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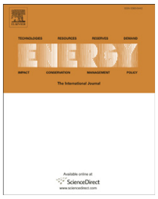

Fuelling of spark ignition and homogenous charge compression ignition engines with low calorific value producer gas

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ABSTRACT

The present paper summarizes results of experimental trails with the SI and HCCI engine fuelling with a producer gas substitute. Both engines are single cylinder units with similar displacement volume. In its original version, the HCCI engine used to be a three cylinder CI engine. Two of those cylinders were disabled when the engine was modified for the HCCI operation. The SI engine used in this was a component of commercially available generator. The engine original intake manifold and ignition system were rebuild for the purpose of this study. Engines were fuelled with the producer gas substitute that simulated real producer gas composition. The SI engine was charged with a stoichiometric air/fuel mixture, while the HCCI engine with a lean air/fuel mixture with equivalence ratio of 0.5. The main control variable in the SI engine operation was the spark timing. The initial air preheat temperature was the equivalent control variable in the HCCI engine trials. This paper reports on both engines indicated performance and combustion phasing parameters that were derived based on in-cylinder, cycle resolved pressure measurements.

1. Introduction

1.1. Biomass gasification and producer gas properties

Producer gas (PG) is a product of biomass (such as wood saw dust, chips or pellets) conversion to mostly gaseous products in reactors commonly referred to as gasifiers. The producer gas is characterized by its low calorific value (LCV) and it can be used as a fuel in internal combustion engines and in process heat generation (boilers). The LCV of producer gas varies with its composition that is heavily dependent on the gasification process. The main variable that determines the producer gas composition is the relative air flow direction. Gasifiers with a parallel flow of biomass feedstock and air impose higher technological requirements on the biomass feedstock compare to those with a counter-flow arrangement of biomass and air feeds. However, the producer gas from parallel flow gasifiers contains less undesired liquid residuals, such as tar and water. For application, where small and medium power outputs are needed, the most advanced technologies offer gasifiers with a parallel downdraft biomass and air delivery [8–10].

The major components of producer gas are nitrogen (N_2), carbon dioxide (CO_2), hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and water (H_2O). Occasionally minute amounts of higher hydrocarbons such as ethane (C_2H_6) can be traced. In this mixture CO, H_2, and CH_4 are combustibles, while other components are inert fractions that nevertheless will affect the subsequent combustion of producer gas. At the exit from a gasifier the producer gas is usually at elevated, 500 °C–800 °C, than ambient temperature. Therefore, the producer gas energy content exceeds its lower caloric heating value, by the enthalpy change between these temperatures. It follows that efficiency of the gasification process can be asset based on hot or cooled gasification products. In both methods, the energy content of producer gas is referenced with respect to the biomass energy input. The process efficiency based on hot products can as high as 90%, while the cold products efficiencies are in 40–70% range. It is interesting to note the high enthalpy PG flow, before it is delivered to a combustion engine or burner, could be diverted back to the gasifier and used for the air stream preheating to assist with the gasification process. Concurrently, lowering of the PG temperature should increase the engine volumetric efficiency.

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Mole fractions of combustible components in a dry producer gas vary and depend on the gasification process operational variables; 15–40% for CO, 10–35% for H_2, and 2–5% for CH_4. Similarly the producer gas LCV can range from 4 to 10 MJ/Nm^3 [1]. Literature reporting on producer gas properties and the gasification process efficiencies is extensive [19–24].

The present work reports on the performance of two reciprocating piston internal combustion engines, both fuelled with a producer gas substitute, but with two very different combustion processes. One engine was a typical small displacement volume spark-ignited (SI) engine, while the second was a small displacement volume compression ignition engine converted to operate as a homogenous charge compression ignition (HCCI) engine. The substitute gas compositions (a pressurized gas cylinder mixture) used if SI and HCCI engines are shown in Table 1.

The LCV of producer gas substitute mixtures are also listed in Table 1. The SI and HCCI engine were charged with air/fuel mixtures of different equivalence ratio; the SI engine mixture equivalence ratio was $\phi = 1.0$, while the HCCI engine mixture was at $\phi = 0.5$. The heating value of air/fuel mixture at these equivalence ratios are listed in Table 1 under e_{dv}. The much lower equivalence ratio of the HCCI engine air/fuel mixture (in effect a very lean mixture as oppose to the stoichiometric mixture of the SI engine) is dictated by the nature of HCCI combustion mode, in which the premixed charge is ignited due to compression rather than by a spark ignition. Both producer gas substitutes were dry and did not contain any solid impurities.

1.2. *The potential offered by the LCV producer gas*

Producer gas that is obtained from biomass gasification can be utilized in various combustion technologies, such as power plant boilers, burners, internal combustion engines, and gas turbine combustors. The producer gas with high initial enthalpy can be used directly for fuelling burners in the power plant boilers. The internal combustion engine fuelling is different for it requires that the producer gas is cooled down first, not to compromise the engine volumetric efficiency. The high initial enthalpy can be used for the HCCI engine combustion air preheating allowing to use the raw producer gas that includes tars. By this way the system overall efficiency can be improved. In particular, fuelling of HCCI engines with the producer gas seems to be an attractive proposition because of its lower heating value. HCCI mode of combustion requires that an engine is charged with very lean mixtures and regular fuels need to be mixed with excessive amounts of air. Therefore, the LCV producer gas does not require as much dilution as it was previously demonstrated in Ref. [5]. The critical issue in all combustion applications of the producer gas is removal of undesirable solid particles, tars, alkali compounds, and nitrogen containing compounds. Condensation of tars, in particular, can result in deposits on engine's components (intake manifold, valves and piston crowns and cylinder walls) and in effect derating the engine operation and performance [2]. According to Insig et al. [3] the allowed limit of tar content for engine fuelling is 50–100 mg/Nm^3. Available literature includes reports on both, spark ignition (SI) and compression ignition (CI) engines being charged with the producer gas. However, those are mostly pilot or research set-ups, with expectation of a few commercial installations. In Europe SI engines fuelled with the producer gas are operated in Denmark (Harbøøre), Austria (Güssing), Switzerland (Spiez), and Finland (Kokemäki). Commercial installations of CI engines are offered by Mothermik in Germany. The producer gas is a poor compression ignition engine fuel and its application in CI engine requires that a pilot injection of high cetane number fuel is done, making this a dual fuel CI engine, with the potential to use a biodiesel fuel for the pilot injection [4].

Table 1
The substitute of producer gas properties.

Gas composition	SI engine	HCCI engine
CO, %	24.7	24.9
H_2, %	10.3	10.1
CH_4, %	2.1	2
CO_2, %	5.4	5.2
N_2, %	57.5	57.8
LHV, MJ/m$^3{}_n$	4.98	4.95
e_{dv}, MJ/m$^3{}_n$	2.35	1.55

2. Characteristic features of combustion process in internal combustion engines

2.1. *Combustion in spark ignition engines*

Spark ignition internal combustion engines are usually fuelled by stoichiometric air-fuel mixture. In some stationary engines the combustion process occurs for a range of lean mixtures. This results in a decrease of NOx emissions and increase of engine efficiency. In both cases, the mixing of fuel and air occurs in intake manifold and cylinders are supplied with a mixture of high homogeneity. Combustion normally proceeds in through the following subsequent phases; 1) ignition due to a spark discharge, 2) early (laminar) flame development and transition to turbulent flame, 3) turbulent flame propagation, 4) flame quenching. The ignition energy required to initiate burn of a stoichiometric gasoline/air mixture is about 0.2 mJ. That requirement is different for the producer gas/air mixture and it heavily depends on content of hydrogen and carbon monoxide in the gas. The minimum ignition energy for the stoichiometric hydrogen/air mixture is about 0.02 mJ, while for the carbon monoxide/air mixture it is much higher, about 0.3 mJ [11,12]. The combined mole fraction of combustible components in producer gas is usually less than 40% and the high ignition energy system is needed when fuelling engines with the producer gas. The regular SI engine ignition system produces about 30–50 mJ of energy [7,13]. Depending on local conditions in the spark plug vicinity (temperature, pressure, humidity) the duration of spark discharge usually exceeds 0.5 ms [7,13]. The small region of plasma that is created initiates chain of chemical reactions in the neighboring fuel/air mixture and the propagating laminar flame is established. The early flame development period, is measured from the spark release time to the moment of 5% (or 10%) mixture mass being burned [7,14,17]. In some publication that period is referred to as an initiation time or start of combustion (SOC) phase [16,18]. The early flame development period lasts from 1 to 2 ms [7]. The flame in this period is laminar (and in transition to turbulent flame), and as such it is mostly affected by the local heat transfer conditions and mixture composition. The main combustion period, in which 10–90% (eventually 5–95%) of mixture mass is burned, is normally characterized by a turbulent fast propagating flame. The local flow conditions (turbulence intensity and scales) with underlying heat transfer conditions and mixture composition are major variables that determine duration of that period [15]. The SOC duration and the duration of the 90% burn period constitute the set of combustion phasing parameters. The laminar flame propagation speeds for the stoichiometric gasoline/air and gaseous hydrocarbons/air mixtures are not that different, 0.4 m/s (gasoline) and 0.38 m/s (methane). The notable exception is hydrogen, with 1.9 m/s laminar speed for the stoichiometric mixture with air [25–27]. The laminar flame speeds of the producer gas/air mixtures are much lower because of the large inert gases fraction (N_2 and CO_2). In addition the water vapor content affects the flame speed. The reported

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