INTERNATIONAL SYMPOSIUM ON AUTOMOTIVE SCIENCE AND TECHNOLOGY
5-6 September 2019 Ankara, TURKEY
www.isastech.org

An Experimental Study on the Variation of COV_{IMEP} and Ringing Intensity at Different Air Excess Coefficients in a HCCI Engine

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Abstract

Homogenous charge compression ignition (HCCI) engine have low emission characteristics and specific fuel consumption compared to conventional spark plug ignition and compression ignition engines. But, HCCI engines cannot be operated at wide load and speed range due to misfiring problems at low loads and knocking at high loads. Especially at high loads, the pressure rise rate reaches very high levels. Moreover, controlling the starting of combustion and duration of combustion are one of the biggest difficulties in HCCI engines. In this study, the variation of COVIMEP, ringing intensity and pressure rise rate at different air excess coefficients were investigated as experimentally using a 2.0 liter, four-strokes, four cylinders and early direct injection HCCI engine with n-heptane fuel. It was seen that the COVIMEP is high in low and high air excess coefficient values and it is low at medium air excess coefficient values. It has been observed that the ringing intensity increased at richer mixtures. It was also observed that the pressure rise rate and the tendency of knocking increased in low air excess coefficient values.

Keywords: HCCI Engines; COVIMEP; Ringing Intensity; Knocking; Misfiring

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1. Introduction

Increasing depletion of petroleum-based fuels and consequently increasing cost have led researchers to develop new engines with low fuel consumption, high thermal efficiency and high performance. In addition, researchers are working intensively to reduce the pollutant effect of exhaust gases from internal combustion engines on the environment and to meet emission regulations imposed by governments [1-3]. The homogeneous charge compression ignition (HCCI) engines are more advantageous compared to conventional spark ignition (SI) and compression ignition (CI) engines due to their high thermal efficiency, low NOx emissions and low heat transfer losses. In SI engines, when the air/fuel mixture is ignited by spark plug, high temperatures are generated in the regions where the flame front spreads, which causes high NOx emissions to occur. In order to meet emission limitations in SI engines, three-way catalytic converter or EGR applications are being tried to reduce NOx emissions. In CI engines, fuel is injected into compressed high-pressure air to start combustion. For this reason, soot emissions are obtained to result of the ignition of the fuel in the rich mixing zone. Moreover, high-temperature combustion zones cause to NOx emissions in CI engines. In HCCI engines, the air fuel mixture is formed outside of the cylinder or fuel injected into the cylinder too early crank angle. The homogeneous mixture in the cylinder is then compressed and simultaneous self-ignition occurs throughout the entire cylinder. As a result of, HCCI combustion mode is able to reduce both NOx and soot emissions simultaneously and effectively. HCCI engine can operate in lean mixtures without flame propagation. Therefore, low temperature combustion can be achieved [3-4]. In addition to the current benefits of HCCI engines, problems such as ignition timing and control of combustion rate must be solved before commercial use is practically applied. It is rather difficult to come up with these two problems. First, there is no mechanism in the HCCI engine that controls ignition as a spark plug or controls the diffusion combustion phase by injecting fuel after combustion, such as direct injection. Secondly, chemical reactions due to fuel properties are more dominant in HCCI combustion. This means that low loads can cause misfiring and high loads can lead to knocking. Hence, the HCCI engine has a limited operating range. A number of studies have recently been conducted on potential control methods (such as intake air heating [5-6], variable compression ratio [7-8], variable valve timing [9-10], EGR system [11-12], and supercharging applications [13-14]). In these experiments, considerable distance has been involved in the control of the HCCI combustion process. However, since there is no direct control method to determine the self-ignition process, satisfactory results have not been obtained in the extending of the operating range of the HCCI engines especially at high loads. In order to extend the operating range of HCCI engines, knocking and misfiring zones must be specified so that combustion control methods can be applied. COVIMEP and COVPMAX are widely used to determine the misfire zone in HCCI engines. In addition, the maximum pressure rise rate and ringing intensity are commonly used in the determination of the knocking zones. Maurya and Saxena [15] presented characterization of ringing intensity with chemical kinetics and artificial neural network for hydrogen HCCI engine. They investigated the effects of equivalence ratio, inlet air temperature and engine speed on ringing intensity. They showed that ringing intensity increased with the advance of combustion. They also noticed that CA50 should be retarded in order to control ringing intensity. They pointed out that ringing intensity is highly dependent on CA50. Bahri et al. [16] found similar results that ringing intensity is highly affected by CA50. Ringing intensity increased with the advance of CA50. They observed that artificial neural network could predict ringing intensity with very low error. Li et al. [17] developed a phenomenological knock intensity improve predictability of engine cycle. They have found that energy density and heat release are the main factors affecting knock intensity. Heat release rate is dependent on EGR rate, air-fuel ratio and end gas temperature in the combustion chamber whereas energy density is dependent on fresh charge mixture. In another study [18] Bahri et al. investigated the combustion noise and ringing operation in a HCCI engine. Injected fuel fraction was changed in order to observe ringing region. It was found that there was a good relationship between combustion noise level and in-cylinder pressure. Saxena and Bedoya [19] discussed the emission characteristics in order to meet emission regulations. So, HCCI operating range at high load limits and controlling combustion phasing were discussed in a detail. They showed that HCCI has good potential to achieve performance compared diesel in view of clean emissions. Kaleli et al. [20] have motivated to reduce cyclic variations in spark ignition engine altering spark timing.

They predicted the maximum in-cylinder pressure for the next cycle. They showed that it was achieved well and spark timing could be changed to control maximum in-cylinder pressure and cyclic variations. Li et al. [21] studied the knocking tendency and cyclic variations in HCCI engine fueled with n-butanol, n-heptane and their blends. They showed that n-butanol highly affected knocking tendency. In addition, knocking combustion was determined with heat release rate. COVPMAX increased with trhe increase of n-butanol fraction and excess air –fuel ratio. Maurya and Agarwal [22] investigated the effects of intake air temperature, air-fuel ratio and engine speed on cyclic variations in HCCI engine. They showed that COVimep increased at low intake air temperatures. Moreover, cyclic variations increased with leaner charge mixtures.

In this study, the variation of COVimep and ringing intensity were investigated experimentally with different air excess coefficients in a HCCI engine fueled with n-heptane. The experiments were conducted at different inlet air temperature including 40-60-80-100 °C and 800 rpm engine speed.

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2. Experimental Setup And Procedures

The experiments were conducted at the Advanced Power System Research Center, Michigan Technological University. For test engine a 2.0 liter, 4 cylinder, four stroke, direct injection, GM Ecotec gasoline engine was converted to operate in HCCI mode. The test engine specifications are shown in Table-1. The engine load and speed were controlled using 460 hp GE adjustable speed AC dynamometer.

Table 1. Engine specifications

Engine Specification	Value/Description
Engine Model	GM Ecotec LHU Gen I
Bore x Stroke	86 x 86 (mm)
Cylinder Number	4
Displacement Volume	2.0 (L)
Compression Ratio	9.2:1 (mm)
Connecting Rod Length	145.5 (mm)
Max Power	270 kW@6000 rpm
Fuel Injection System	Gasoline Direct Injection
Valve System	DOHC 4 Valves

In-cylinder pressures were measured using piezo pressure transducers and the pressure data as voltage processed using ACAP combustion analysis system. The crank angle was measured using an encoder with a resolution of one degree. A schematic of the experimental engine setup is shown in Fig.1. HCCI engine was controlled using dSPACE MicroAutoBox and RapidPro units with a MATLAB Simulink model was developed for the engine management system.

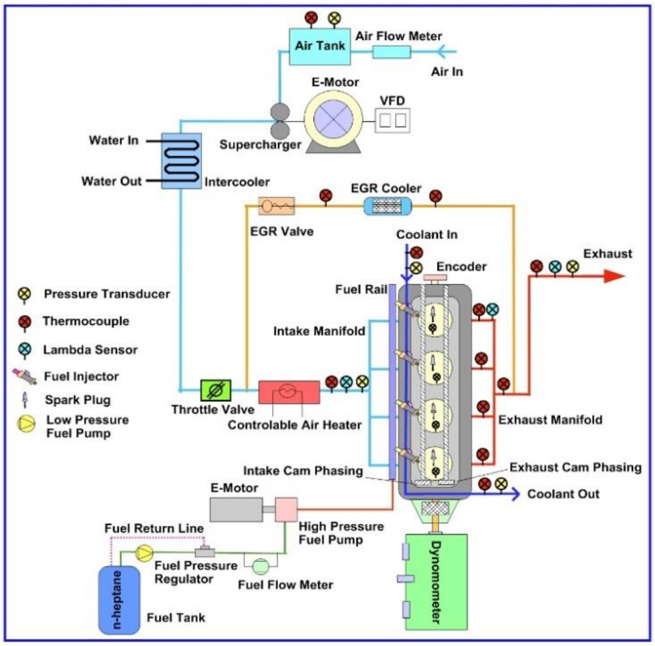

Fig. 1. Schematic of experimental setup [1]

In this study, the ringing intensity was calculated using below equation [23-25];

$$RI = \frac{1}{2\gamma} \frac{\left(0.05\left(\frac{dP}{dt}\right)_{\max}\right)^2}{P_{\max}} \sqrt{\gamma.R.T_{\max}} \qquad (1)$$

where RI is ringing intensity, P_{MAX} is maximum cylinder pressure, $\left(dP/dt\right)_{\max}$ is maximum pressure rise rate, γ is specific heat rate, R is ideal gas constant, $T_{\max}$ is maximum cylinder temperature. The COVIMEP was calculated using below equations[1,23];

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{\bar{X}} \times 100 \qquad (2)$$

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n_{cycle}} \qquad (3)$$

$$\sigma_{IMEP} = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}{n_{cycle}}} \qquad (4)$$

where σ_{IMEP} is standard deviation of IMEP values, $\bar{X}$ is mean of IMEP values, X is IMEP value for each cycle, n_{cycle} is number of cycles (100 cycles in this study). The COVPMAX was calculated using same method as COVIMEP. The experiments were performed at different air excess ratio, constant engine speed, four different intake air temperature as 40 ºC, 60 ºC, 80 ºC and 100 ºC, different loads using n-heptane fuel as the fuel. The test conditions can be seen in Table 2.

Table 2. Test conditions

Test Parameters	Value/Description
Engine Speed	800 (rpm)
Injection Pressure	100 (bar)
Injection Starting Angle	100 (bTDC Degree)
Fuel Type	n-heptane
Intk. Valve Open. Angle	25.5 (bTDC Degree)
Exhst. Valve Clos. Angle	22 (bTDC Degree)
Throttle Body Position	100 (%)
Intake Air Temperature	40-60-80-100 (℃)

3. Result and Discussion

HCCI combustion is dependent on the charge composition and initial combustion condition (inlet air temperature, air-fuel ratio, compression ratio, inlet air pressure etc.) at the end of compression stroke. Sudden and rapid heat release and uncontrolling of combustion are some difficulties on HCCI combustion mode. Knocking can be seen at high engine loads. Likely, charge mixture could not be ignited at low engine load called as misfiring. So, the observation of in-cylinder pressure history is evident in HCCI combustion.

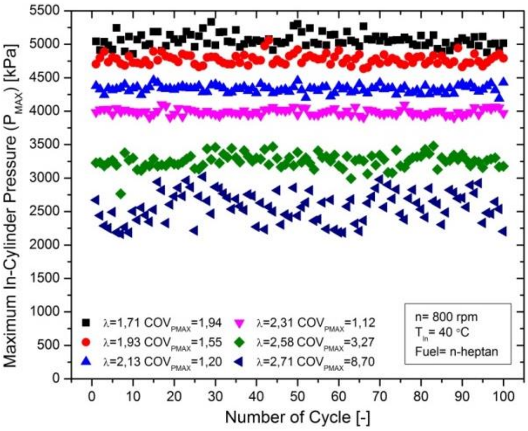

Fig. 2. In-cylinder pressure history and COVpmax variations

Figure 2 shows the in-cylinder pressure history and COVpmax with different lambda values at 40°C inlet air temperature. As expected, maximum in-cylinder pressure decreased due to lower fuel energy with lean charge mixtures. COVpmax decreased until lambda values of 2.31 and then started to increase. The highest COVpmax was determined as 12.65 % at 2.71 lambda whereas the lowest COVpmax was computed as 0.93% at 2.31 lambda. In-cylinder pressure variations are clearly seen with 2.71 lambda values as seen in Figure 1-f. Gas motion and the composition of charge mixture change cycle by cycle at leaner mixtures (λ=2.58, 2.71). Auto-ignition timing is affected and changes with higher lambda in the combustion chamber. The amount of remaining mixture for the next cycle increases at leaner and richer charge composition. Also, the amount of remaining mixture changes the thermodynamical properties and temperature of fresh charge mixture. Hence, cyclic variations increases. Çınar et al. [26] found that in-cylinder pressure and heat release rate increased when 5.5 mm intake valve and 3.5 mm exhaust valve lift were used compared to 3.5 mm intake and exhaust valve lift. In HCCI combustion operating range could be extended using low lift cams without knocking and misfiring [27]. In another study [28] Çınar et al. showed that in-cylinder pressure increased with the increase of intake air temperature on HCCI mode. In addition combustion was advanced and combustion duration decreased. They also pointed out that COVimep decreased with the increase of intake air temperature until 100 and 110°C. COVimep exceeds 10% at lambda value of 0.7 and 110°C on HCCI combustion mode. Polat [4] investigated the effects of diethyl ether–ethanol fuel blends on HCCI combustion and and exhaust emissions. He found that lower in-cylinder pressure and heat release were obtained with the increase of lambda. He also observed that combustion duration increased with the increase of inlet air temperature.

Imep is defined as significant parameter that shows the engine performance. It is averaged in-cylinder pressure which exerted to the piston in a cycle. So, imep is affected by excess air coefficient and inlet air temperature, because HCCI combustion is highly dependent on these parameters at the start of compression stroke. Figure 3 depicts the variations of imep at different excess air coefficients and inlet air temperatures in HCCI combustion mode. It is evident that lean charge mixture caused to obtain lower imep. Lower fuel molecule concentration leads to release lower heating energy. Thus, lower gas force is applied to the piston at the end of combustion. As seen in Figure 3, imep decreased with the increase of excess air coefficient at a given inlet air temperature. It was also seen that maximum imep values decreased with the increase of inlet air temperature at constant excess air coefficient value. Warmer inlet air temperature decreases oxygen molecules by mass that is taken to the cylinder due to lower density of air at higher temperatures. This phenomena deteriorates the auto-ignition chemical reactions between oxygen and fuel molecules. One of the most important point is that HCCI combustion can be performed at leaner charge mixture when the engine was run with higher inlet air temperature. Higher inlet temperature allowed occurring chemical oxidation reactions in HCCI mode. It improves the auto-ignition combustion conditions in the combustion chamber. HCCI engine could be ever operated with 3.31 excess air coefficient value at 100°C inlet air temperature. COVimep first decreased and then started to increase with the increase of excess air coefficient. Higher COVimep was obtained at richest and leanest charge mixtures. Polat [29] showed that imep decreased with the increase of lambda with diethyl ether–ethanol fuel blends whereas increased with the increase of inlet air temperature at a given lambda at 1200 rpm engine speed in HCCI combustion mode. Uyumaz [30] researched the effects of pure n-heptane, the blends of n-heptane and n-butanol fuels in a HCCI engine with different inlet air temperatures. Imep decreased with the increase of inlet air temperature. He also showed that imep decreased due to knocking with pure n-heptane in spite of higher calorific value compared to isopropanol and n-butanol.

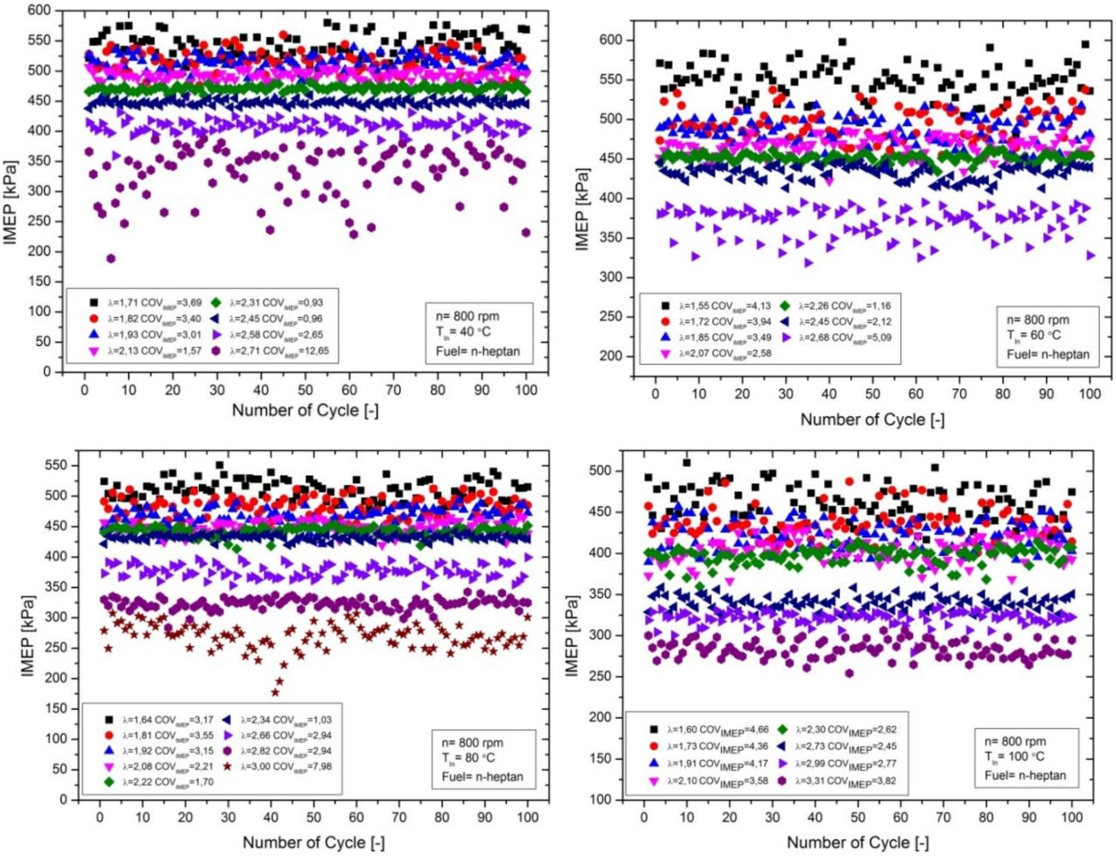

Fig. 3. The variations of imep and COVimep at different excess air coefficients and inlet air temperatures

COVimep defines the cyclic variations of imep during combustion. Figure shows the effects of lambda and inlet air temperature on COVimep. It can be stated that COVimep first decreased and then started to increase with the increase of lambda for a given inlet air temperature. COVimep is caused by nonhomogeneous charge mixture, gas motion and exhaust gases that are exited in the combustion chamber. The composition of charge mixture is complex, because there is exhaust gases and fresh air-fuel mixture in the combustion chamber. This mixture varies the start of combustion and causes cyclic variations. Cyclic variations are important because auto-ignition timing is highly affected. In addition, cyclic variation limits the engine operation [31-33]. The charge composition at the end of compression stroke determines the cyclic variations and combustion phasing in HCCI combustion. Since nonuniformities of the charge composition exist in the combustion chamber, COVimep is high at richest and leanest charge mixtures. Variations and thermodynamical properties change in leaner and richer charge mixtures. Fuel could not be automatically ignited due to lower fuel concentration at richer mixtures. Some fuel molecules will remain and wait in order to combust for the next cycle. These fuel molecules will mix with exhaust gases and other combustion products. So, start of combustion and combustion process vary cycle by cycle. The lowest COVimep were obtained at lambda values of 2.4 and 2.6. Moreover, there is no huge differences on COVimep between 40, 60 and 80°C inlet air temperatures. However, it is seen that COVimep increased with 100°C.

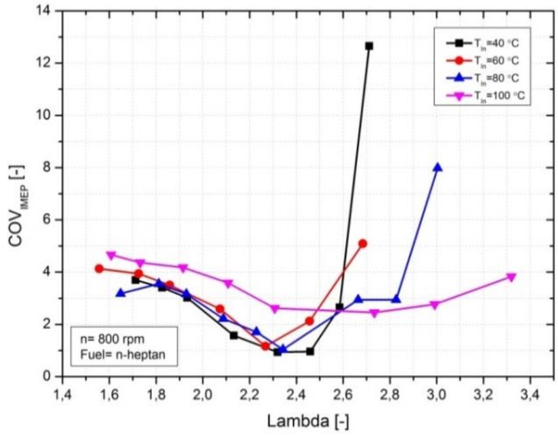

Fig. 4 . The effects of lambda and inlet air temperature on COVimep

Figure 5 illustrates the effects of lambda and inlet air temperature on ringing intensity versus lambda. As it is known HCCI combustion can occur with leaner charge mixtures at towards the combustion chamber simultaneously. More oxygen molecules are needed in order to ignite whole charge mixture, because fuel and oxygen molecules should react easily in HCCI mode. Ringing intensity is attributed pressure rise rate, maximum in-cylinder pressure and engine speed [34-37]. It is seen that ringing intensity decreased with the increase of lambda. At this point, more stable combustion can enhance with higher lambda. Leaner charge mixture prevented rapid and sudden heat release resulting in lower ringing intensity. It can be said that the highest ringing intensity was computed with 100°C inlet air temperature. Auto-ignition condition improves at higher air inlet temperatures. Fuel can be easily vaporized and ignited with higher temperatures. This situation resulted in higher heat release and ringing intensity. Higher inlet temperature increases the knocking tendency in HCCI mode. Furthermore, more fuel molecules react at richer mixtures such as 1.5 and 1.6 lambda values. Normally, released heat energy and ringing intensity increased. Uyumaz [38] has found that higher ringing intensity was determined with mustard oil biodiesel-diesel fuel mixture (B20) compared to diesel due to higher viscosity and density of biodiesel. Wildman et al. [34] have revealed that ringing intensity increased with the increase of pressure rise rate. In another study, Jia et al. [37] examined the effects of injection timing and intake valve closing timing on performance and exhaust emissions using computational fluid Dynamics program. They have seen that ringing intensity showed complex characteristics. Ringing intensity increased when the injection timing was advanced.

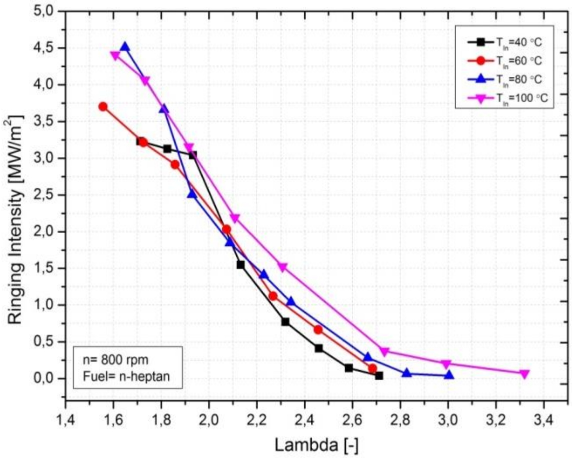

Fig. 5. The effects of lambda and inlet air temperature on ringing intensity

The most important handicap is that sudden and rapid heat release in HCCI combustion mode. In addition, in-cylinder pressure rise rate increased much due to sudden and simultaneous combustion in HCCI mode. Because, there is no external control mechanism on HCCI combustion. Figure 6 demonstrates the effects of lambda and inlet air temperature on pressure rise rate. Pressure rise rate decreased with the increase of lambda like ringing intensity. When Figure 6 is examined similar results were obtained with pressure rise rate like ringing intensity. Lower fuel concentration in the combustion chamber resulted in lower heat energy. In-cylinder pressure exerted to the piston decreased for each crank angle position at leaner mixtures. On the contrary, higher in-cylinder pressure was applied on the piston with richer mixture (λ=1.5, 1.6) due to higher heating energy. Figure 6 also showed that higher pressure rise rate determined with 100°C inlet air temperature in spite of lean charge mixture. Auto-ignition condition improves with higher inlet air temperature resulting sudden heat release and higher pressure rise rate.

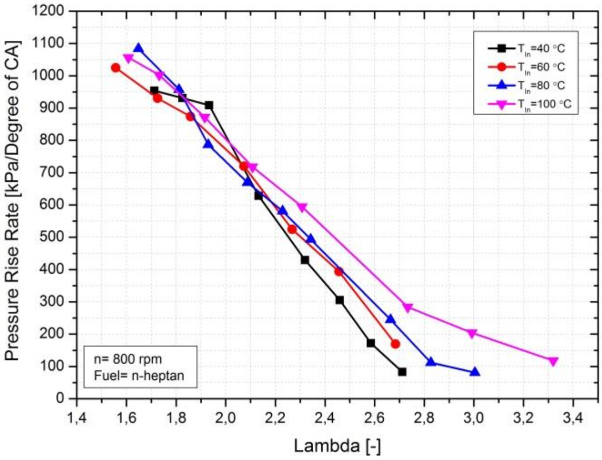

Fig. 6. The effects of lambda and inlet air temperature on pressure rise rate

Acknowledgment

TUBITAK institute in Turkey is acknowledged for providing financial support for Seyfi Polat to perform this study. In addition, financial support from United States' National Science Foundation for conducting HCCI engine experiments is acknowledged.

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