REAL TIME HC CONCENTRATION MEASUTREMENT IN EXHAUST GAS FROM A SPARK-IGNITION ENGINE BY USING 3.392 μm ABSORPTION METHOD

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Abstract

It is a problem that unburned hydrocarbons are exhausted at cold start in spark-ignition engines. In this study, an infrared absorption method was applied to in-situ measurement of hydrocarbon concentration. A He-Ne laser was used as an incident light and reflected three times in the exhaust pipe to make the measurement length long enough to determine the HC. As a result, misfire is detected without fail. It was found that the HC concentration has a relation to indicated mean effective pressure. In late ignition timing, the temperature of the exhaust gas increases and the HC concentration decreases while the cycle-to-cycle fluctuation of mean effective pressure increases. When the fluctuation is large, the HC is larger in the cycle of lower mean effective pressure and the HC is smaller higher one.

Keywords: Internal Combustion Engine, Spark-ignition Engine, Laser Diagnostics, Absorption, Concentration, Unburned Hydrocarbons

1. Introduction

Higher thermal efficiency and lower exhaust emissions are always important issues for internal combustion engines. In a spark-ignition engine, unburned hydrocarbons emitted at cold start are one of the problems. Some studies have shown that unburned hydrocarbon emissions are due to the gases trapped in the crevice of the engine. Namazian and Heywood (1982) used a square piston engine with an optical access and took photos of outgassing of hydrocarbons both from the crevices of ring and spark plug when the pressure in the cylinder decreases. Therefore, it is very important to detect the fuel concentration history in the exhaust pipe to understand the behavior of the exhaust process well. Gas sampling is considered to be the most reliable method. Collings (1988) developed a fast-response flame ionization detector to measure the cycle-to-cycle hydrocarbons concentration in the cylinder.

Infrared absorption methods have often been applied to detect hydrocarbons after the extraction of sample gas from the object of measurement. However, in-situ measurement is desirable for detecting the concentration of the fuel. Yoshiyama et al. (1996) showed the possibility of concentration measurement near the spark plug and in the exhaust pipe, using an in-situ infrared absorption method with Lambert-Beer's law. A laser light with a wavelength of 3.39μm was directly passed through windows near a spark plug without optical fibers in a test engine. Propane was used as the fuel and the effects of pressure and temperature on the molar absorption coefficient were obtained in advance. They also determined the unburned concentrations in the exhaust pipe. The in-situ local mixing ratio of methane was determined

with fibers in a non-premixed burner by the 3.39μm absorption method [2]. Recently, some efforts using an optical sensor in the spark plug and an infrared absorption method have been made by Koenig and Hall et al. (1996). They developed a measurement system using a lamp with infrared wavelengths and a band-pass-filter of relatively wide range. Various kinds of fuel concentration measurements were performed in a spark-ignition engine even under the firing condition. This system requires calibration for each optical arrangement. Tomita et al. (2002, 2003a, 2003b) developed a special optical sensor in the spark plug and showed some examples of fuel concentration history near the spark- plug. Nishiyama et al. (2003, 2004) developed another sensor and measured the concentration history in a stratified charge engine with a port injection type.

On the other hand, although unburned hydrocarbon concentration in the exhaust pipe is often determined with HC analyzer, which uses infrared absorption method after extracting the exhaust gas with a long sampling pipe, the result shows time-averaged one. Yoshiyama et al. (1996) applied in-situ absorption method with 3.39μm He-Ne laser to measure the unburned hydrocarbon concentration and confirmed the cycle of misfire. Mizaikoff et al. (1998) showed that infrared absorption method could be applied to measure the concentration history in the exhaust gas because the value of the concentration agreed with the value obtained with an FID system.

In this study, an optical system for an in-situ absorption method with a 3.39μm laser for concentration measurement in exhaust pipe of a spark-ignition engine was developed and unburned hydrocarbons were determined under some conditions including cold water temperature. The molar absorption coefficient of propane was determined under various pressure and temperature conditions in advance.

2. Principle of absorption method

When light with only one wavelength is used and the intensity of the light, I_0, decays to the value of I, through a gas along the measurement length, L, the transmissivity, I/I_0, is expressed from Lambert-Beer's law as follows:

$$Log(I/I_0) = - \varepsilon cL$$

where c and ε denote the molar concentration of the gas that absorbs the light and the molar absorption coefficient, respectively. The measurement length is constant in this study. When the molar absorption coefficient is known, the molar concentration is determined by measuring the transmissivity.

In general, hydrocarbons absorb the light near 3.4μm strongly. Figure 1 shows the absorption lines for methane obtained from HITRAN code (Rothman et al., 1998). The wavelength of a helium-neon laser with 3.392μm coincides with one of the absorption lines of hydrocarbons. This strong absorbance is in conjunction with a C-H bond in the molecule structure of the hydrocarbon.

The value of the absorption coefficient is a function of pressure and temperature. The function depends on the molecule structure, so that the value should be obtained before the experiment. In this study, the absorption coefficient of propane was investigated in changing pressure and temperature.
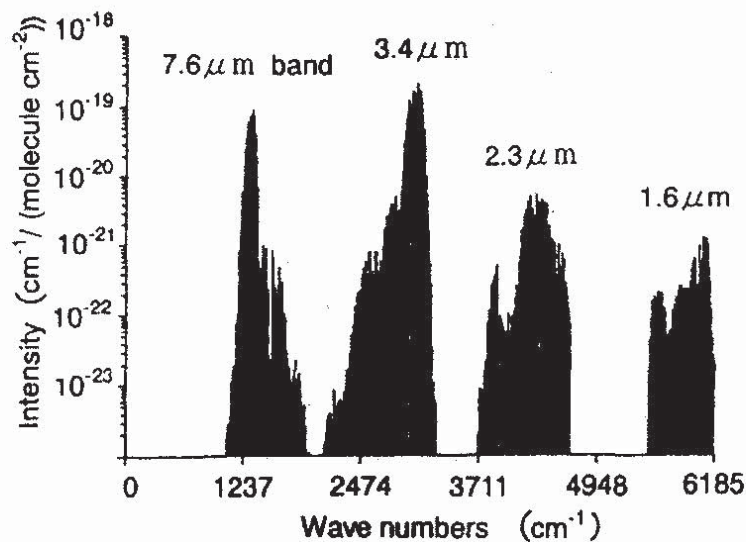
Figure 1. Absorption lines of methane obtained from HITRAN

3. Experimental procedure

A spark-ignition test engine with a single cylinder, four valves and a pentroof combustion chamber was used for this study. The bore and stroke are 76 mm and 82.6 mm, respectively. As shown in Fig.2, an optical arrangement was installed between the cylinder head and the exhaust pipe. A laser beam with a wavelength of 3.392μm passed into and out of the measurement part through a window after being reflected with two mirrors. The measurement length was changed and tested for one, three, and five reflections. As a result, three reflections were chosen in this study, so that the measurement length was 240.7 mm in total. An ordinary HC analyzer for exhaust gas inspection for commercial cars (Horiba MEXA 5541) was also used for the comparison of the averaged HC concentration. The HC value was translated to that of propane because the analyzer displays the value of hexane.
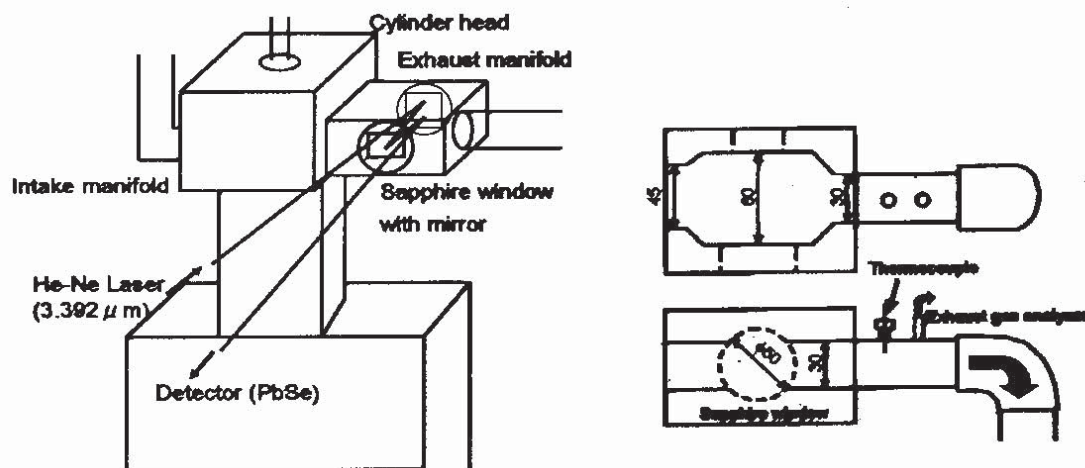

Figure 2. Optical arrangement for measurement of hydrocarbon concentration in the exhaust pipe

The analyzer is usually compensated using the conversion factor by calibrating with propane. All the hydrocarbons were assumed to be propane. The exhaust temperature was determined with a thermocouple of K-type.

The engine speed was 800 rpm and volumetric efficiency was set to 0.35. The

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temperature of cooling water and lubricant oil was changed from 80 to 35 degrees centigrade.

4. Results

Figure 3 shows examples of pressure and HC concentration histories in equivalence ratio, ϕ, of 0.65 at water temperature of 80 degrees centigrade. The ignition timing for MET was 37.5 degrees BTDC. Advanced and retarded ignition timings were chosen at 47.5 and 27.5 degrees BTDC. Figure 4 shows the effect of ignition timing on HC concentration and
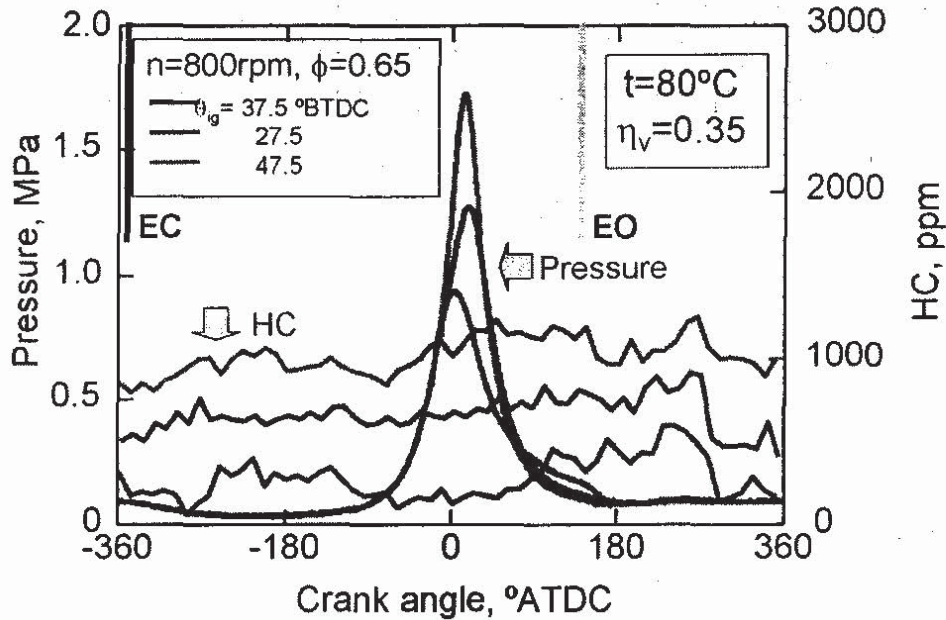

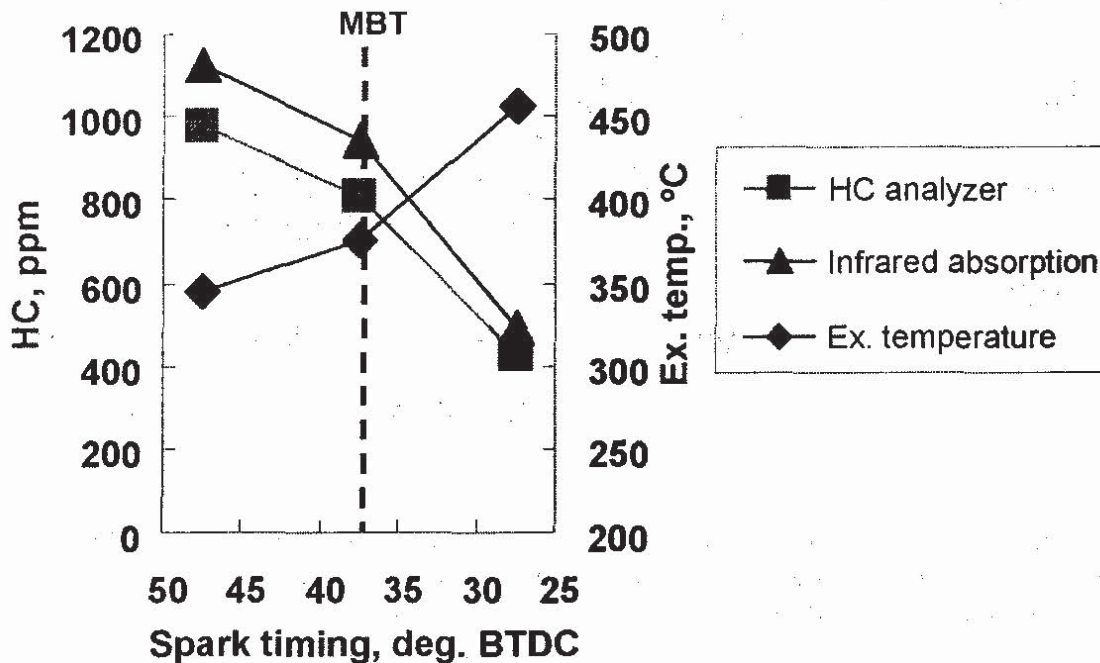*Figure 3. Examples of pressure and hydrocarbons concentration histories*

Figure 4. Effect of ignition timing on HC concentration and exhaust temperature
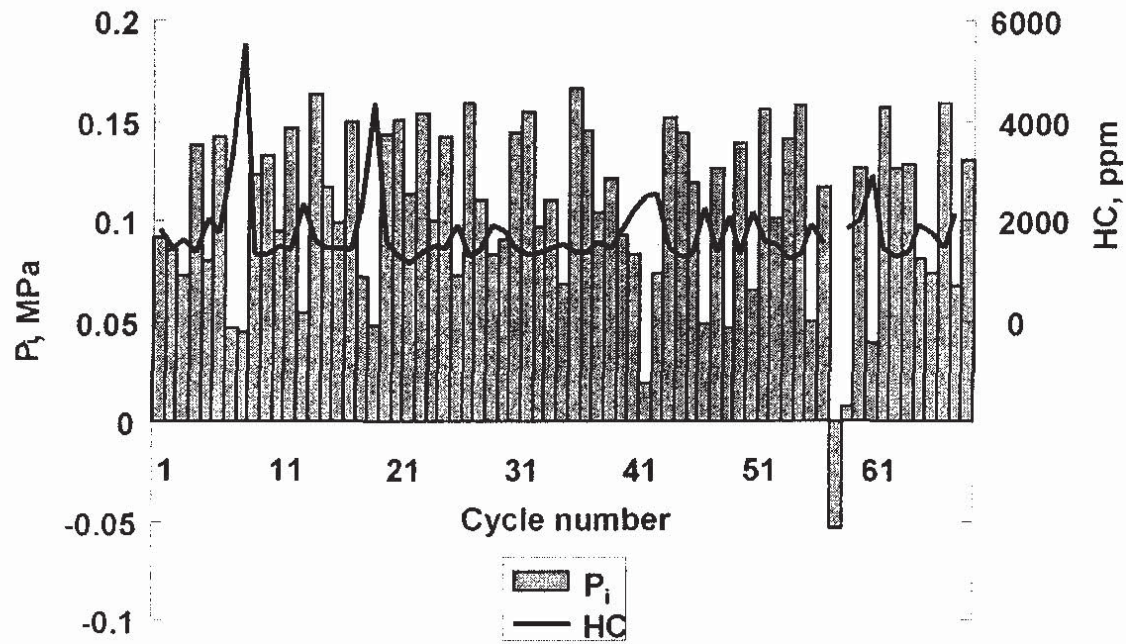
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Figure 5. Indicated mean effective pressure and hydrocarbon concentration for successive 69 cycles
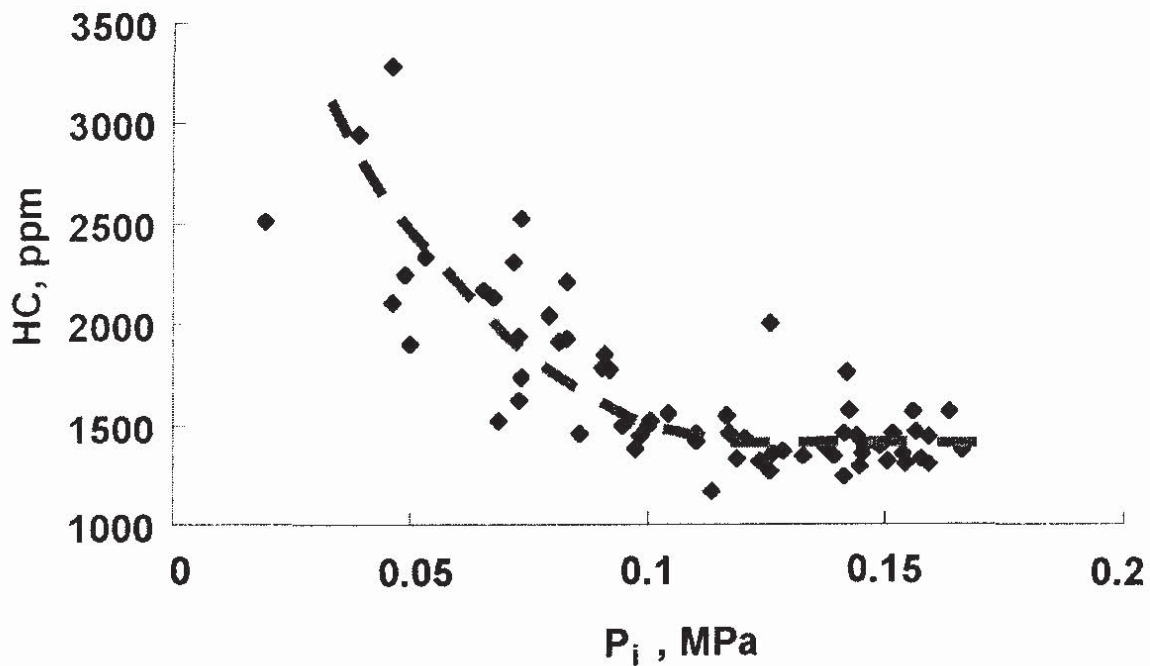

Figure 6. Relation between indicated mean effective pressure and hydrocarbon concentration

exhaust temperature. The trend shown in Figure 3 corresponds to the results obtained from the ordinary HC analyzer although the value itself is slightly different. Here, the value of the concentration of hydrocarbons is obtained from averaging over 69 cycles versus crank angle. The time-averaged value does not present the correct value because the flow rate is not considered. However, this optical method was confirmed to be valid to estimate the hydrocarbon concentrations. When the ignition timing is retarded, the combustion delays so that the concentration of hydrocarbons in the exhaust gas was higher. And when the ignition timing was advanced, the HC concentration was lower. The temperature of exhaust gas

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temperature increased with retarding the ignition timing.

The indicated mean effective pressure and hydrocarbons of each cycle for successive 69 cycles were shown in Figure 5 for ignition timing of MET in φ=0.65. When the misfire occurred at 58th cycle, the hydrocarbon concentration was too large to show the value. The laser beam was absorbed very much because of too much hydrocarbons flowed across the light. The relation between indicated mean effective pressure and hydrocarbon concentration was investigated for each cycle as shown in Figure 6. The hydrocarbon concentration shows almost the same value over 0.1 MPa of EvIEP. However, when the mean effective pressure decreased, the hydrocarbon concentration for its cycle increased as indicated in a dashed line.

Figure 7 shows the histories of pressure in the cylinder and hydrocarbon concentration for three successive cycles when the pressure in the cylinder changed. Here, the 17, 18 and 19th cycles were chosen from the same condition in Figure 5. The timings of open and close of exhaust vales presented in Figure 7, too. When the maximum of the pressure decreased, the concentration of the hydrocarbons increased. The mean effective pressures for 17, 18 and 19th cycles are 0.15, 0.08 and 0.05 MPa, respectively. The combustion becomes incomplete when the pressure in the cylinder and the indicated mean effective pressure decreased, so that the unburned hydrocarbons increased. After the exhaust vales opened, the hydrocarbon concentration increased a little in the 17th cycle. The concentration presented about 1600ppm at the opening of the exhaust valve and increased up to 2000ppm in the middle of exhaust stroke. And after that, the concentration decreased to 1200ppm at the end of the exhaust stroke. When the exhaust valve begins to open, the unburned hydrocarbons in the quench zone are exhausted toward the exhaust pipe. And the hydrocarbons from the lubricating oil in the top ring crevice are exhausted for a while (Mizaikoff et al, 1998). And after the middle of the exhaust stroke, the hydrocarbons does not remain very much in the exhaust gas and the velocity of the exhaust flow decreased, so that the hydrocarbons showed lower value compared to the beginning of the exhaust stroke.
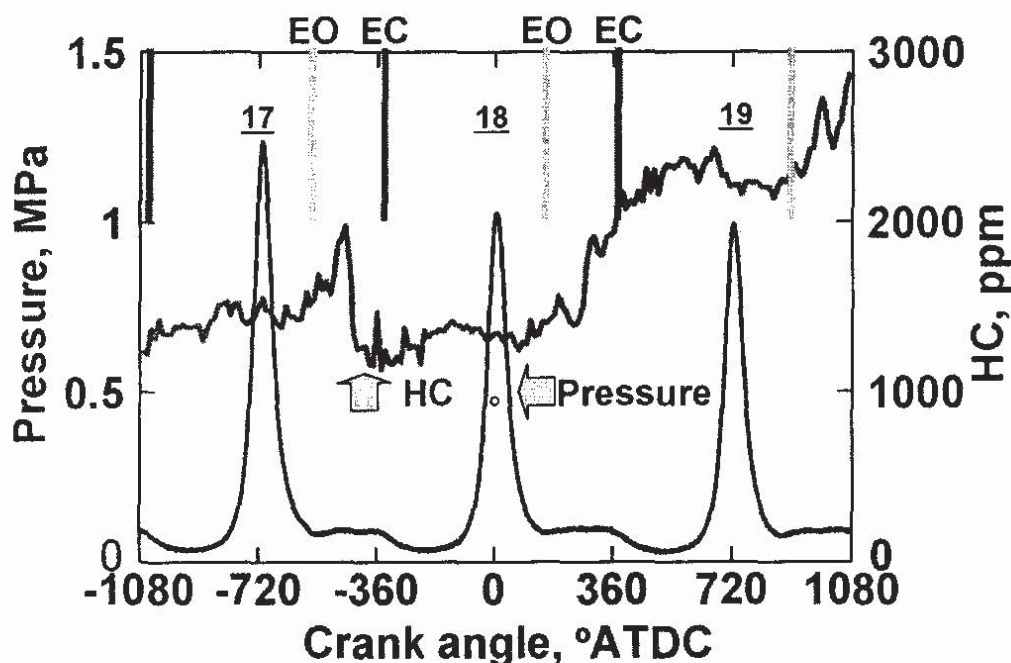

Figure 7. Pressure and hydrocarbons concentration histories for three successive cycles

On the other hand, in the 18 cycle, hydrocarbons concentration continued to increase from 1500 to 2100 ppm during the open of the exhaust valves. And after the close of the exhaust valves, the hydrocarbons concentration increased gradually because of the time lag that is induced from the difference of the measurement location and the exhaust valve.

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The situation in the 19th cycle is almost the same although the value of the hydrocarbons concentration is larger than that in the 18th cycle.

Figure 8 shows the indicated mean effective pressure and hydrocarbon concentrations when the temperatures of cooling water and lubricating oil were changed at 30, 50 and 80 degrees centigrade. The indicated mean effective pressure and the hydrocarbons concentration are presented with bar and line, respectively. The value of coefficient of variance in indicated mean effective pressure is also shown in Figure 8. In the temperature of 80 degrees, the fluctuation of IMEP was very small (CV=3 %) and the hydrocarbons concentration was also small (about 500ppm). When the temperature decreased, the fluctuation of IMEP became large. In the temperature of 50 and 30 degrees, the fluctuation of IMEP showed 26% and 41% and the concentration showed about 1000 and 2000ppm.
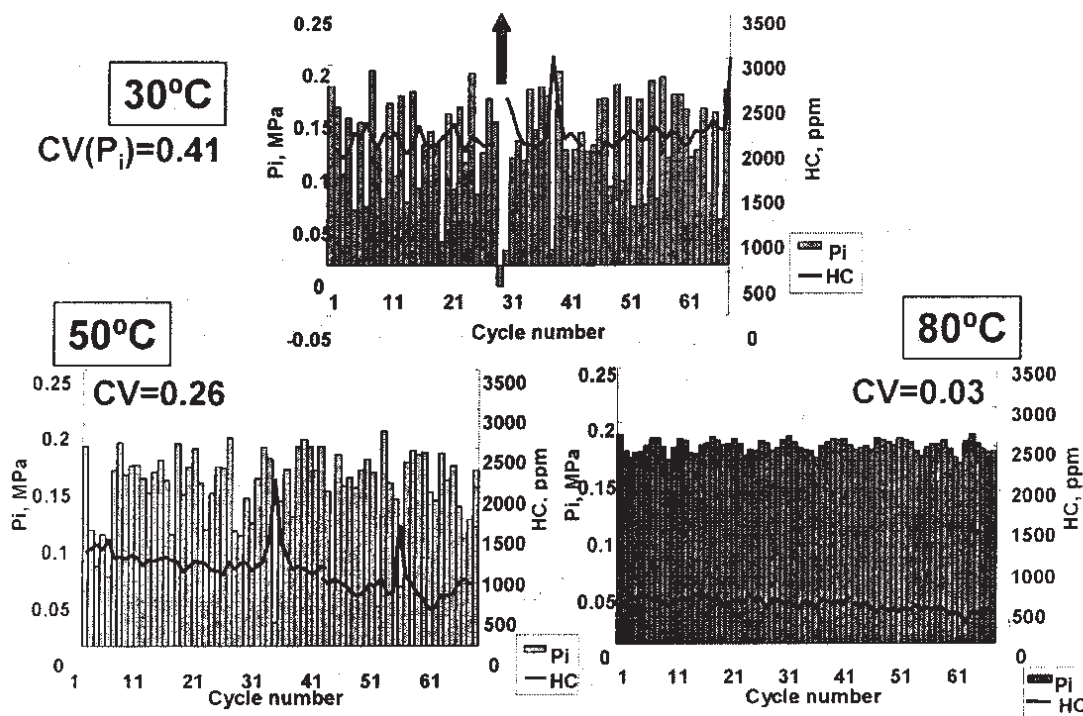

Figure 8. Indicated mean effective pressure and hydrocarbons concentration for various temperatures of cooling water

5. Summary

An optical system using 3.392μm absorption method was applied to measure the HC concentration of exhaust emissions. Main results obtained in this study are as follows:

1) The cycle when misfire occurs is detected clearly.
2) When ignition timing is retarded, HC concentration of exhaust gas decreases. However, the cycle-to-cycle fluctuations of indicated mean effective pressure increase.
3) The effect of cycle-to-cycle fluctuations on HC concentration of exhaust gas is very large. When the IMEP is larger, the HC concentration of the exhaust gas between this and the next cycles decreases. On the contrary, when the IMEP is smaller, the HC concentration increases.

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