Proceedings of the 2009 International Conference on

Chemical, Biological and Environmental Engineering

Singapore 9 – 11 October 2009

CBEE 2009

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AN EXPERIMENTAL STUDY ON THE EFFECTS OF EGR AND EQUIVALENCE RATIO ON CO AND SOOT EMISSIONS OF DUAL FUEL HCCI ENGINE

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HCCI engines improvements are challenged with high CO emissions. In this study, effects of EGR and equivalence ratio on CO and soot emissions of a dual fuel HCCI engine are investigated. The experiments were conducted on a variable compression ratio (VCR) single-cylinder research engine with compression ratio of 17.5:1. Premixed gasoline is provided by a carburetor connected to intake manifold and equipped with a screw to adjust premixed air-fuel ratio, and diesel fuel is injected directly into the cylinder through an injector at pressure of 250 bars. Intake charge temperature was increased up to 110-115°C by using an electrical heater. The higher advanced injection timing (35 BTDC) was used to initiate the gasoline auto-ignition in the HCCI dual fuel engine. The results show that increasing EGR rate increases CO emissions due to dilution effect which reduces combustion temperature, also addition of EGR increases soot emission as a result of decreases the inlet air and its oxygen, which create rich points in the cylinder mixture. Results also show that the CO emission decreases by increasing the equivalence ratio due to formation of more OH radicals in the cylinder and increasing the overall reactivity.

Keywords: Dual fuel HCCI engine, EGR, equivalence ratio, CO and soot emissions.

1. Introduction

With the rapid development of world economy, the problems of energy resource crisis and environment pollution become more and more serious. As one of the main energy consumers and the main source of environment pollution, the automobile receives comprehensive attentions of worldwide researchers [1]. In the history of research and development of IC engines, two engine concepts have played dominant roles which are SI (gasoline) engine and CI (diesel) engine. In conventional stoichiometric charge SI engines, a spark plug ignites the air-fuel mixture in the cylinder, creating high local temperatures and resulting in high NO_X emissions. In CI engines, after taking air into the cylinder and compressing it, the start of combustion is controlled by the injection of fuel into the hot and high-pressure air. This system creates a combustion pattern that produces a high temperature combustion zone and a fuel-rich zone, which yield NO_X and PM emissions, respectively. Many studies are focused on the reduction of both NO_X and PM from these engines. However, due to the combustion mechanism, it is difficult to reduce both NO_X and PM simultaneously [2-4]. Respecting the Euro IV emission norms in 2005, possibilities as the catalytic oxidation, the NO_X traps and the particulate traps can be used, in other words: post-treatment. However, for the future Euro emission norms, the restrictions are more severe and another solution has to be found. The world-wide fuel consumption and exhaust emissions can realistically be reduced if an alternative for the IC engine is developed with characteristics that are significantly better than those of present engines. Concerning the emission reduction during the combustion process, Homogeneous Charge Compression Ignition (HCCI) promises to be a good solution to respect these future Euro norms [5, 6]. HCCI has been researched for some thirty years. It was first identified by Noguchi et al. and Onishi et al. as a method to reduce emissions and fuel consumption of two-stroke engines at part-load conditions [7]. The main concepts of HCCI are breathing premixed air/fuel mixture, as in conventional spark ignition (SI) engines, and ignition without a spark plug, as in conventional compression ignition (CI) engines [8, 9]. In HCCI engine the fuel and air are premixed to form a homogeneous mixture before the compression stroke. As a result, the mixture ignites throughout the bulk without discernable flame propagation due to occurrence of auto-ignition at various locations in the combustion chamber (multi-point ignition), which may cause extremely high rates of heat release, and consequently, high rates of pressurization [10-13]. HCCI combustion is the process in which a homogeneous mixture is auto-ignited by the compression from the piston motion, so the fuel chemical kinetics plays a dominate role during the whole

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Abstract: HCCI engines improvements are challenged with high CO emissions. In this study, effects of EGR and equivalence ratio on CO and soot emissions of a dual fuel HCCI engine are investigated. The experiments were conducted on a variable compression ratio(VCR) single-cylinder research engine with compression ratio of 17.5:1. Premixed gasoline is provided by a carburetor connected to intake manifold and equipped with a screw to adjust premixed air-fuel ratio, and diesel fuel is injected directly into the cylinder through an injector at pressure of 250 bars. Intake charge temperature was increased up to 110-115ºC by using an electrical heater. The higher advanced injection timing (35 BTDC) was used to initiate the gasoline auto-ignition in the HCCI dual fuel engine. The results show that increasing EGR rate increases CO emissions due to dilution effect which reduces combustion temperature, also addition of EGR increases soot emission as a result of decreases the inlet air and its oxygen, which create rich points in the cylinder mixture. Results also show that the CO emission decreases by increasing the equivalence ratio due to formation of more OH radicals in the cylinder and increasing the overall reactivity.

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Nomenclature

HCCI	Homogeneous Charge Compression Ignition
EGR	Exhaust Gas Recirculation
BTDC	Before Top Dead Center
DI	Direct injection
CI	Compression Ignition
SI	Spark Ignition
IC	Internal Combustion
r_p	Premixed ratio
h_{up}	Heating value of premixed fuel (kJ/kg)
$\dot{m}_p$	Mass flow rate of premixed gasoline (kg/s))
$\dot{m}_d$	Mass flow rate of injected fuel (kg/s)
h_{ud}	Heating value of diesel fuel (kJ/kg)
$\dot{m}_{aEGR}$	Mass flow rate of intake air with EGR (kg/s)
$\dot{m}_{EGR}$	Mass flow rate of EGR gases (kg/s)
ϕ	Equivalence ratio
MON	Measured octane number
$(A/F)_s$	Stoichiometric air-fuel ratio
UHC	Unburned hydrocarbon
CO	Carbon monoxide
CO_2	Carbon dioxide
NO_X	Oxides of nitrogen
PM	Particulate matter

ignition is determined by the charge mixture composition and its time–temperature history. Several parameters affect the quality of the HCCI combustion and the ignition delay: mixture homogeneity, inlet charge temperature, fuel composition, equivalence ratio, coolant temperature, internal and external EGR, engine speed and kinetics of the fuel oxidation at lower temperatures [14-18]. Since the HCCI combustion is lean burn and occurs without flame propagation, it provides much lower combustion temperature than that of conventional SI and CI engines. As a result, HCCI combustion produces very low levels of NOx and particulate matter (PM) while maintaining high thermal efficiency. However, greater amounts of hydrocarbon (HC) and carbon monoxide (CO) emissions are released in HCCI engine relative to conventional SI and CI engines [8,19-21].

Although stable HCCI operation and its substantial benefits have been demonstrated at selected steady state conditions, several technical barriers must be overcome before HCCI can be widely applied to IC engines. Control of auto-ignition process over different engine operating conditions, achieving cold start, the expansion of operating range and meeting emission standards are challenges. Several potential control methods have been proposed so far, the most effective including EGR, variable compression ratio (VCR) mechanisms or variable valve timing (VVT) to change the effective compression ratio and the amount of hot residual gas respectively [4,8,11]. Now, it is generally accepted that the EGR technique is an efficient way to control HCCI combustion. HCCI combustion can occur in internal combustion engines by varying the inlet air temperature and exhaust gas recirculation (EGR) fraction over a range of equivalence ratios [15,22].

EGR is widely used as the main method to depress the NO_X emission from diesel engines. Currently, EGR is also used as the basic method to control the ignition timing and burn rate of HCCI combustion [15]. EGR consists of many gaseous chemical species, which includes the main components of burned gases, CO_2, H_2O, N_2 and O_2, partial burned gases such as CO, particular matters, HCs and high temperature combustion products NO_X. Different species has different heat capacity and chemical reactivity, therefore has different effect towards ignition timing and heat release rate of HCCI combustion [23]. The application of EGR on HCCI combustion engine has a number of effects on the combustion process and emissions. The effects of EGR on HCCI combustion that have been investigated are: increase in intake charge temperature (heating effect), reduction of oxygen concentration (dilution effect), increase in specific heat of the mixture (heat-capacity effect), chemical interactions involving the CO_2 and H_2O species of the recycled burned gases (chemical effect; this influences not only the overall kinetics, but also can change a specific reaction path [24, 25]) and stratification of the recycled burned gases (stratification effect). The dilution and heat capacity effects are responsible for reducing the heat-release rates and extending the combustion duration. The heating effect is mainly responsible for the advance of auto-ignition timing, and the residuals-stratification effect facilitates HCCI combustion. Reactive species, present in the residuals, facilitate auto-ignition [10, 15, 23].

The objective of this study is to investigate the effects of EGR and equivalence ratio on CO and soot emissions of dual fuel HCCI engine using premixed gasoline.

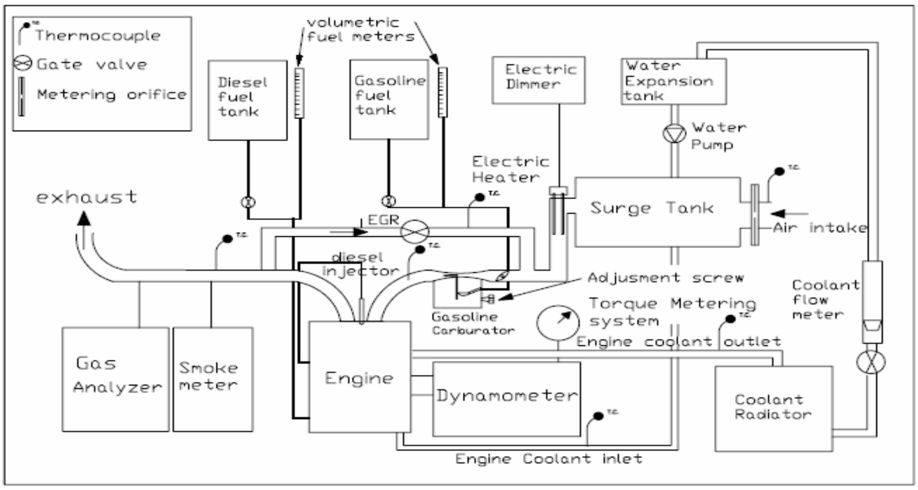

Figure 1: Schematic diagram of experimental apparatus

2. Experimental setup and procedure

2.1. *Experimental setup*

In this study all experiments were conducted on a four stroke VCR single-cylinder naturally-aspired research engine with a displacement volume of 582 cm^3, which the test rig is TD43 model equipped by Techquipment Co. The engine has a bowel type piston with a bowel diameter of 41.5 mm. The base engine can operate as SI engine with the compression ratio in the range of 7 to 11, and also can convert to diesel type (spark plug is replaced by an injector) in the range of 14 to 18 for the compression ratio. Premixed gasoline is introduced to the inlet manifold by means of a carburetor which is mounted on 180 mm from intake valve upstream and equipped with a fuel adjustment needle screw. Diesel fuel is injected into the cylinder through an injector. The specifications of the test engine are listed in the table1.

The experimental apparatus is composed of electrical dynamometer, AVL-415 smoke meter, RE 205 Plint exhaust analyzer, which measures HC (as C_6), K-type thermocouples, 220 V single-phase 2Kw intake air heater which placed in the air flow stream, external EGR system, adjustable coolant system and air mass flow meter (surge tank and orifice system). Fig. 1 shows the schematic diagram of the experimental apparatus.

Table 1: Engine specifications

Engine	Four stroke
Number of cylinders	1
Compression ratio	17.5:1
Displacement volume	582 cm^3
Bore	82 mm
Stroke	95 mm
Injection mode	DI
Number of injection holes	4
Injection pressure (bar)	250
Gasoline fueling	Carburetor

2.2. *Experimental procedure*

In this work, the diesel engine was firstly started at idle position in the compression ratio of 17.5:1. Then intake charge temperature was adjusted on 115 ^{0}C. After a few minutes to achieve steady condition at constant cooling temperature of 50 ^{0}C, premixed gasoline was introduced to engine and torque increased gradually. Then by using an external EGR system different rates of EGR were introduced to get HCCI auto-ignition close to TDC. Table 3 shows the specifications of the fuels used in dual fuel HCCI engine. It should be noted that using early injection (35BTDC) in HCCI engine in compare with conventional CI engine was the necessity of initiating the auto-ignition of dual fuel HCCI engine.

To show the effect of fuels in dual fuel HCCI engine, the premixed ratio (r_p) is defined as a ratio of premixed fuel energy (Q_p) to total energy (Q_t). It can be obtained from the following equation [1]:

$$r_p = \frac{\dot{Q}_p}{\dot{Q}_t} = \frac{\dot{m}_p h_{up}}{\dot{m}_p h_{up} + \dot{m}_d h_{ud}} \qquad (1)$$

In the equation (1), $\dot{m}_P$ represents mass flow rate of premixed gasoline, $\dot{m}_d$ is mass flow rate of injected fuel, hup is heating value of premixed fuel and hud is heating value of diesel fuel. Therefore, rp=1 corresponds to single fuel HCCI combustion and rp =0 corresponds to typical CIDI combustion.

EGR rate also is calculated as follow [25]:

$$EGR\,(\%) = \frac{\dot{m}_{EGR}}{\dot{m}_{EGR} + \dot{m}_{aEGR}} \times 100 \qquad (2)$$

Where, $\dot{m}_{aEGR}$ is mass flow rate of intake air with EGR, and $\dot{m}_{EGR}$ is mass flow rate of EGR.

Different EGR rates were applied in each test by using a simple computer code. The code can estimate the orifice pressure drop at specific EGR rate in term of engine speed, ambient conditions and intake air properties at orifice.

The electrical dynamometer which is connected directly to the engine plays the role of rotating initiator in starting mode, and when running the engine, consumes the power output for generating electricity. The stator of dynamometer can rotate freely around its shaft and as a result of engine torque during power generation; it is forced out from the horizontal equilibrium position. Using a Newton-meter on a known-length beam, for bringing the dynamometer back to the horizontal, the engine torque is measured.

In this study the intake charge temperature was increased up to 115 ^{0}C, which helps the fuel to overcome its activation energy and improves the pre-ignition chemical reactions. Altering the coolant temperature at the 40 to 70 ^{0}C, HCCI-DI combustion showed better results at 50 ^{0}C. Therefore, coolant temperature was maintained 50 ^{0}C throughout all the tests.

Engine tests were carried out at the operating conditions shown in Table 2, trying to modify every one of the main parameters affecting the oxidation kinetics of any fuel, such as the engine speed, injection timing and the charge composition (quantified by the EGR percentage). All these parameter combinations provide different levels of pressure and temperature in the cylinder. As it can be observed in Table 2, HCCI conditions were achieved by an early start of injection (SOI) diesel fuel, which promote the auto-ignition of gasoline premixed fuel due to heat releases by diesel fuel before HCCI combustion of premixed fuel. Having reached HCCI combustion, emissions and other data were recorded.

Table 2:Test conditions

Speed (rpm)	1200-1700
Intake charge temperature (^{0}C)	110-115
Coolant temperature (^{0}C)	50
EGR rate (based on mass flow rate of intake air)	0-15%
Injection timing	35 BTDC
Premixed ratio (r_p)	0-1

Table 3: Fuel specifications [19].

Fuel type	Gasoline	Diesel fuel
MON	87	-
Cetane number	-	54
Higher Heating Value (kJ/kg)	47300	46100
Lower Heating Value (kJ/kg)	44000	43200
Heat of vaporization (kJ/kg), at 1 atm, 25 ^{0}C)	305	270
Density (kg/m^3)	720	780
$(A/F)_S$	14.6	14.5

3. Results

3.1. *Soot emission*

Fig. 2 shows the effects of EGR and engine speed on soot emission of dual fuel HCCI engine. As it can be seen, for any EGR rates, soot emission increases by increasing the engine speed due to reduction of mixture homogeneity and incomplete combustion. Also, as the engine speed is raised, due to insufficient time for re-burning the soot, which is produced in diesel fuel combustion process, during the HCCI combustion of premixed fuel (gasoline), soot emission increases according to Fig. 2.

In these experiments due to usage of diesel fuel as the pilot fuel, scrutiny of the production of soot emission in dual fuel HCCI engine is substantial. Soot emission in dual fuel HCCI engine is produced in the first combustion step (diesel fuel combustion), and then some portion of it is burned in the HCCI combustion step of gasoline premixed fuel. The measured soot emission in the exhaust is a part of produced solid carbon in the combustion process of diesel fuel which cannot be burned in HCCI combustion of premixed fuel.

The comparison of soot emission between with EGR and without EGR in Fig. 2 shows that, at the presence of the EGR, soot emission increases due to reduction of inlet air and its oxygen which create more rich points in the cylinder mixture.

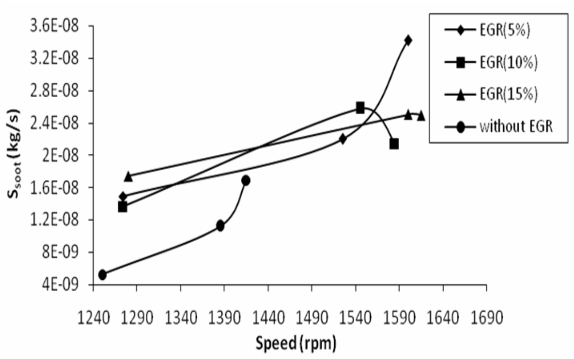

Figure 2: effects of EGR and engine speed on soot emission of dual fuel HCCI engine

3.2. *CO emissions*

Variation of CO emission of dual fuel HCCI engine with equivalence ratio and engine speed for different EGR rates are shown in Figure 3-6.

CO emissions variations as a function of equivalent ratio and engine speed for 5 and 10 percentages of EGR are shown in Figures 3 and 4, respectively. According to these Figures, by increasing the engine speed, there is insufficient time for formation a completely homogenous mixture, therefore CO emission increases at first due to incomplete combustion. However, gradual increase in equivalation ratio as the engine speed rises, CO emissions decrease due to high reactivity created by producing more radicals (as OH) at higher equivalence ratio.

In Fig. 5, it is observed that for 15% EGR despite the rise in engine speed, CO emission decreases because of increase the equivalence ratio which raises the reactivity.

CO emissions for without EGR is shown in Fig. 6, in which it is observed that in high engine speed, regarding to the decrease in equivalent ratio that reduces the reactivity, CO emission increases.

Moreover, in general, CO formation in a HCCI engine can be explained as follows:

Chemical kinetics is essential to the formation and consumption of CO, and the equivalence ratio is a crucial parameter of CO emission. Also, overall reactivity is the key phenomenon in at HCCI engine for explains most of the results. This implies that the emissions are not independent of the auto-ignition timing. Furthermore, a certain minimum equivalence ratio is need in order for the system to have enough energy to convert CO into CO_2. For any other cases, however, a higher equivalence ratio will only increase the CO in the emission.

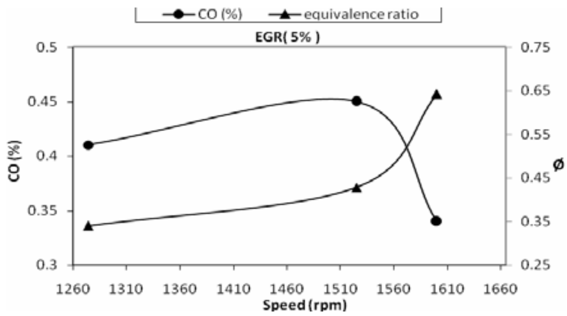

Figure 3: Variation of CO emission with equivalence ratio and engine speed at 5% EGR

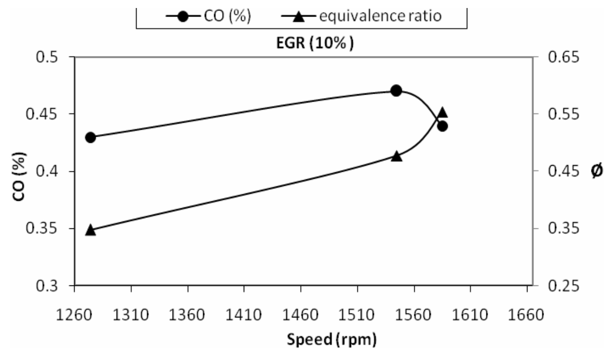

Figure 4: Variation of CO emission with equivalence ratio and engine speed at 10% EGR

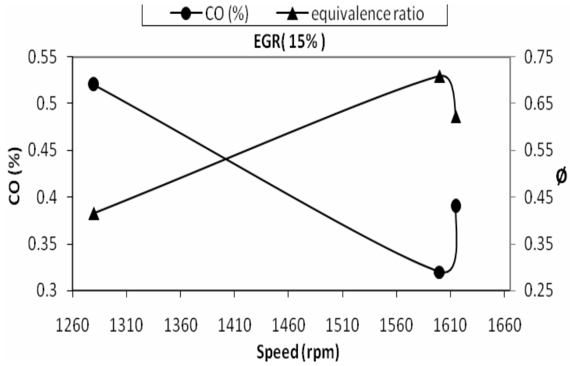

Figure 5: Variation of CO emission with equivalence ratio and engine speed at 15% EGR

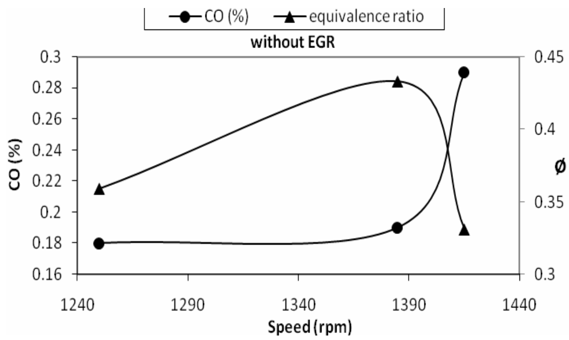

Figure 6: Variation of CO emission with equivalence ratio and engine speed for without EGR

3.3. *Effects of EGR and equivalence ratio on soot and CO emissions and operating range of dual fuel HCCI engine*

With scrutiny and analysis of CO and soot emissions of dual fuel HCCI engine in Figures 2-6, the general results can be explained as follow:

In a HCCI engine, a higher overall reactivity would be expressed by a decreasing ignition delay. As the OH radicals increases, combustion delay decreases which results in rise in overall reactivity. Generally, the effect of the chemical species in EGR played a very important role in influencing the amount of OH radicals that are present in the cylinder. Since, at higher equivalence ratios more OH radicals are formed, the effect of chemical species of EGR in the producing of OH radicals is negligible at higher equivalence ratios. Accordingly, the main effect of EGR at high equivalence ratios is dilution of in-cylinder mixture and reduction of maximum combustion temperature. Decrease in maximum combustion temperature, results in knock to occur in higher engine speeds and equivalent ratios. Therefore, EGR can extend the operating range of HCCI engine to higher speeds and equivalence ratios. This can be noticed in the Figures 2-6. It can explain why the engine operating range is limited to lower engine speeds and equivalence ratios with no EGR.

As could be seen in Fig. 2, addition of EGR leads to decrease the inlet air and its oxygen, which create rich points in the in-cylinder mixture and results in increase the soot emission. Also, as it can be observed in Fig. 3-6, CO emission decreases with increasing the equivalent ratio due to formation of more OH radicals which increase the overall reactivity.

4. Conclusions

In this study, the effects of EGR and equivalence ratios on CO and soot emissions of dual fuel HCCI engine were investigated. Results can be summarized as:

1) Engine speed rise for any EGR rate results in increase the CO and soot emissions due to reduction of mixture homogeneity and incomplete combustion.

2) EGR rise increases the soot emission due to decreases the inlet air and its oxygen, which create rich points in the cylinder.

3) As the equivalence ratio increases CO emission decreases due to formation of more OH radicals in the cylinder and increasing the overall reactivity.

4) Addition of EGR can extend the operating range of dual fuel HCCI engine to higher engine speeds and equivalence ratios due to dilution effect and reduction of maximum combustion temperature.

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