UNDERSTANDING THE EFFECTS OF RESIDUAL GAS TRAPPING ON COMBUSTION CHARACTERISTICS, ENGINE PERFORMANCE AND OPERATING RANGE IN A HCCI ENGINE

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Abstract- In this study, experimental investigation was performed in order to determine the effects of residual gas fraction (RGF) using low lift cams in a single cylinder, four stroke gasoline HCCI engine. For this purpose, the test engine was equipped with variable valve lift mechanism including intake and exhaust cam with 5.5 and 3.5 mm valve lift. The experiments have been carried out to understand the effects of RGF with three pairs of cam mechanisms (IN 5.5-EX 5.5, IN 5.5-EX 3.5 and IN 3.5-EX 3.5). The test results showed the test engine was run between 800-1900 rpm at different air fuel ratios and inlet air temperatures on HCCI mode. It was found that IN 5.5-EX 3.5 cam mechanism presented the more reasonable results among the other cam mechanisms and HCCI operating range was extended when misfiring and knocking boundaries were examined. Higher RGF was obtained with IN 3.5-EX 3.5 cam mechanism. Indicated thermal efficiency was obtained 26.67 % for IN 3.5 EX 3.5 whereas 27.5 % for IN 5.5-EX 3.5 at stoichiometric ratio and 1000 rpm engine speed. As a result, it was seen that combustion phasing could be controlled with RGF and HCCI operating range could be extended trapping exhaust gases in the combustion chamber.

Index Terms- HCCI, Combustion, Operating range, Residual gas fraction, Performance

I. INTRODUCTION

The development of internal combustion engines with higher thermal efficiency and lower exhaust emissions is required by limited emission regulations. The increase in energy consumption with higher level of environmental pollution caused by harmful exhaust emissions from motored vehicles has led researchers to investigate alternative fuels and combustion mode. In addition, oil reserves are consumed rapidly and the number of motored vehicles increase day by day. [1]-[5]. One significant approach to favorably address for developing internal combustion engines is to achieve HCCI (homogeneous charged compression ignition) which gives higher thermal efficieny with lower emissions. So, todays HCCI combustion has receieved much attention due to excellent advantages for efficiency and low emissions. One of the most important advantage of HCCI engine is to reduce NO_x (nitrogen oxides) and soot emissions simulataneously in HCCI engines, because they can be operated with lenaer mixture resulting in lower in-cylinder gas temperature at the end of combustion. NO_x and soot emissions could not be reduced in CI (compression ignition) engines, because higher gas temperature is obtained at the end of combustion. But, HCCI combustion is achieved at lower gas temperature [5]-[8]. In HCCI engines, premixed charge mixture is compressed with higher compression ratio and all charge mixture is ignited spontaneously in the combustion chamber unlike combustion principles such as SI (spark ignition) and CI engines. Moreover, higher compression ratio led engine to operate with higher thermal efficiency which is the most important handicap faced with SI engines due to knocking problem. Autoignition occurs across the combustion chamber without existing richer zones resulting in lower gas temperature in HCCI combustion. HCCI engines suffer from some difficulties such as uncontrolling combustion phasing, higher HC (hydrocarbon) and CO (carbonmonoxide) emissions and narrow operating range. These difficulties limit the usage of HCCI combustion in the internal combuston engines. Limited operating range of HCCI engines probably is the most difficult hurdle that must be overcome. Furthermore, charge mixture can not be ignited with leaner mixture due to unsufficient in-cylinder temperature especially at low engine loads which is called misfiring. In contrast, knocking problem is observed due to higher pressure rise rate at high engine loads, because higher in-cylinder temperature and pressure cause to rapid heat release rate and pressure oscillations in the combustion chamber at higher engine loads. To overcome these difficulties some methods have been used such as EGR (exhaust gas recirculation) [12-16], [19] variable cam mechanisms and VVT (variable valve timing), [18], [20]-[24], heating inlet air [3],[25],[26], alternative fuels and supercharging [27] in order to control combustion and expand the HCCI operating range. Among them residual gases have great potential in order to control autoignition and extend HCCI operating range. Residual gases have attractive effects on HCCI combustion. Firstly, the temperature of the charge mixture increases with residual gases, because hot exhaust gases help to warm up cooler charge which is called heating effect. It also allows to achieve HCCI combustion at lower engine loads. The ratio of

specific heat value also decreases and heat capacity of the charge mixture increases with residual gases that is called heat capacity effect. Trapped exhaust gases absorb the heat during combustion which prevents the rapid heat release. Dilution effect is also observed with residual gases, because oxygen concentration decreases in the combustion chamber with residual gas trapping. Burnt gases include combustion products which can participate to the chemical reactions which is called chemical effect [7],[9],[25]-[27]. Çınar et al. [26] investigated the effects of RGF on performance, combustion and emission characteristics in a HCCI engine. They showed that more residual gases were trapped with 3.5 mm valve lift for intake and exhaust valves.

It was also seen that combustion was retarded with low lift cams. They concluded that HCCI operating range can be expanded with residual gases. In another study, Çınar et al. [23] researched the effects of valve lift on HCCI combustion and emission characteristics. They showed that HCCI combustion could be controlled using low lift cams. They have also observed that the test engine was run with leaner mixture at higher inlet air temperatures. Zhang et al. [22] intended to determine the effects of residual gases on CAI combustion. They have realized that spark timing affected combustion phasing. Less effect was seen on initial flame propagation by the concentration of residual gases.

In this study, a single cylinder, four stroke Ricardo Hydra test engine was converted to HCCI engine increasing compression ratio and heating inlet air. For HCCI combustion mode, a new variable cam mechanism was also designed and adapted to the test engine. The aim of this study is to see the effects of RGF (residual gas fraction) on performance, HCCI combustion characteristics and operating range in a more detail. The variation of in-cylinder pressure, heat release rate, indicated thermal efficiency, CA10-90 (combustion duration) CA50, SOC (start of combustion), and imep were researched with RGF. Besides, the effects of different cam mechanisms on misfiring and knocking boundaries were also studied in depth.

II. EXPERIMENTAL SETUP AND PROCEDURES

A single cylinder, port injection naturally aspirated Ricardo Hydra test engine was operated on HCCI mode. For this reason, the compression ratio of the test engine was increased to 13:1 and inlet air was warmed up. In addition, different cam mechanisms were also designed and adapted into the test engine. The technical specifications of the test engine are given in Tab. 1. The test engine was coupled with Eddy current DC (direct current) dynamometer that can absorb 30 kW power output at 6500 rpm engine speed. The schematic view of the experimental setup is also seen in Fig. 1.

Table 1. The technical specifications of test engine

	Spark ignition	HCCI
Model	Ricardo Hydra	Ricardo Hydra
Cylinder number	1	1
Bore x Stroke [mm]	80.26 x 88.9	80.26 x 88.9
Swept volume [cc]	540	540
Compression ratio	5:1 – 13:1	13:1
Intake valve opening timing	12° CA Before Top Dead Center (BTDC)	12° CA BTDC
Intake valve closing timing	56° CA After Bottom Dead Center) ABDC	56° CA ABDC
Exhaust valve opening timing	56° CA Before Bottom Dead Center (BBDC)	56° CA BBDC
Exhaust valve closing timing	12° CA After Top Dead Center (ATDC)	12° CA ATDC
Valve lifts [mm]	9.5	5.5, 3.5

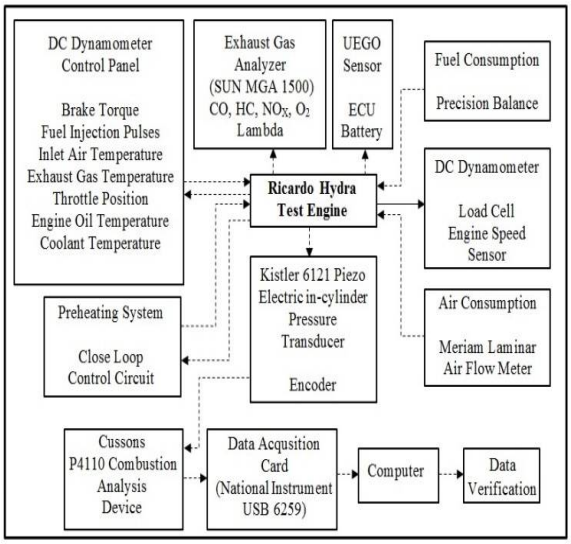


Figure 1. Schematic view of the experimental setup

Preheating system was also mounted into the suction line of the test engine. Inlet air could be controlled and changed using close loop controller. Determining the air /fuel ratio is very important during the tests. So, UEGO (Universal exhaust gas oxygen) sensor was adapted to the exhaust line in order to determine the fueling ratio. Besides, exhaust gas analyzer was also used in order to determine the air/ratio, because it can also measure lambda apart from exhaust emissions. Fuel injection pulses were also altered from the dynamometer control panel using potantiometer. In-cylinder pressure was measured using Kistler 6125 piezo electric sensor that mounted into the cylinder head. Moreover, encoder which generates 1000 pulses per rotation was mounted to the crankshaft in order to determine the top dead center (TDC) and engine speed. In-cylinder pressure data were measured at a resolution of 0.36°CA crank angle degrees. In-cylinder pressure data were amplified using Cussons P4110

combustion analysis device and converted from analog to digital data with National Instruments USB 6259 Data acqusition card. Converted digital in-cylinder pressure data were then recorded in the computer. In-cylinder pressure data were verified using a programme developed with MATLAB in order to perform combustion analysis. Heat release rate, indicated thermal efficiency, combustion duration and SOC were investigated in order to determine the effects of RGF on HCCI combustion. In order to reduce cyclic variations, pressure trace was determined averaging the pressure data of 50 consecutive cycles at a given operation condition. Before the experiments, the test engine is first run on SI mode in order to reach operation temperature and provide stable operation condition. After that, HCCI combustion was achieved switching of the spark plug for all test condition. During the experiments coolant and engine oil temperature were kept constant at 85°C and 75°C respectively for stable HCCI operation condition and.

In the present study, residual gases were trapped using low lift cams. Exhaust gases could not be discharged well when low lift cam was used. So, some exhaust gases existed in the combustion chamber at the end of cycle. Orijinal valve timing of the test engine was not changed. Tab. 2 presents the variable cam mechanisms used in the experiments and abbreviations.

Table 2. Variable cam mechanisms used in the experiments and abbreviations

Valve mechanisms	Intake	Exhaust	Abbreviations
1	5.5 mm lift	5.5 mm lift	IN 5.5-EX 5.5
2	3.5 mm lift	3.5 mm lift	IN 3.5-EX 3.5
3	5.5 mm lift	3.5 mm lift	IN 5.5-EX 3.5

PRF80 (primary reference fuel) fuel was used in the experiments as the test fuel. It consists of 80 % isooctane and 20 % n-heptane by vol. Test fuels were purchased from a distributor. The properties of the test fuels are given in Tab. 3.

Table 3. The properties of test fuels

	Isooctane	n-heptane
RON (Research octane number)	100	0
Chemical formula	C_8H_{18}	C_7H_{16}
Molar mass [gr/mol]	114.23	100.21
Density [kg/m^3 at 15.4°C]	692	695
Boiling point [K]	372.2 - 372.6	371
Low heating value [kJ/kg]	44310	44566

In-cylinder pressure data were verified using a MATLAB programme in order to analyze HCCI combustion. Imep (indicated mean effective pressure) is an important performance indication. It was computed as seen in Eq.(1). W_{net} and V_d are define the net work and swept volume in Eq. (1).

$$imep = \frac{W_{net}}{V_d} \quad (1)$$

W_{net} was determined with Eq. (2). P and dV show the in-cylinder pressure and the variation of cylinder volume.

$$W_{net} = \int P\, dV \quad (2)$$

In-cylinder pressure and cylinder volume versus crank angle were used in order to calculate the net heat release rate. Net heat release rate was calculated by Eq. (3). During the calculations, it is considered that charge mixture is ideal gas and thermodynamic state of the mixture is uniform. Gas leakages and heat losses from the piston and ring crevices were also assumed negligible.

$$\frac{dQ}{d\theta} = \frac{k}{k-1}P\frac{dV}{d\theta} + \frac{1}{k-1}V\frac{dP}{d\theta} + \frac{dQ_{heat}}{d\theta} \quad (3)$$

dQ is the net heat release, P and V cylinder pressure and cylinder volume $d\theta$ is the variation of crank angle and k is the ratio of the specific. $\frac{dQ_{heat}}{d\theta}$ is the heat transfer from cylinder to cylinder walls. Indicated thermal efficiency was calculated with Eq. (4). $m_{isooctane}$ and $m_{n-heptane}$ are the fuel consumption per cycle for isooctane and n-heptane. Q_{LHV} is the calorific value of the test fuels.

$$\eta_T = \frac{W_{net}}{m_{isooctane}Q_{LHV} + m_{n-heptane}Q_{LHV}} \quad (4)$$

RGF can be defined as the ratio of residual gas mass to total mass in the cylinder. Residual gases include exhaust gases remained from the previous cycle and combustion products. Residual gases could not be measured directly. So, RGF was computed as follows. Residual gas mass was calculated based on ideal gas law.

$$P\,V = m_r\,R\,T \quad (5)$$

$$X_{rg} = \frac{m_r}{m_{total}} \quad (6)$$

P and V are in-cylinder pressure and cylinder volume at EVC (exhaust valve closing) timing. m_r defines the residual gas mass. T is the gas temperature at EVC. It can be assumed as exhaust temperature. In Eq.(6) X_{rg}, and m_{total} define the RGF and total gas mass respectively.

III. RESULTS AND DISCUSSION

The test engine was operated on stable HCCI combustion mode at different inlet air temperature (40-120°C) and air/fuel ratio (λ=0.5-2) and engine speeds ranging from 800 to 1900 rpm. In the current study, residual gases were intended to be trapped using

low lift cams including 5.5 and 3.5 mm valve lift on HCCI combustion. So, the valve timing was not altered but valve lift in the experiments. For this reason, three pairs of cam mechanisms were used during the experiments on HCCI combustion mode. Fig. 2 presents the variation of indicated thermal efficiency versus inlet air temperature at different engine speeds with IN 5.5-EX 3.5 cam mechanism. It was seen that indicated thermal efficiency increased with the increase of inlet air temperature for two engine speeds. In contrast, specific fuel consumption decreased when higher thermal efficiency was obtained. Higher inlet air temperature increases the heat that allows to occur autoignition chemical reactions easily. So, the increase of inlet air temperature causes to increase thermal efficiency.

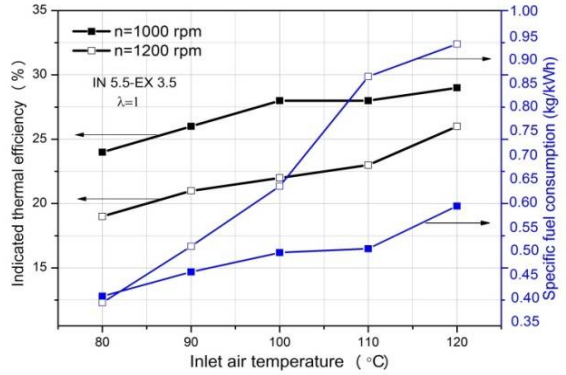
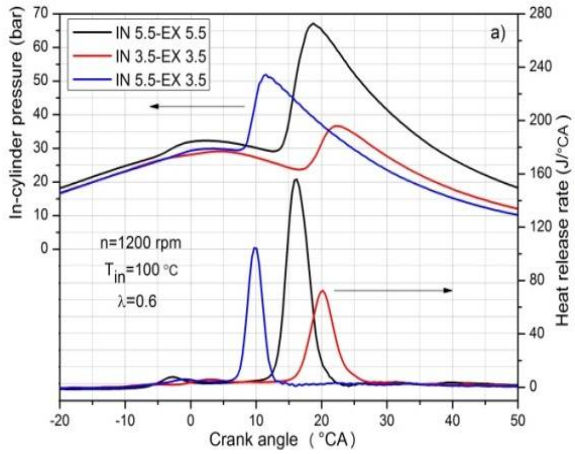


Figure 2. The variation of indicated thermal efficiency versus inlet air temperature at different engine speeds with IN 5.5-EX 3.5 cam mechanism

Fig. 3 shows the effects of different cam mechanisms on cylinder pressure and heat release rate versus crank angle. As seen in Fig. 3-a, highest in-cylinder pressure and heat release rate are obtained with IN 5.5-EX 5.5 due to higher energy driven to the cylinder. The major finding is to advance combustion with IN 5.5-EX 3.5 in Figure 3-a. At 1600 rpm, higher in-cylinder pressure and heat release were obtained with IN 5.5-EX 3.5 compared to IN 5.5-EX 5.5 at λ=1.2. It can be stated that less residual gases exist in the combustion chamber with IN 5.5-EX 3.5 resulting in higher in-cylinder pressure due to better autoignition chemical reactions.



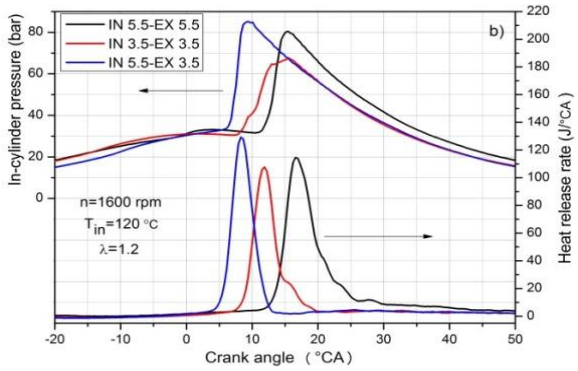


Figure 3. The effects of different cam mechanisms on cylinder pressure and heat release rate

Fig. 4 concludes the effects of inlet air temperature and lambda on RGF with IN 5.5-EX 3.5 cam mechanism. The increase of inlet air temperature caused to increase RGF, because less fresh charge mass is driven to the cylinder owing to lower density of mixture. The concentration of fresh charge decreased resulting in higher RGF with the increase of inlet air temperatıre as seen in Fig. 4-a. It was also noticed that more residual gases are trapped in the combustion chamber, because burnt gases are replaced with fresh charge in the cylinder. Fig. 4-b shows the effect of lambda on RGF at constant engine speed of 1000 rpm and fixed inlet air temperature of 100°C. RGF decrases with the increase of lambda.

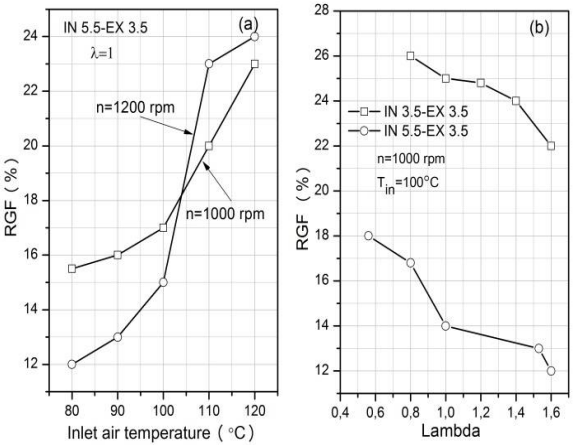


Figure 4. The effects of inlet air temperature and lambda on RGF

The variations of SOC and CA10-90 versus lambda with different cam mechanisms are given in Fig. 5. SOC was delayed with the increase of lambda. Autoignition was initiated later with lenaer mixtures due to lower fuel energy density in the combustion chamber. The increase of intake valve lift caused to take more chaerge mass compared to IN 3.5-EX 3.5. Compression pressure and temperature increased at the end of compression stroke with IN 5.5-EX 3.5 according to IN 3.5-EX 3.5 due to more charge mass. This situation helps to start autoignition chemical reactions earlier. So, SOC is advanced as seen in Fig.5. Combustion duration increased with the increase of lambda as seen in Fig.5. CA10-90 is prolonged with higher lambda due to lower in-cylinder temperature. It

was pointed that combustion duration increased with IN 5.5-EX 3.5 compared to IN 3.5-EX 3.5 at a given lambda.

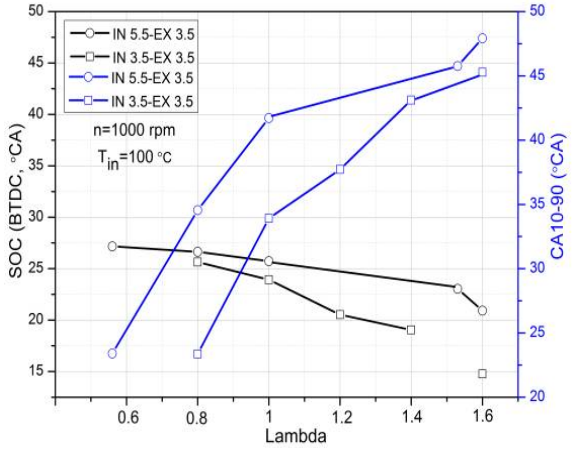


Figure 5. The variations of SOC and CA10-90

Fig. 6 shows the variations of CA50 and indicated thermal efficiency versus lambda with different cam mechanisms. CA50 is the point when the half of the charge mixture is completed to combust. There is a strong relationship between CA50 and indicated thermal efficiency, because CA50 should be slightly after TDC for higher thermal efficiency. When figure 10-a is examined, CA50 is obtained toward to TDC until stoichiometric ratio and then start to retard with the increase of lambda for two cam mechanisms at fixed engine speed and inlet air temperature. It was pointed that CA50 was obtained earlier with IN 5.5-EX 3.5 compared to IN 3.5-EX 3.5 cam mechanism for all lambda values.

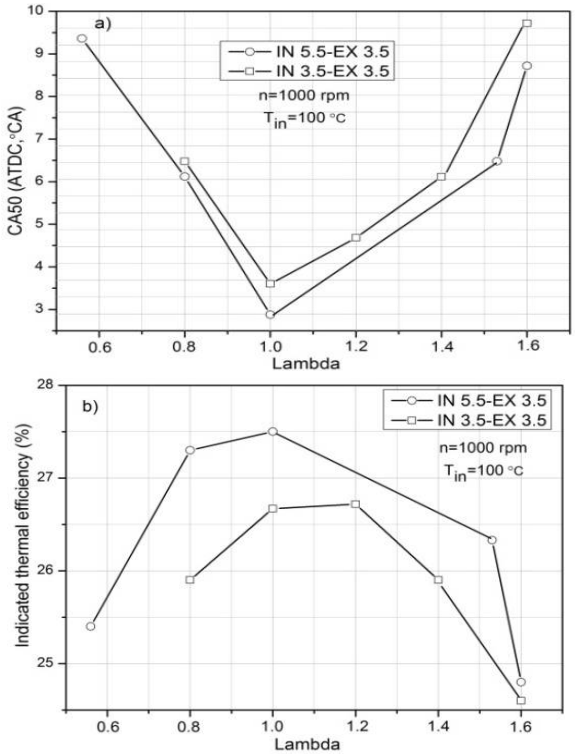


Figure 6. The variations of CA50 and indicated thermal efficiency versus lambda with different cam mechanisms

Fig. 7 shows the effects of different cam mechanisms on HCCI operating range, knocking and misfiring zones versus RGF.

It is concluded from Fig. 7-a that more residual gases were trapped with IN 3.5-EX 3.5 cam mechanism compared to other cam mechanisms. The narrowest operating range was obtained with IN 5.5-EX 5.5 cam mechanism, because HCCI combustion could not be achieved with leaner mixture with IN 5.5-EX 5.5. Misfiring problem was faced with IN 3.5-EX 3.5 cam mechanism. When Figure 7-b is examined, wider operating range was obtained with IN 5.5-EX 3.5 cam mechanism.

It was also depicted from Figure 11-b that HCCI combustion was achieved away from knocking zone with IN 5.5-EX 3.5. misfiring problem was observed with IN 3.5-EX 3.5 cam mechanism due to higher RGF. Higher residual gases prevent to occur auto ignition chemical reactions. It was also seen that knocking tendency increased with IN 5.5-EX 3.5 cam mechanism at lower RGF due to rapid heat release rate.

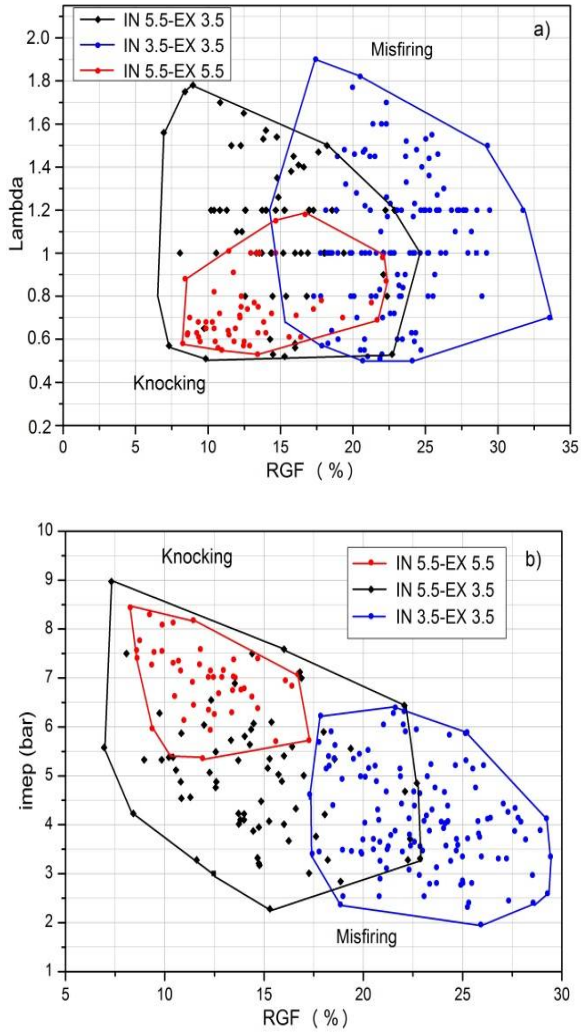


Figure 11. The effects of different cam mechanisms on HCCI operating range, knocking and misfiring zones versus RGF

CONCLUSION

This study includes experimental findings related to the effects of RGF on HCCI combustion characteristics, engine performance and HCCI operating range. For this reason, low lift cam mechanisms were used in the experiments in order to trap burnt gases in the combustion chamber. The experimental results can be summarized as follows

• RGF can be used as an approach to extend the HCCI operating range. It is also seen that the usage of low lift cam mechanisms is the practical and useful method for this purpose. Largest HCCI operating range was determined with IN 5.5-EX 3.5 cam mechanism.
• It was concluded that RGF had remarkable effect on misfiring and knocking zones in HCCI combustion. So, HCCI operating range could be extended trapping residual gases. Test results showed that burnt gases diluted the fresh charge mixture resulting in slowing down the rapid heat release rate.
• Residual gases increases the heat capacity of mixture and dilute the charge mixture.
• Indicated thermal efficiency increased with IN 5.5-EX 3.5 compared to IN 3.5-EX 3.5 cam mechanism at stoichiometric condition. Combustion duration was also prolonged with IN 5.5-EX 3.5 cam mechanism. The test results also showed that the increase of inlet air temperature caused to increase RGF. It was also found that burnt gases are replaced with fresh charge in the combustion chamber at higher ibnlet air temperature due to lower density of charge mixture.
• Indicated thermal efficiency was obtained 26.67 % for IN 3.5 EX 3.5 whereas 27.5 % for IN 5.5-EX 3.5 at stoichiometric ratio and 1000 rpm engine speed.
• As a result, low lift cams can be used in order to trap exhaust gases and HCCI operating range can be extended using residual gas trapping. Knocking tendency can be also reduced with residual gases.

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