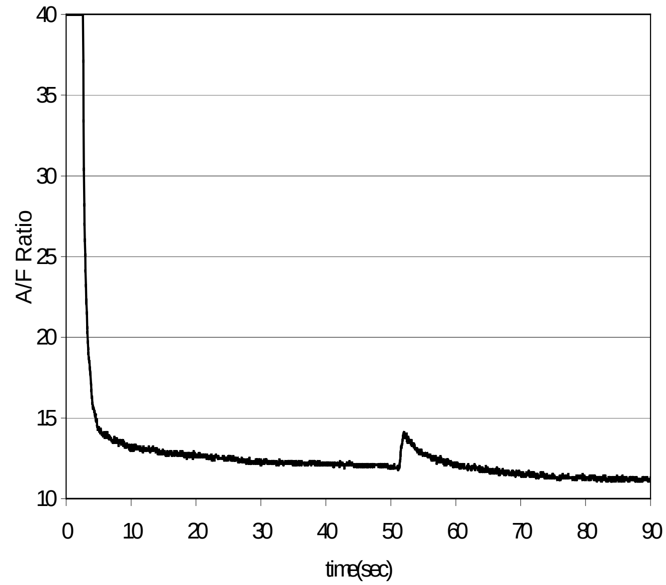

Figure 7. Measured exhaust A/F (UEGO)(1000 rpm, throttle from 6% to 10%(at 50 sec), A/F=11).

EXHAUST GAS TEMPERATURE MEASUREMENT

Exhaust gas temperatures were measured by the K-type fast response (fine wire type) thermocouples and the slow response thermocouple together. The results are given in Fig. 8. The throttle position was also suddenly changed from 6% to 10% at 50 second as shown in Fig.7.

Exhaust gas temperature was measured according to this procedure, and the neural network algorithm estimates the A/F using the measured temperature. There is about 3 ~ 4 seconds of time delay between the slow response thermocouple and fast response thermocouples. The slow response thermocouple data show lower temperature, because it is equipped on farther downstream position in the exhaust manifold and does not have a radiation shield.

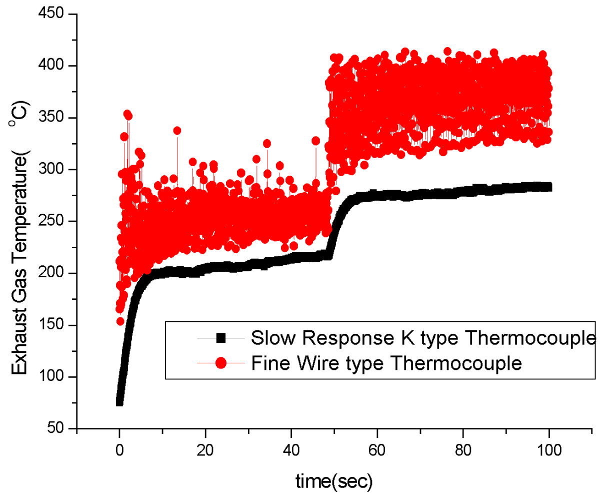

Figure 8. Results of exhaust gas temperature measurement with two different thermocouples corresponding to Fig. 7. (1000rpm, throttle opening from 6% to 10% at 50sec, supplied A/F=11, starting at 25°C coolant temperature).

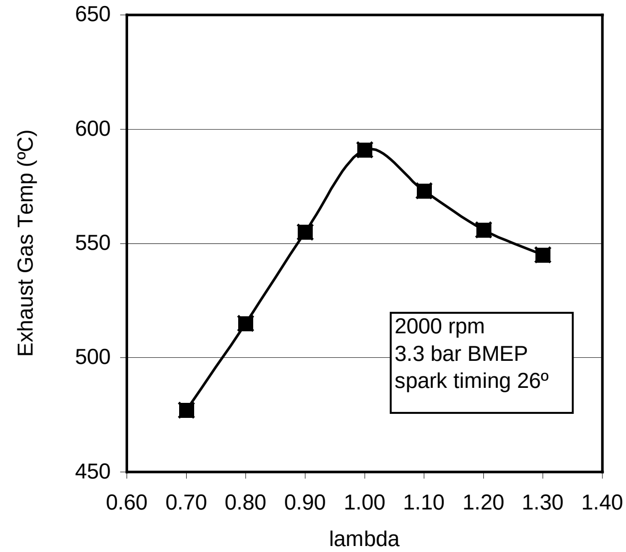

Figure 10. Exhaust gas temperatures before the catalyst brick as a function of lambda (measured by slow response K type thermocouple).

Figure 9 shows the exhaust gas temperature measured by the fast response thermocouple at 1500rpm, throttle opening 10%, A/F=13 corresponding the conditions of Fig.6.

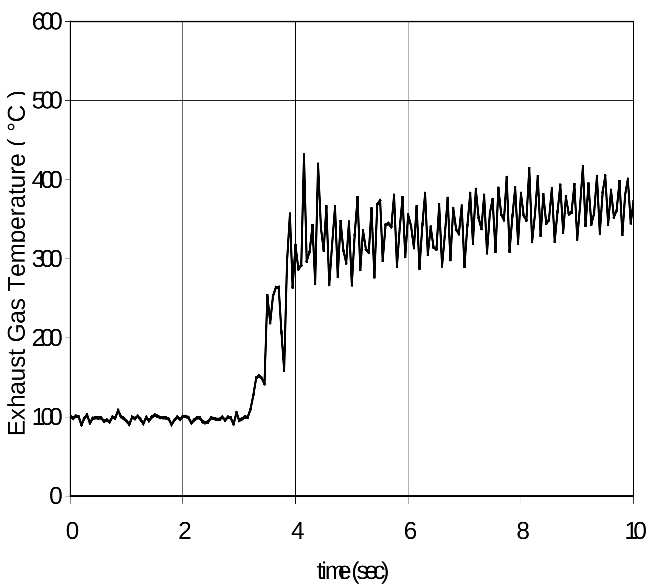

Figure 9. Exhaust gas temperature measured by the fast response thermocouple (1500rpm, throttle 10%, A/F=13).

Figure 10 shows how that exhaust gas temperature before the catalyst changes with lambda. This proves that A/F could be estimated from the exhaust gas temperature. Rich mixtures cool down the exhaust more than lean mixtures because a rich mixture has a higher specific heat and also burns faster which allows more expansion work to be extracted.

HYDROCARBON EMISSIONS

The total hydrocarbon (HC) concentration of the exhaust gas, detected by the fast FID, is shown in Fig. 11. During the initial part of a cold start, large amounts of unburned hydrocarbons are produced. The HC concentration briefly decreases, and then gradually increases again. The high HC concentration at the beginning is due to the unburned fuel.

During the period when HC level is gradually increasing, it seems that the fuel film in intake system and combustion chamber is evaporating and being emitted. After about 50 seconds engine operation, the throttle position was suddenly changed from 6% to 10% and the hydrocarbon concentration drops considerably. After that, the hydrocarbon concentration gradually increases and combustion becomes steady.

Figure 12 shows the unburned hydrocarbon concentration at 1500 rpm, throttle opening 10%, A/F=13, when the measurement starts at 25° C coolant temperature using a fast FID analyzer. At the beginning, unburned hydrocarbon concentration is very high, the peak value exceeds 12,000 ppm. After about 2~3 seconds, the concentration becomes stable at about

2000 ppm. This graph shows that the hydrocarbon emission is significant at the early stages of cold start.

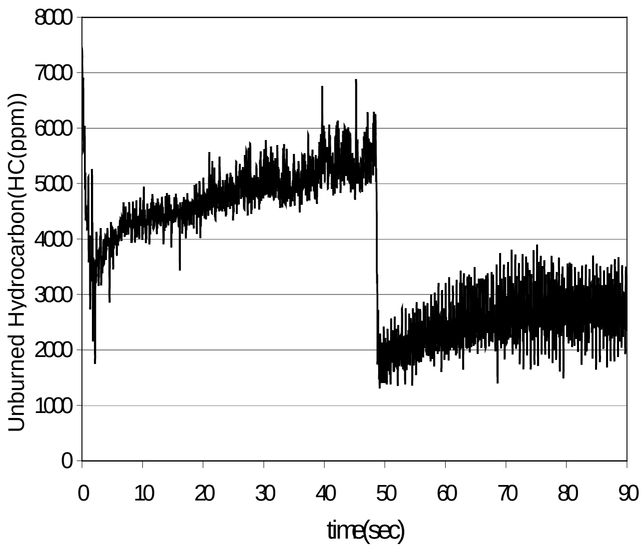

Figure 11. Unburned hydrocarbon concentration (1000 rpm, throttle opening changed from 6% to 10% at 50 sec, supplied A/F=11, measurement starting at 25° C coolant temperature).

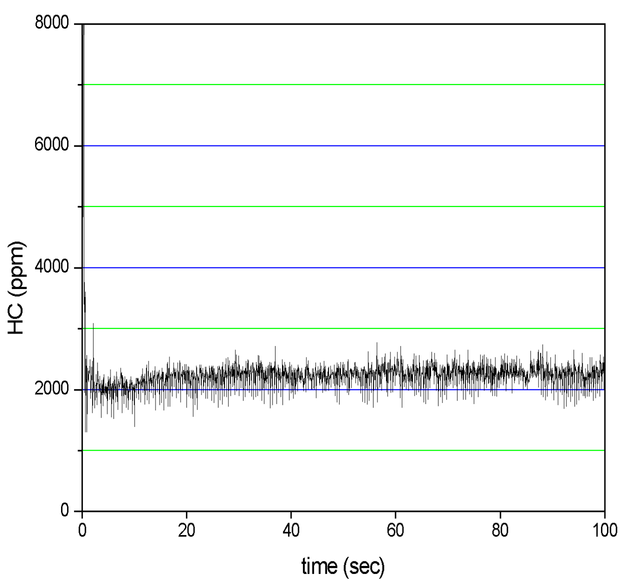

Figure 12. Unburned hydrocarbon concentration (1500 rpm, throttle 10%, A/F=13, measurement starting at 25° C coolant temperature).

ESTIMATION OF A/F BY NEURAL NETWORK ALGORITHM

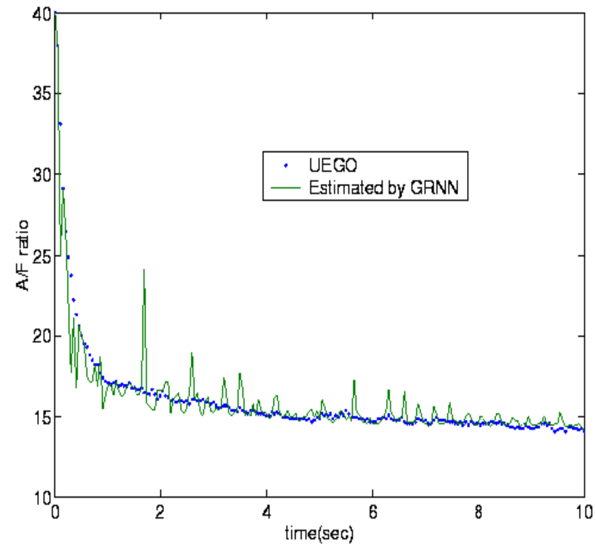

Figure 13 Measured and estimated A/F (estimated by single input GRNN, 2000rpm, 12% throttle opening, supplied A/F 13, GRNN training with a single input (Exhaust Temp. only)).

Figure 13 shows A/F estimated by the Generalized Regression Neural Network (GRNN) algorithm with a single input, compared to the experimental data. The exhaust gas temperature is the only input, and the output is measured A/F at the wide range lambda sensor position.

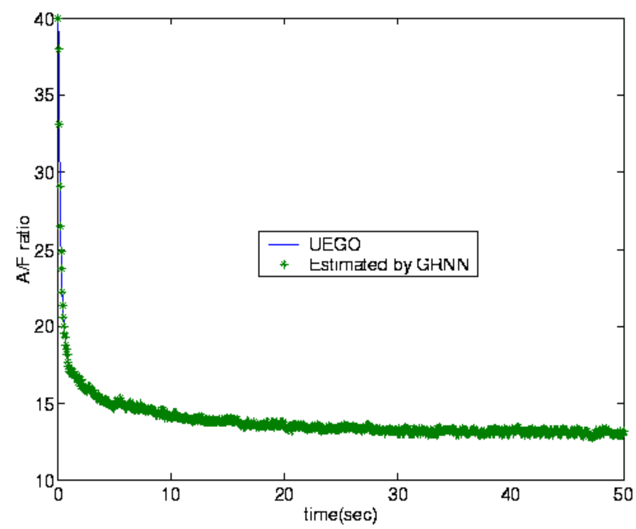

Figure 14. Measured and estimated A/F (estimated by multiple input GRNN, 2000rpm, 12% throttle opening, supplied A/F 13, GRNN training with multiple inputs).

Figure 14 shows A/F estimation by GRNN algorithm with multiple input parameters. A/F was estimated using the Generalized Regression Neural Network (GRNN) algorithm. The input parameters are exhaust gas temperature, engine rpm, air flow rate, coolant outlet temperature, oil outlet temperature, HC concentration in the exhaust gas and air temperature. The output is exhaust A/F ratio. The A/F ratio measured from the UEGO sensor and estimation are in good agreement. Figure 13 and Fig. 14 seem to show that more input parameters cause the model to work better. Three different conditions have been tested and their comparisons are shown in Fig. 15. Each trace was acquired during 10sec in cold start condition. The calculated values using the GRNN algorithm showed good agreement to the experimental results.

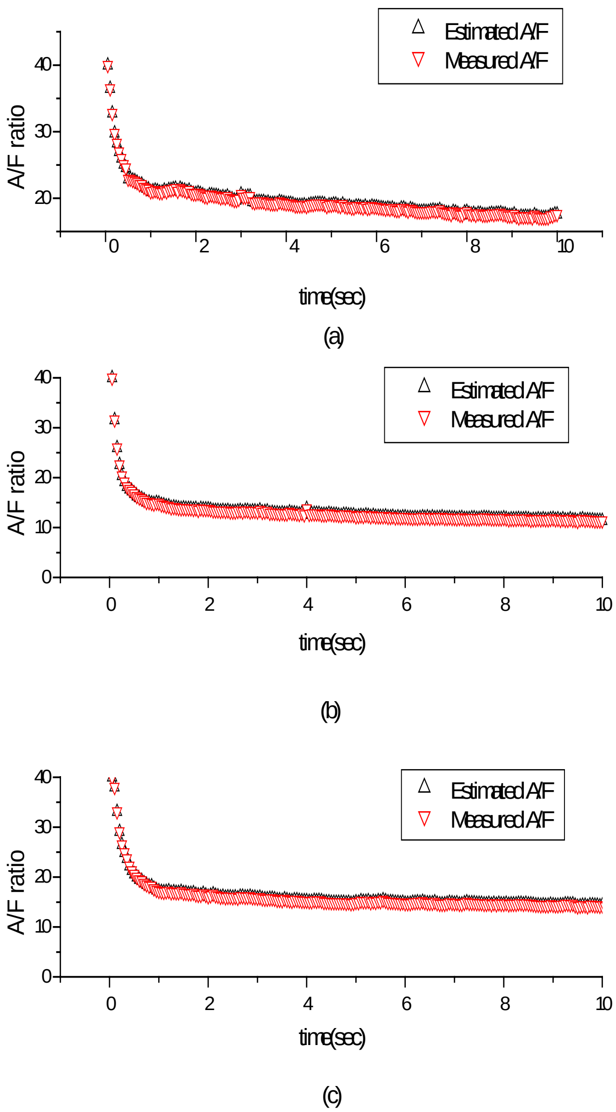

Figure 15. Estimated A/F by GRNN and measured A/F from engine (calculated with combination of 3 different conditions) (a) 2000rpm, 12% throttle, supplied A/F = 13 (b) 2000rpm, 15% throttle, supplied A/F = 11 (c) 2000rpm, 15% throttle, supplied A/F = 16.

For more robust results, experimental data should be acquired for a wider range of engine operating conditions.

Figures 15 verifies that the A/F estimation method proposed here could be used as a tool for A/F control during cold start conditions (See also [10-14]). The fast response thermocouple is very sensitive and useful to measure the exhaust gas temperature in the medium range of engine speed and load conditions in spite of its fine wire size. However, the durability problem and the price of the sensor make it un-practical. Further studies of durability and cost are necessary in the future. The thermocouple measuring the metal surface temperature could be a practical option.

CONCLUSIONS

A new estimator was developed to predict the A/F from the exhaust gas during cold start. In this research, many parameters such as exhaust gas temperature, coolant temperature are used to estimate the A/F of the exhaust gas. Important conclusions are as follows:

1. The concentration of the hydrocarbon emissions in the exhaust gas is very high at the early stage, decreases shortly after, and gradually increases again. It implies that the "wall wetting" phenomenon occurs in the intake manifold, cylinder wall and piston crevice.
2. During cold start, the algorithm to estimate A/F has been developed coupled with exhaust gas temperature measurement. GRNN (Generalized Regression Neural Network) algorithm was used for estimation. From the experiment at the condition of 2000 rpm, 12% throttle opening with supplied A/F=13, it was found that A/F was very lean at the beginning and converged to A/F 13 gradually. The discrepancy between the supplied A/F of 13 and the measured A/F is supposed due to the contribution of fuel film (wall wetting) in the intake manifold and the cylinder.
3. As engine temperature rises gradually, the amount of fuel film due to "wall wetting" decreases, while the amount of fuel supplied to engine is fixed. Fast response thermocouple with a fine wire was used to measure the exhaust gas temperature precisely.
4. A method to estimate the A/F of the exhaust gas is developed using many engine parameters including the exhaust gas temperature. The GRNN algorithm can trace the A/F very well with neglected error.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ABDC After Bottom Dead Center

A/F Air Fuel Ratio

ATDC After Top Dead Center

BMEP Brake Mean Effective Pressure

BSFC Brake Specific Fuel Consumption Rate

BTDC Before Top Dead Center

ECU Engine Control Unit

EVC Exhaust Valve Close

EVO Exhaust Valve Open

Fast FID Fast Flame Ionization Detector

FTP75 Federal Test Procedure for testing emissions and fuel economy Performed on chassis dynamometer

GRNN Generalized Regression Neural Network

HC Hydrocarbon

HEGO Heated Exhaust Gas Oxygen sensor

IVC Intake Valve Close

IVO Intake Valve Open

Lambda Air excess ratio

THC Total Hydrocarbon

UEGO Universal Exhaust Gas Oxygen sensor

WOT Wide Open Throttle

λ Air excess ratio