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Numerical Study of the Effects of Exhaust Gas Recirculation on Combustion Performance of a Homogeneous Charge Compression Ignition Engine

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ABSTRACT

Homogeneous Charge Compression Ignition (HCCI) engine offers several advantages like, high thermal efficiency, lower emission, fuel flexibility etc.; however successful implementation of this new engine technology is mainly challenged by difficulties in controlling start of autoignition, engine knock, emission of hydrocarbon (HC) and carbon monoxide (CO). Though, Exhaust gas recirculation (EGR) is mainly employed in conventional engine for NOx emission reduction, however, in HCCI engine EGR could be an effective method for controlling combustion timing, and reducing knock at high load while maintaining lower level of NOx emission. In this study, effects of EGR on the combustion and emission performance of a single cylinder four-stroke HCCI engine is investigated by using ANSYS Forte software. A sector with periodic boundary conditions is considered as the computational domain instead of using the whole geometry of a single-cylinder HCCI engine. Simulations are carried out at different EGR percentage varying from 0% to 30% by mass. Results show that, combustion duration become much shorter while apparent heat release rate (ROHR) is getting higher with increasing the EGR percentage. Compared to HCCI engine combustion without using EGR (i.e. 0% EGR), emission of NOx is reduced to 97.2% for addition of 10% EGR, 98.5% for 20% EGR and 90.4% for 30% EGR. It is found that, combustion timing can be controlled by adjusting the mass percentage of exhaust gas recirculation while maintaining very low level of NOx emissions with a slight increase in emission of CO.

Keywords: Homogeneous Charge Compression Ignition engine, Exhaust gas recirculation, Sector mesh, Autoignition, Combustion performance.

1. Introduction

Internal combustion (IC) engines are still dominating the transportation sector though there are wide range of applications of IC engines. Due to finite sources of fossil fuel, ever increasing energy demand and evolving emissions legislation; automobile manufacturers are under severe pressure to develop alternative forms of engine operation in order to improve the fuel economy, reduce the emissions while maintaining higher engine efficiency. In recent years, extensive research on Homogeneous Charge Compression Ignition (HCCI) engine is going on as one of the viable solutions to meet the stringent emission regulations and the demand for next generation highly efficient engine vehicles [1-4]. Homogeneous charge compression ignition (HCCI) is an internal combustion process in which the fuel and oxidizers (typically the air) are mixed homogenously before the start of combustion (SOC). In this type of engine, near the end of compression stroke, auto-ignition from multiple locations of the homogeneous air-fuel mixture take place as a result of rise in temperature; followed by a combustion process that is significantly faster than either spark-ignition (SI) or compression-ignition (CI) engine combustion, thereby releasing parallel energy during the entire combustion zone. HCCI engine offers several advantages like, high thermal efficiency, lower NOx and particulate matter (PM) emission, fuel flexibility etc. [5-6]. However, successful implementation of this new engine technology is challenged by difficulties in controlling start of autoignition, combustion phasing, cold start, operation range, engine knock and emission of hydrocarbon (HC) and carbon monoxide (CO) [7-8]. To overcome these challenges, extensive researches are carried out over the last few decades. High combustion efficiency and low CO emission was achieved in an experimental investigation of operating conditions in a natural gas HCCI engine by Jun and Iida [9]. Numerical investigation on the effects of equivalence ratio and intake temperature on a natural gas HCCI engine was carried out by Jamsran et al. [10]. At low to medium loads, HCCI combustion generates comparatively higher HC and CO emissions as well as high NOx at high loads. The autoignition timing or start of combustion in HCCI engines is determined by the reactivity of the mixture, which can be changed by modification of fuel, fuel blending or exhaust gas recirculation (EGR) through intake port of the engine. EGR is a promising technology for HCCI engine as it has the potential to delay the auto-ignition timing by affecting chemical reaction rate which led to reduced heat release rate, and to reduce NOx emission. Valentino et al. [11] investigated the effect of EGR on ignition delay and the exhaust emissions. According to their report, higher rate of EGR reduces combustion noise, NOx emissions, and increases the smoke emissions by increasing ignition delay and lowering pressure rise rate. In experiments on HCCI engines by other researchers, reduction in NOx emission up to 95% have been achieved [12-13]. Combustion efficiency found to increase remarkably by EGR in HCCI engine operation at low load condition [14]. The numerical studies on the effects of EGR on HCCI engines performance are very limited, though many experimental investigations are available in the literature. Therefore,

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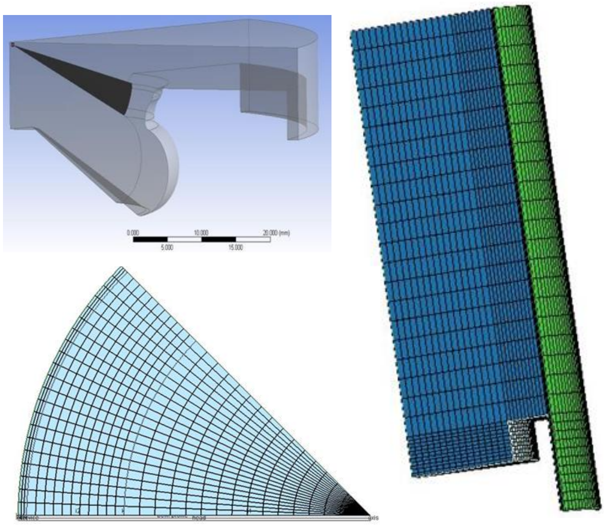
this study attempts to bridge this gap by performing numerical investigations on the effects of different rate of EGR varying from 0% to 30% by mass on the combustion and emission performance of a natural gas fueled four-stroke single cylinder HCCI engine.

2. Computational Approach

A commercially available software ANSYS Forte incorporated with highly efficient advanced chemistry solver module CHEMKIN is used to simulate the HCCI Engine operation. This software involves the solution of full Reynolds-averaged Navier–Stokes (RANS) equations. Model transport equations of mass, momentum, and energy conservation laws are formulated for the compressible, gas-phase flows, and represent the turbulent nature of the flow. Re-Normalization Group (RNG) k-ε model is employed as the turbulence model to describe the flow field. A sector of 45^{o} angle is considered as computational domain and for mesh generation (Fig.1). Here, periodic boundary conditions are applied at the periodic faces of the sector. The key advantage of using sector mesh is that it saves the computational time and cost compared to using the whole geometry of the engine. Engine specifications are given in Table-1. To accurately model the combustion event of natural gas, thermodynamic properties and chemical reaction mechanisms of natural gas are added in the CFD code. Detailed chemical kinetics of natural gas include 39 gas phase species and 268 elementary reactions.

Fig.1 A 45^{o} sector mesh for modeling HCCI engine.



The percentage of exhaust gas recirculation (EGR) is calculated by the following:

$$\mathrm{EGR}(\%) = \frac{m_{EGR}}{m_a + m_f}$$

Here,

m_a = Mass of air

m_f = Mass of fuel

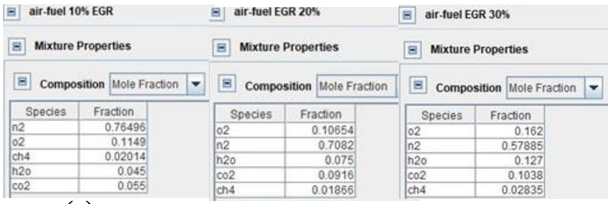
m_{EGR}= Mass of EGR

Table 1 Engine Specifications

No. of cylinders	1
Bore	13.97 cm
Stroke	15.70 cm
Connecting Rod Length	30.48 cm
Compression Ratio	16.168
Engine Speed	1500 rpm
Strokes Per Engine Cycle	4
Sector Angle	45^{o}
Squish	0.56 cm

2.1 Initial Condition

In the initial condition, the composition of the air-fuel and EGR mixture was added for different percentage of EGR. For 10-30% EGR, the mole fractions of air-fuel and EGR mixture are:



air-fuel 10% EGR — Mixture Properties — Composition: Mole Fraction

Species	Fraction
n2	0.76496
o2	0.1149
ch4	0.02014
h2o	0.045
co2	0.055

air-fuel EGR 20% — Mixture Properties — Composition: Mole Fraction

Species	Fraction
o2	0.10654
n2	0.7082
h2o	0.075
co2	0.0916
ch4	0.01866

air-fuel EGR 30% — Mixture Properties — Composition: Mole Fraction

Species	Fraction
o2	0.162
n2	0.57885
h2o	0.127
co2	0.1038
ch4	0.02835

(a) (b) (c)

Fig.2 Mixture Composition for (a) 10% EGR, (b) 20% EGR, (c) 30% EGR,

2.2 Boundary Condition

In order to capture wall boundary layer effects in head, liner and piston; Law of the Wall model is considered.

Table 2 Boundary Conditions

Boundary	Wall model	Temperature (K)
Piston	Law of the wall	500
Head	Law of the wall	470
Liner	Law of the wall	420

3. Results & Discussion

3.1 Effects of different percentage of EGR on combustion performance

The influences of EGR on in-cylinder pressure, rate of heat release, and combustion duration are elucidated in Fig.3, Fig.4, and Fig.5.

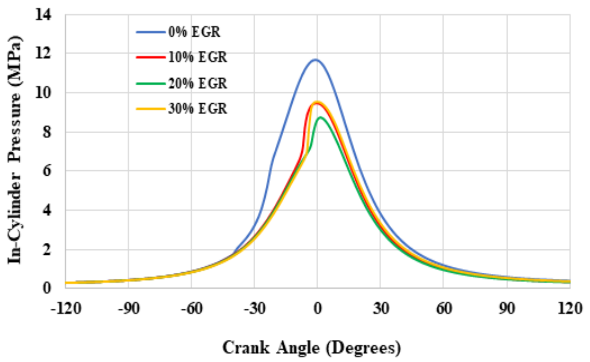


Fig.3 In-cylinder pressure history with different EGR rate.

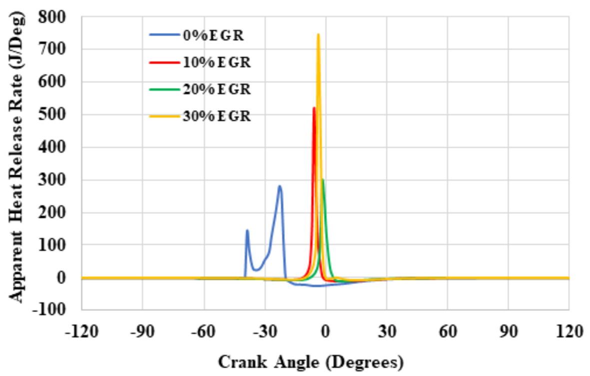


Fig.4 Apparent Heat Release Rate with different EGR rate.

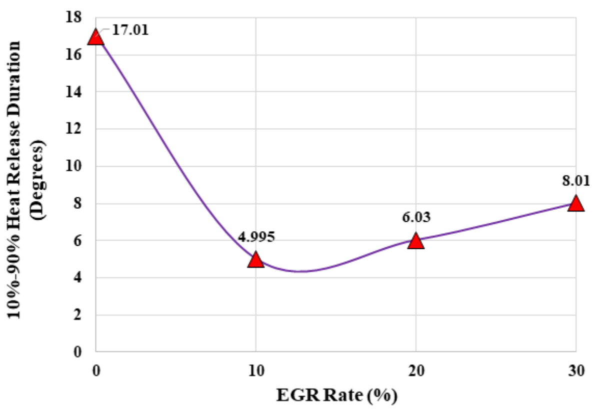


Fig.5 Effect of EGR rate on combustion duration.

It is evident from Fig.3 that the addition of exhaust gas to air-fuel mixture significantly reduces the rate of pressure rise and peak in-cylinder pressure. This lower pressure rises as well as lower combustion temperature inside the combustion chamber suppress the tendency to engine knock which is inherent problem of HCCI engine operation at medium to high load. From Fig.4, it can be observed that the auto-ignition of fuel-air mixture without EGR occurs at near 40^0 before TDC (top dead center; here, 0^0 crank angle represents TDC). Whereas for mixture with 10% EGR, auto-ignition occurs at near 10^0 before TDC. This evidence indicates that the start of combustion (i.e. combustion timing) in HCCI engine is much delayed due to the addition of EGR. It is well known that the primary constituents of exhaust gas from the engine are CO_2 and H_2O; therefore, addition of these gases to air-fuel mixture remarkably dilutes the overall mixture strength and hence, reduces the mixture reactivity. This weak mixture with reduced reactivity takes much longer time to get ready for auto-ignition which is clearly demonstrated in Fig.4. However, though EGR delays the start of combustion but mixture with EGR burns rapidly as total duration of heat release due to combustion become much shorter. Fig.5 depicts that the duration of 10%-90% heat release, which is often termed as the main combustion duration, is notably reduced for engine operation with EGR compared to that of the mixture without EGR. This might be attributed to the fact that with EGR, combustion take place near the end or during the last part of the compression stroke (i.e. near TDC) when temperature inside the combustion chamber is higher compared to combustion of mixture without EGR which takes place near 40^0 before TDC. As a consequence, relatively higher temperature leads to instantaneous burning of the fuel-air mixture with EGR. The shorter combustion duration with EGR results in lower heat loss to cylinder wall which will ultimately contributes to higher thermal efficiency.

3.2 Effects of different percentage of EGR on engine-out emissions

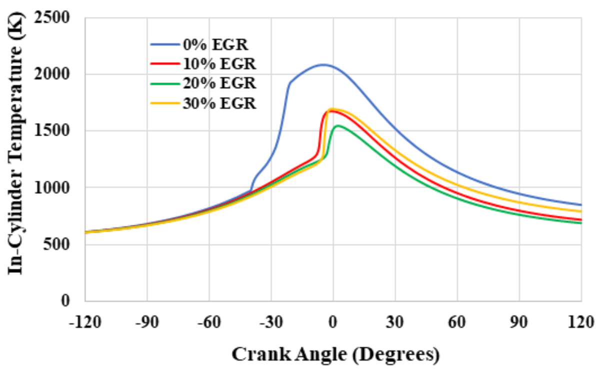


Fig.6 In-cylinder temperature with different EGR rate.

From Fig.7 and Fig.8, it can be seen that for 0% EGR, the exhaust emission of NOx (both NO and NO_2) is much higher but with the addition of EGR like, 10%, 20% and 30% by mass, NOx emission is reduced drastically. In comparison with 0% EGR, level of NOx is reduced to 97.2% for 10% EGR, 98.5% for 20% EGR and 90.4% for 30% EGR. According to Zeldovich mechanism- NOx formation is greatly influenced by temperature and oxygen concentration [15]. This mechanism is highly sensitive to temperature [16]. The combustion temperature could be reduced due to the high heat capacity of EGR and low heating value of lean mixtures (Fig.6), which results in lower emission NOx.

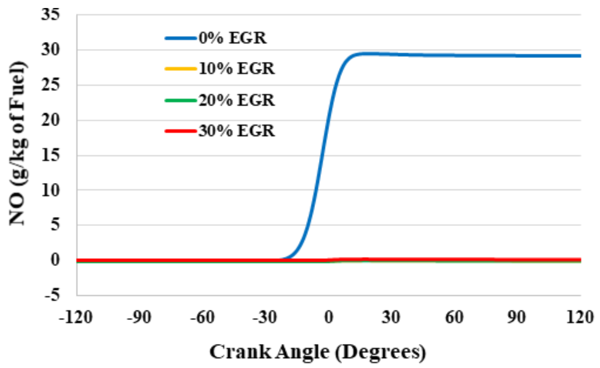


Fig.7 Effect of EGR rate on NO formation.

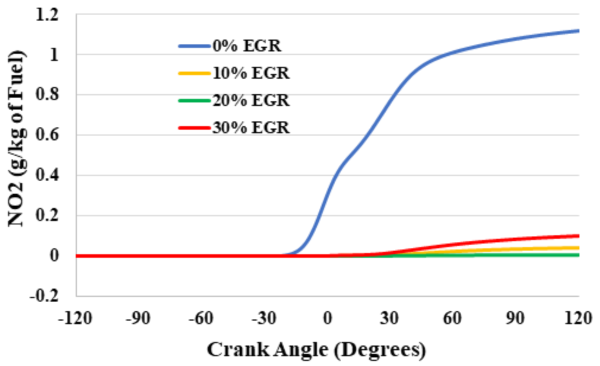


Fig.8 Effect of EGR rate on NO_2 formation.

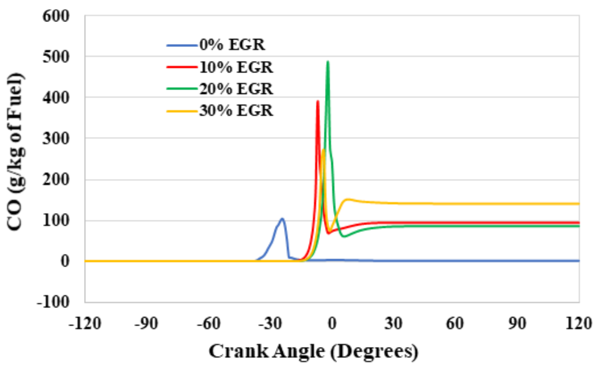


Fig.9 Effect of EGR rate on CO formation.

Addition of EGR has diluted the mixture as CO_2 present in exhaust gas is a non-combustible gas, which reduced the mixture reactivity as explained earlier and significantly lowers the combustion temperature as shown in Fig.6. Therefore, as a result of poor oxidation or incomplete combustion due to addition of CO_2 through EGR; NOx formation was suppressed while CO emissions increased remarkably as can be observed in Fig.9

4. Conclusions

In this study, numerical investigations of the influences of EGR on combustion characteristics in terms of in-cylinder pressure, temperature, rate of heat release, combustion duration and engine-out emission of NOx and CO level from a single cylinder HCCI engine fueled with natural gas, was investigated. EGR ratios is varied from 0% to 30% by mass. The major findings of this study could be summarized as follows:

- Addition of EGR could lower the in-cylinder pressure as well as combustion temperature which suppress the tendency to engine knock which is inherent problem of HCCI engine operation at medium to high load.
- Mixture reactivity is reduced due to adding CO_2 and H_2O to the fuel-air mixture through EGR, therefore, it takes much longer time for auto-ignition to occur. Thus, combustion timing in HCCI engine could be controlled by adjusting the mass percentage of exhaust gas recirculation.
- Combustion duration become much shorter with increasing the EGR percentage. This could lead to higher thermal efficiency by reducing heat loss to cylinder wall.
- Compared to HCCI engine combustion without using EGR (i.e. 0% EGR), up to 98.5% reduction in NOx emissions is achieved with a slight increase in CO emission.

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