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INFLUENCE OF INITIAL COMBUSTION IN SI ENGINE ON FOLLOWING COMBUSTION STAGE AND CYCLE-BY-CYCLE VARIATIONS IN COMBUSTION PROCESS

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ABSTRACT−It is necessary to understand the combustion process and cycle-by-cycle variation in combustion to improve the engine stability and consequently to improve the fuel economy and exhaust emissions. The pressure related parameters instead of mass fraction burned were compared for the effect of initial combustion pressures on the following combustion and the analysis of cycle-by-cycle variation in combustion for two port injected SI engines. The correlation between IMEP and pressures at referenced crank angles showed almost the same trends for equivalence ratios, but the different mixture preparations indicated different tendency. The dependency of IMEP on pressure at the referenced crank angles increases as the mixture becomes leaner for both engines. The mixture distribution in the combustion chamber was varied with the coolant temperature and intake valve deactivation due to the evaporation of fuel and air motion. The correlation between pressure related parameters were also compared for the coolant temperatures and air motion.

KEY WORDS : SI engine, IMEP, Cycle-by-cycle variations, Combustion pressure, Correlation, Cold start

1. INTRODUCTION

Even under steady state engine operation, the combustion process does not repeat identically for successive cycles. This cycle-by-cycle in the combustion process is variation generally known to be caused by variation in the mixture motion, mixing between the induced air, supplied fuel, residual gas, and their distribution in combustion chamber (Young, 1981; Ozdor *et al*., 1994). In addition, the variations in the spark energy, location of spark occurrence, and heat transfer in the electrode of spark plug are also known to be another source of cycle-by-cycle variations in combustion (Bates, 1989). Especially, in the cold starting, idling, and lean mixture operation where the burning velocity is slow and flame development is difficult, the combustion is relatively unstable and shows excessive cyclic variation.

The cycle-by-cycle variations in combustion process can be analyzed with the flame propagation related parameters and combustion pressure related parameters.

With the application of high speed cinematography and laser diagnostics for flame propagation visualization and combustion process, it is possible to lead to deeper understanding of the variation in combustion process (Kerstein and Witze, 1990; Keck and Heywood, 1987). However, the measurement of combustion pressure can be used as a useful tool to comprehend the combustion variation in combustion chamber with the analysis on pressure related parameters. This measurement can also be applied to the detection of misfire, knocking, and optimization of spark timing to achieve efficient operating conditions (Spicher and Backer, 1990; Lee *et al*., 1998).

The combustion pressure can be measured to evaluate in-cylinder combustion state and confirm the cycle-by-cycle variations in combustion process (Lee and Foster, 1996). Especially, to improve the engine stability at the relatively unstable operation conditions it is important to understand how the initial combustion state affects the later combustion process and engine performance.

In this research it is intended to analyze the effects of initial combustion on later combustion stage for different air-fuel mixture and the coolant temperature with the pressure data instead of mass fraction burned. One intake valve was also deactivated to confirm the effect of mixture motion on cycle-by-cycle variation in combustion. Two different spark ignition engines with the port injected fuel system were compared for the consistence in engines.

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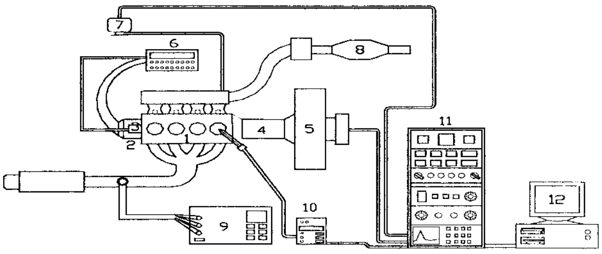


Figure 1. Schematic diagram of experimental apparatus. 1. Test engine, 2. ECU, 3. Encoder, 4. Pressure-transducer, 5. Dynamometer, 6. Fuelling & spark-timing controller, 7. Throttle actuator, 8. Laminar flow meter, 9. Exhaust gas analyzer, 10. Charge amplifier, 11. Dynamometer controller & data acquisition system, 12. Computer.

2. EXPERIMENTAL SET-UP AND PROCEDURES

Through the experimental apparatus schematically described in Figure 1, the fuelling and ignition controller controls the spark timing and injection periods and timings to operate the engine at different air-fuel ratios and spark timings according to the operating conditions.

A piezo-electric pressure transducer, Kistler 6053C, was mounted in the cylinder head to measure the combustion pressure and analyze the combustion process. The pressure data were sampled at a rate of 1° CA (Crank Angle) interval for 200 cycles in the data acquisition system and processed to obtain the pressures at referenced crank angles and IMEP (Indicated Mean Effective Pressure). The exhaust gas analyzer and laminar flow meter were also applied to measure the air-fuel ratio. Two different four stroke SI (Spark Ignition) engines whose specifications are summarized in Table 1 were used for the experiments. Both engines have four valves and port injected fuel supply system. The engine coolant temperatures in engine A were also changed to investigate the effect of fuel vaporization and mixing at low temperature conditions. In engine B one intake valve was deactivated to induce higher swirl in the combustion chamber and change the mixture distribution in the combustion chamber.

Table 1. Engines specifications.

	Engine A	Engine B
Bore (mm)	75.5	82.0
Stroke (mm)	83.5	85.0
Connecting rod length (mm)	131.0	141.0
Cylinder displacement (cc)	1495	1796
Compression ratio	9.5:1	10:1
Valve timing (°CA)	5/35 43/5	9/43 50/6

These engines were operated at some specific part load conditions, that is 2000 rpm/2.0 bar BMEP (Brake Mean Effective Pressure) for engine A and 1600 rpm/2.0 bar BMEP for engine B. For the coolant temperature effect on combustion variation, two different engine operating conditions were applied. One operating condition was the idling condition during warming-up period, in which the engine speed and mixture ratio were varied as the operating time elapsed. Another operating condition with the fixed engine speed, intake pressure, and fuelling was applied. The data were analyzed to understand the effect of fuel evaporation on cycle-by-cycle variations in combustion process.

The analysis of regression will be given by the explanation described in Dunn and Clark (1974). When two variables (X, Y) have been measured on the same set of individuals, a simple and effective way of describing them is the scatter diagram. From the scatter diagram it can be seen how the two variables X and Y are related. The usual statistic to measure the degree of association between the two variables is called correlation coefficient. Let X and Y denote two variables and

Xi : X on the i-th individual for i=1, ..., n
Yi : Y on the i-th individual for i=1, ..., n

The covariance of X and Y for this set of data is defined as follows:

$$\mathrm{Covar}(X,\ Y)=\frac{\sum_{i=1}^{n}(Xi-\bar{X})(Yi-\bar{Y})}{n-1}$$

where $\bar{X}$: mean value of X
$\bar{Y}$: mean value of Y

The standard deviation for X, $V(X)$ is given as follows:

$$V(X)=\left[\frac{\Sigma(Xi-\bar{X})}{n-1}\right]^{1/2}$$

Therefore, the correlation coefficient between X and Y usually denoted by R, where

$$R=\frac{\mathrm{Covar}(X,\ Y)}{\{V(X)V(Y)\}}=\frac{\Sigma(Xi-\bar{X})(Yi-\bar{Y})}{\left[\Sigma(Xi-\bar{X})^{2}\ \Sigma(Yi-\bar{Y})^{2}\right]^{1/2}}$$

3. RESULTS AND DISCUSSION

3.1. Variations in Pressures at Referenced Crank Angles

The pressure variations at referenced crank angles were compared to confirm the validity of initial combustion pressures as parameters for the cycle-by-cycle variation in combustion. The variation in pressure is represented as the standard deviation divided with mean pressure at referenced crank angle for the entire cycles.

In the motoring condition, the variations in pressure at referenced crank angles were usually within 0.2~0.3%. However, the firing condition indicated much higher variations in pressure than the motoring condition as presented in Figure 2. The variations in pressure at referenced crank angles for different equivalence ratios are compared in Figure 2, where $C.A_{Ppeak}$ means the crank angle at which the peak pressure occurs. The variation in pressure at 15° BTDC (Before Top Dead Center) for equivalence ratio Φ=1.0 is approximately 1.3%, which is slightly higher than the variations in pressures of motoring condition. It is believed that these small variations are caused by the insufficient elapsed time of combustion after ignition. However, it is clear that the variations increase rapidly as combustion proceeds. In addition, the leaner mixture shows more fluctuation in the combustion pressure than the stoichiometric condition, which means the combustion with leaner mixture is more unstable.

3.2. Correlation Between Pressures at Referenced Crank Angles

It was investigated to assess the validity of initial combustion pressures as a cycle-by-cycle combustion parameter and the dependence of later stages of combustion on the early portion of combustion. The effect of pressures at 15° BTDC on later pressures for different equivalence ratios was compared in Figure 3. From this result, it is seen that the pressures at 10° BTDC show a high dependence on the pressures at 15° BTDC, however, the later pressures at TDC (Top Dead Center), 10°ATDC (After Top Dead Center), and 20° ATDC don't show any correlation with the initial pressure. That is, the combustion after TDC is not affected by the very early combustion state.

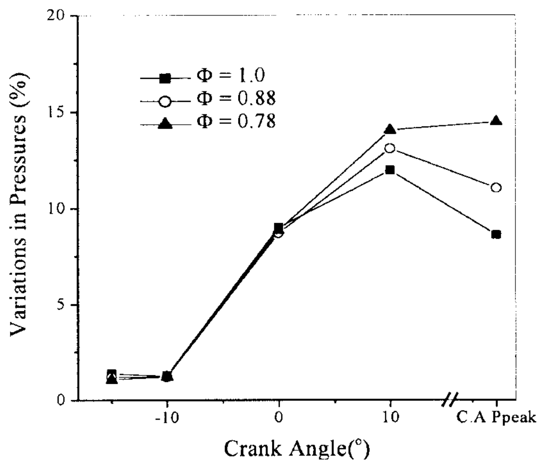


Figure 2. Variations of pressures at referenced crank angle for various mixtures.

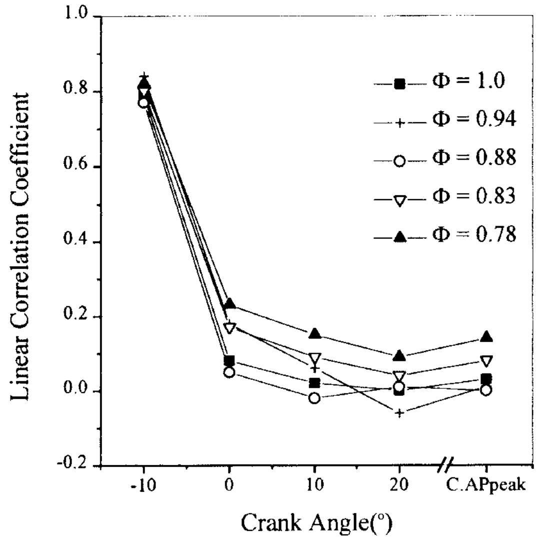


Figure 3. Correlation between the pressure at 15° BTDC and later pressures.

However, the correlation between the pressure at 10° BTDC and later pressures indicate relatively increased tendency as shown in Figure 4. Especially, it is seen that the correlation coefficient improves as the mixture becomes leaner. These correlation coefficients also decrease linearly and become worse, especially after TDC, as the combustion proceeds for all operating conditions. From these results, it is thought that the combustion is accelerated as the combustion proceeds and the effect on the following combustion becomes weaker as the combustion becomes faster. It is also presumed that, for the port injection

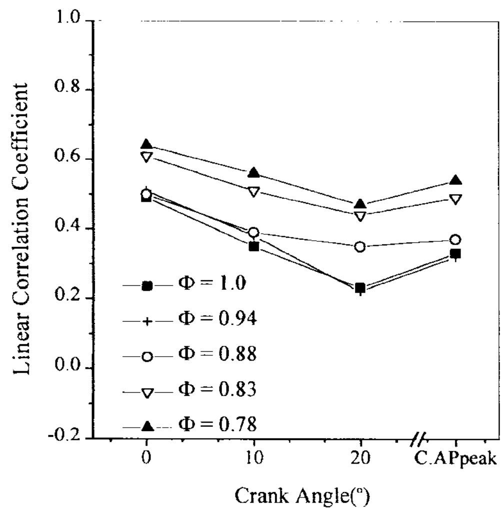


Figure 4. Correlation between the pressure at 10° BTDC and later pressures.

system, the mixture distribution in the combustion chamber is not complete homogeneous and the subsequent combustion is less affected by the early reaction with the less uniform distribution in mixture. As seen in the previous research (Lee and Foster, 1996), the homogeneous mixture showed higher correlation between the initial and later pressures. Through these results, it is surmised that the effect of mixture inhomogeneity can be reflected on the combustion pressure data.

3.3. Correlation Between IMEP and Pressures at Referenced Crank Angles

To confirm the effect of combustion procedure on IMEP, the correlation between IMEP and pressures at referenced crank angles are analyzed as presented in Figure 5, in which R means the linear correlation coefficient. It is also applied for different engines and equivalence ratios. The linear correlation coefficients between IMEP and pressures at referenced crank angles for different mixture ratios are compared in Figure 6. The correlation coefficients are increased as the combustion proceeds regardless of mixture ratios. This implies that the IMEP is more closely correlated with the later pressures than the initial pressures. The IMEP also increases as the pressure at referenced crank angle increases. As the mixture gets leaner, the correlation coefficient increases, which means that the IMEP is more dependent on the later stage of combustion.

3.4. Effect of Coolant Temperature

It has been already found that the variations in pressure at specified crank angles increase as the combustion proceeds. Especially, during warming-up period the level of variation in pressures at specified crank angles is changed with the coolant temperature. As the coolant temperature is lower, the variation in combustion is higher as shown in Figure 7. At low temperature, since the fuel is difficult to evaporate, more liquid fuel is induced into the combustion chamber and the inhomogeneity in mixture increases. The cycle-by-cycle variation in mixture distribution also seems to be increased. This inhomogeneity and variation in mixture ratio cause the variation in pressures at the specified crank angles, consequently variation in combustion.

The combustion is also thought to be very slow from the results, which the level of variation in pressure at

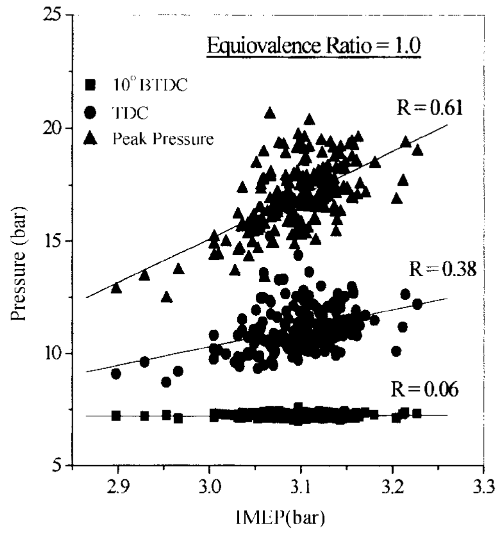


Figure 5. Typical example of correlation between IMEP and pressures at referenced crank angles.

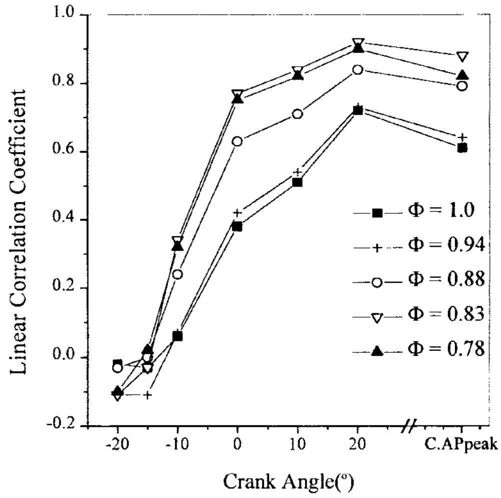


Figure 6. Correlation between IMEP and pressures at referenced crank angles.

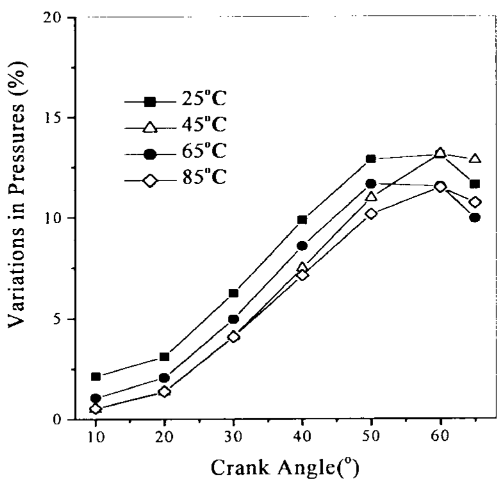


Figure 7. Variations of pressures at referenced crank angles for the idling with coolant temperatures.

specified crank angle after TDC is low and the variations in pressure increase up to 50° ATDC. Especially, the variation in pressure at 85°C is very low and not increased so much, which is thought to be very slow in combustion. The rich mixture in the beginning was changed to the stoichiometry and the engine speed decreased as the engine was warmed up from 1300 rpm to 950 rpm. This change seems to be overlapped with the effect of coolant temperature.

The effect of the initial combustion on later stage of combustion during warming-up period is examined in Figure 8. With the increased coolant temperature, the trend of correlation shows almost same as normal operating conditions, but with the low temperature (25°C) the effect of initial combustion is relatively poor. This means that the mixture distribution at cold start is more inhomogeneous and the initial combustion is not sufficient due to the difficulty in fuel evaporation.

At idling condition, another peculiar phenomena are that the crank angle at which the maximum pressure occurs is very close to the TDC. Due to the retarded spark timing the crank angle at which peak pressure occurred should be retarded, but this angle appeared very close to TDC, which means that the slow combustion is dominant in the peak pressure occurrence at idling.

The COV (Coefficient of Variation) in IMEP are ranged from 13 to 15%, which is typical COV at idling and higher than the normal operating condition. The effect of coolant temperature on the IMEP dependency on the pressures at specified crank angles is shown in Figure 9. This trend is nearly same as the fully warmedup condition, however, the case of 25°C indicates relatively less correlation than the higher coolant temperature cases.

Another approach was performed to understand the effect of fuel vaporization on cycle-by-cycle variations in combustion with the fixed engine speed, intake pressure, and fuelling at the part load condition. In this case, with the lower coolant temperature the correlations between initial pressure and later pressures are very poor and only the case of 85°C shows relatively higher correlation as the normal operating condition as shown in Figure 10.

The correlations between IMEP and pressures at referenced crank angles with coolant temperatures don't present good correlation except the case of 85°C as the combustion proceeds as indicated in Figure 11.

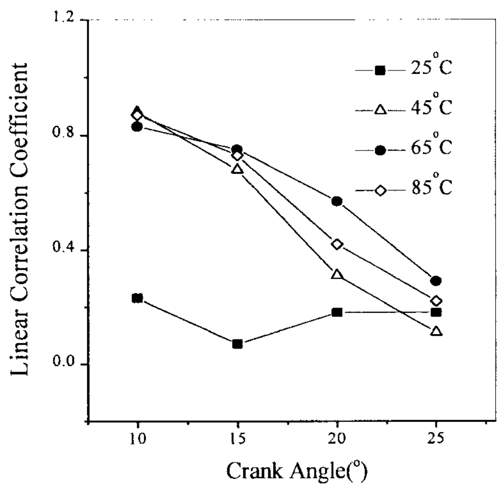


Figure 8. Correlation between the pressure at 5° ATDC and later pressures at idling with coolant temperatures.

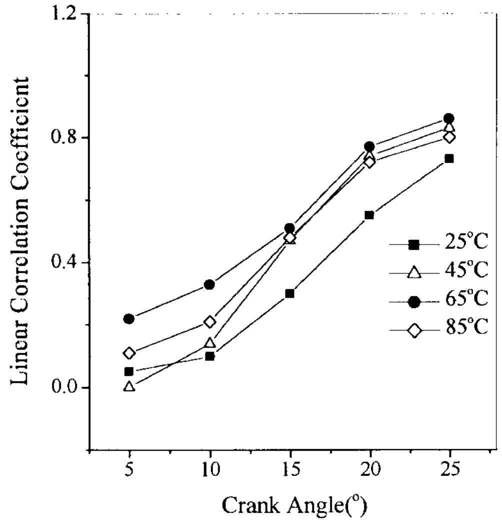


Figure 9. Dependency of IMEP on pressures at referenced crank angles with coolant temperatures at idling.

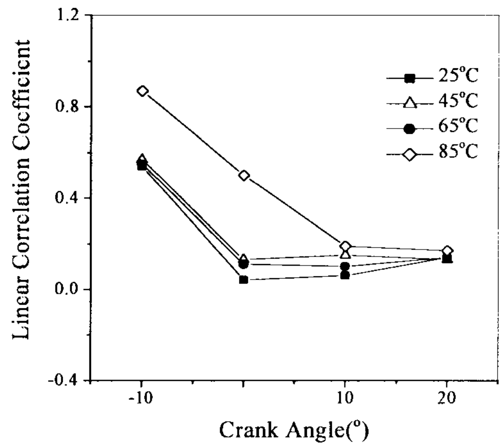


Figure 10. Correlation between the pressures at 15° BTDC and later pressures for coolant temperature at a part load condition.

3.5. Effect of Air Motion

To investigate the effect of intake air motion on the cycle-

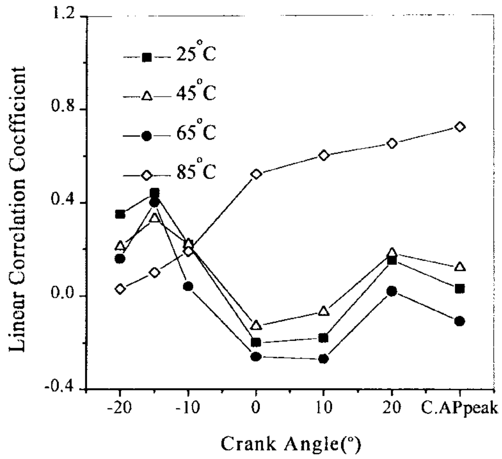
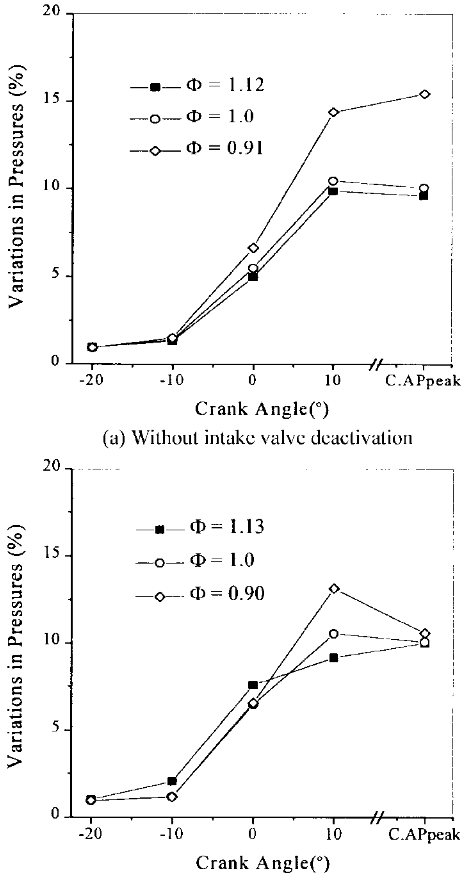


Figure 11. Dependency of IMEP on pressures at referenced crank angles for coolant temperatures at a part load.



(a) Without intake valve deactivation

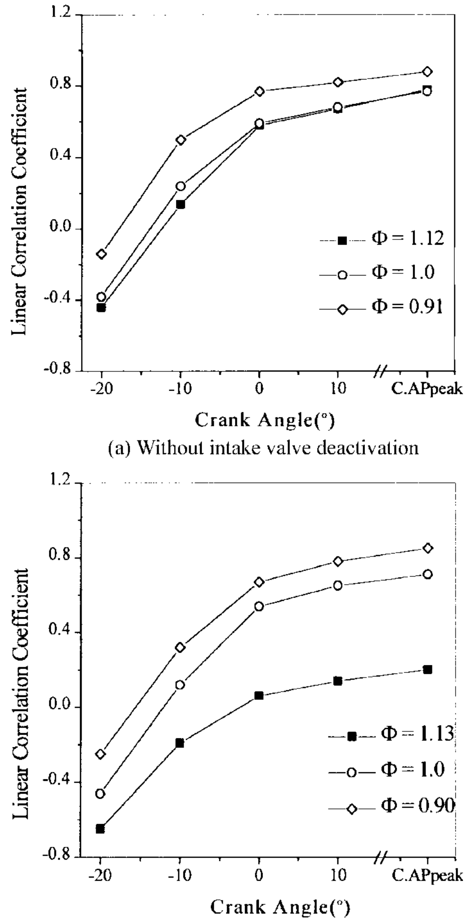
(b) With one intake valve deactivation

Figure 12. Variations of pressures at referenced crank angles for engine B.

by-cycle variation in combustion, engine B was operated with one intake valve deactivated. With one valve deactivation the swirl motion in combustion chamber is elevated and affects the mixing of air and fuel and their distribution.

From Figure 12. it is clear that the pressure variations at referenced crank angles increase as the mixture goes leaner. Without intake valve deactivation regarded as very low swirl level, the variation in combustion for equivalence ratio 0.91 seems to be relatively higher than the rich mixtures as shown in Figure 12(a). With the increased swirl ratio by one intake valve deactivation it shows almost same trend as the case of very low swirl as shown in Figure 12(b). However, the level of pressure variation before TDC with one intake valve open is higher than the low swirl case although the variations in pressure after TDC are lower. This is thought to be due to the faster combustion with the increased swirl.

The COV in IMEP was also examined for both cases. The case of one intake valve deactivation reveals lower cycle-by-cycle variation in combustion than that of the



(a) Without intake valve deactivation

(b) With one intake valve deactivation

Figure 13. Correlation between IMEP and pressures at referenced crank angles for engine B.

two intake valves open, which means that the cycle-by-cycle variation in combustion is more stable with higher swirl motion. Especially, the effect of swirl on combustion variation is thought to be more dominant for leaner mixture. That is, the COV in IMEP for Φ=0.91 with one intake valve deactivation appears as 3.4% contrary to 6.0% for the case of both intake valves open. The effect of pressures at referenced crank angles on IMEP was compared for intake valve deactivation. The case of both intake valves open shows almost the same trend, remarkably seen in Figure 13(b), as the engine B. However, the case of one intake valve deactivation with rich mixture (Φ=1.12) indicates different IMEP decreases especially in the early combustion as the initial pressure increases. This is thought to be that the initial combustion is faster due to the increased turbulence and mixture distribution in the combustion chamber and more mixture was burned in initial combustion stage, less mixture was burned during expansion stroke.

4. CONCLUSIONS

Through the pressure measurement for the different engine coolant temperature and air motion by the one intake valve deactivation, their relationship to cycle-by-cycle variation in combustion has been analyzed as follows:

(1) The variation in pressures at specific referenced crank angles increases as the combustion proceeds. In addition, this variation in pressures increases as the mixture goes leaner and the coolant temperature is lower.

(2) The pressures at specified reference crank angles generally showed good correlation to each other. The correlation becomes larger as the mixture goes leaner. In the port injection, the subsequent combustion is less affected by the early combustion due to the less uniform mixture distribution in the combustion chamber.

(3) The correlation between IMEP and pressures at the referenced crank angles increases as the combustion proceeds and the mixture goes leaner. This correlation is relatively poor at low coolant temperature and increases as the engine warms up.

(4) With one intake valve deactivation the combustion can be more stabilized due to the increased swirl ratio. In this case, the IMEP dependency on the pressures at referenced crank angles shows different trend, especially in early combustion with richer mixture.

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