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Investigation of performance and emission characteristic of a RCCI Engine fueled by mixture of Diesel and syngas derived from biomass gasification

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ABSTRACT: Recently, low-temperature combustion methods have become very popular in the field of combustion. Reactivity controlled compression ignition is a novel combustion concept with its own advantages. The role of these engines in rectifying the disadvantages of other methods is inevitable. This paper studies the influence of using various types of syngas on combustion and emission characteristics of syngas/diesel reactivity controlled compression ignition engine using Converge CFD. Four types of syngas (ideal syngas composed of solely hydrogen and carbon monoxide, two different types of syngases produced by gasifiers and pure hydrogen) are selected for comparison. Results showed the possibility of using various forms of syngases as low reactivity fuel. Using these kinds of syngases compared with ideal one results in fewer nitrogen oxides at the expense of more soot and it gets worse by increasing the fraction of syngas in premixed air. It shouldn't be ignored, due to the presence of nitrogen in some types, the engine may suffer from weak combustion and sometimes misfire at low loads as well. Using pure hydrogen, despite its advantages as the main part of syngas, in high quantities, notwithstanding the significant reduction of soot, causes the increase of nitrogen oxides and pressure rise rate amounts which are not desirable.

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1. INTRODUCTION

Nowadays, highly premixed compression ignition strategies have been offered by many researchers to decrease the heterogeneous combustion of fuels. Most of these strategies classified into the Low-Temperature Combustion (LTC) category [1]. The LTC combustion strategy includes Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI) engines. In contrast with HCCI and PCCI, having control over the combustion phasing is an achievement of the RCCI strategy to reach high efficiency.

Kokjohn et al. [2, 3], showed that a high level of control over combustion could be achieved by the use of two fuels with different reactivity and blending them inside the cylinder. In their approach, named reactivity controlled compression ignition, a low reactivity fuel (i.e. gasoline) is premixed with air before entering the combustion chamber and a second fuel which has higher reactivity (i.e. diesel) is directly injected through injectors. Combustion phasing is controlled by the ratio of the two fuels and combustion duration is controlled by in-cylinder stratification of ignition delay.

In recent years, a substantial amount of attention has been devoted to syngas as a low reactivity fuel. Due to various production techniques, various compositions of syngas are available. It is mainly contained of hydrogen (H_2), carbon monoxide (CO), some methane (CH_4), carbon dioxide (CO_2) and sometimes a large amount of nitrogen (N_2) or steam (H_2O). Chuahy et al. [4] used an RCCI engine to investigate the combustion of reformed fuel (containing CO and H_2). The results of this study showed that reformed fuel RCCI combustion is conceivable over a wide range of H_2/CO ratios. They also indicated replacing CO with H2 resulted in a more reactive charge, decreased the combustion duration, and suppressed low-temperature heat release.

Reviewing the literature, it can be observed that there has been no research in which the actual syngas obtained from various methods of reforming or gasification, is used as the second fuel with low reactivity in RCCI engines to assess the conclusions. Most of the researchers assume just the first two species (H_2 and CO) and use ideal (simulated) syngas instead of the actual ones by neglecting the other species. The present study is conducted to numerically evaluate the potential of using various types of syngases and their impacts on combustion and emission characteristics in a syngas-diesel RCCI engine using computational fluid dynamics modeling. Two types of syngas accompanied with pure hydrogen are selected for comparison with the ideal syngas comprised solely of hydrogen and carbon monoxide. For all cases, a

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premixed substitution ratio sweep at constant fuel energy is utilized to appraise their effects on the performance and emissions characteristics of the engine.

2. METHODOLOGY

The engine used throughout this study is a Caterpillar 3401 Single Cylinder Oil Test Engine (SCOTE). The engine has a bore of 137.2 mm and a displacement of 2.44 l and is typical of a heavy-duty size-class diesel engine [4]. The combustion computational modeling employed for the simulation of this study is performed by Converge version 2.3.5. A detailed list of the sub-models used in Converge is shown in Table 1. Table 2 shows a summary of the test conditions for simulations as well.

The direct-injected fuel's physical and chemical properties were specified by Tetradecane ($C_{14}H_{30}$) and n-heptane respectively. The results were obtained using a reduced multi-fuel mechanism with 178 species and 758 reactions developed by Ren [5]. Closed-Cycle calculations on sector grids that have periodic boundaries were performed. Since the direct injector has seven evenly holes, the geometry of a sector with 51.42 degrees was created. An equivalence ratio of 0.43 was chosen for diesel-syngas RCCI operation with substitutions from 20% to 60% by energy.

3. RESULTS AND DISCUSSIONS

Actual Syngases, as well as a mixture of H_2 and CO, seem to be a promising candidate for low reactivity fuel in RCCI engines. Thus, in this section, the same tests similar to the validation part have been conducted with two different types of syngases obtained through gasification processes [6]. For more assessment, these tests have been conducted with pure hydrogen as well. These fuels and their compositions selected for comparison with the simulated syngas which is consist of only H_2 and CO are listed in Table 3.

Fig. 1 illustrates the cylinder pressure and heat release rate over a range of syngas substitution quantities for all fuel cases. Fig. 2 indicates the number of emissions for all scenarios.

Table 1. Sub-models used in CONVERGE simulations

Physical Phenomenon	Model
Spray Breakup	KH-RT Instability
Vaporization	Frossling Correlation
Turbulence	RNG k-ε
Droplet Collision	No Time Counter (NTC)
Droplet drag	Taylor Analogy Breakup (TAB)
Wall film formation	O'Rourkes Model
Combustion	SAGE

Table 2. Engine operating conditions

Parameter	Diesel/Syngas
Engine Speed [rpm]	1300
Start of Injection [° bTDC]	10
Substitution Ratio [% energy]	20%, 40%, 60%
Fuel Energy [J/cycle]	5100

Table 3. Low reactivity fuel components (all units are in vol. %) 34

	Fuel I Ideal Syngas	Fuel II Actual Syngas	Fuel III Actual Syngas	Fuel IV Hydrogen
H_2	50	5.10	38.10	100
CO	50	13.40	28.10	-
CH_4	-	1.80	8.60	-
CO_2	-	22.00	22.20	-
N_2	-	57.70	-	-
C_2H_4	-	-	3.00	-

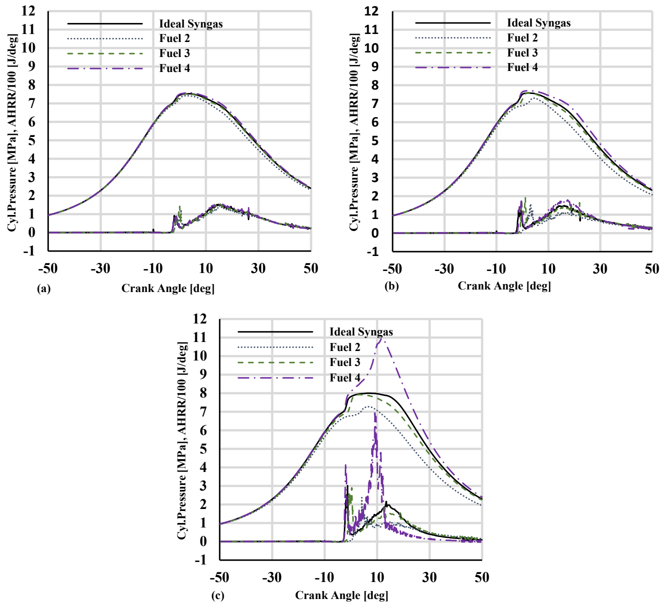

Fig. 1. Cylinder pressure and heat release rate for (a) syngas = 20%, (b) syngas = 40% and (c) syngas = 60%

As it was expected, substituting part of diesel with syngas in premixed form causes the soot reduction due to better mixing and reduction of local rich areas as well. Compared to the ideal one, the other two types of actual syngases cause a less reduction in soot emission. This is due to the existence of other species in syngas like carbon dioxide and nitrogen which decrease the oxygen amount in premixed air. This lack of oxygen prevents the fuels from the complete burning and is the reason for lower volumetric efficiencies. Compared to these reasons, the effect of the presence of other combustible species like CH_4 and C_2H_4 in soot formation shouldn't be ignored. Generally, the effect of premixing is dominant compared to the lack of oxygen. However, it is not true for fuel II in 60% substitution case.

On the other hand, due to the reduction of local maximum temperature during the combustion process, NOx formation decreases. Since nitrogen occupies the majority of syngas volume in fuel II, the maximum pressure for this fuel in all scenarios is lower than the other three ones. In this regard,

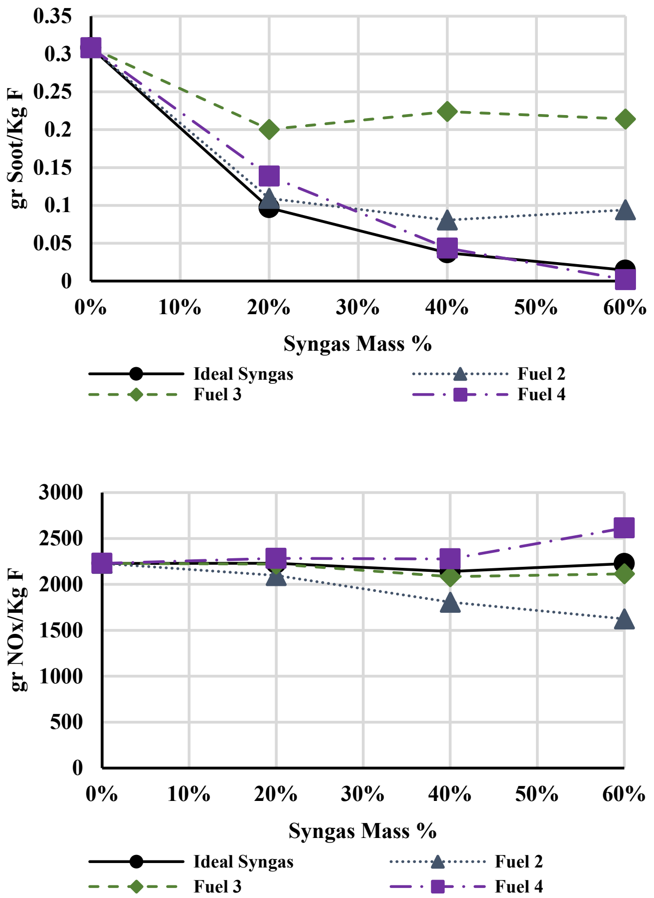

Fig. 2. The trend of emissions (a) Soot, (b) NOx

NOx in Fuel II has the lowest amount among the other fuels. Conditions operating with fuel II lead to a steeper decrease in NOx emissions due to the decreased stratification. Decreased stratification leads to NOx emission reduction by both reducing local equivalence ratio and flame temperature and retarding combustion phasing.

Fuel IV, Due to its higher flame speed, has a congruent effect on temperature and combustion efficiency. The higher amount of NOx and lower amounts of soot are the results of this intrinsic feature. If the amount of hydrogen in either syngas or by the use of fuel IV passes a specified amount, an explosion in the combustion chamber will occur shortly after TDC. This matter can be easily realized in 60% substitution case for fuel IV. Accordingly, although fuels with more hydrogen are better candidates as low reactivity fuel because of their higher heating values which cause the volumetric efficiency remains nearly constant and their low soot emissions, high amounts of NOx and peak pressure rise rates are serious obstacles in use of these fuels.

4. CONCLUSIONS

A numerical analysis has been conducted to analyze the impact of syngas (obtained by gasification) compared to ideal syngas (contains carbon monoxide and hydrogen) on the performance and exhaust emissions characteristics of a syngas-diesel RCCI engine while the energy amount per cycle is constant. The major conclusions are as follows:

1) Peak pressure rise rate and max local temperatures increase significantly with increasing the amount of H_2 in fuel. More NO_x while less soot, are obtained for this reason. However, a hydrogen-rich mixture is favorable for boosting combustion efficiency.
2) The presence of N2 in syngas composition forces the temperatures to be decreased. Thus, less NOx is achieved by the fuels with nitrogen in their composition.
3) It is expected that the engine may suffer from achieving a stable state at low loads using fuel II due to very low volumetric and thermal efficiencies.
4) The results indicate that the syngas with a low amount of nitrogen and a sufficient amount of hydrogen could be a promising candidate for application as the low reactivity fuel in RCCI engines.

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