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EGR control on operation of a tar tolerant HCCI engine with simulated syngas from biomass[☆]

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HIGHLIGHTS

- Novel methodology to directly use unscrubbed biomass syngas in piston engines.
- Demonstration of EGR as an efficient control parameter for HCCI engines operated with synthetic syngas.
- For syngas combustion, EGR has mainly a thermal effect rather than chemical kinetic effect.
- The study spans a large range of conditions and improve by 30% the IMEP.

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ABSTRACT

In combined heat and power plants operated with biomass syngas, the removal of condensible tars is a necessary but expensive step (up to one third of the installation and maintenance costs). This step is required because the syngas has to be cooled down to avoid knocking in the spark ignition engines traditionally used in such plants. To remove the tar condensation problem, we developed an alternative system based on an Homogeneous Charge Compression Ignition (HCCI) engine operated at intake temperatures above the tar dew point. To address the challenge of power derating of such engine setups, the current paper focuses on the application of Exhaust Gas Recirculation (EGR) as a control parameter that would indirectly allow the improvement of the engine performance. Based on a conservative estimate of tar dew points, HCCI combustion was studied at an intake temperature of 250 °C using synthetic biomass syngas and synthetic EGR on a mono-cylinder HCCI engine operated at 1000 RPM. The effects of charge dilution, thermal and kinetic damping due to the EGR gases were also analysed to understand their main effects. The use of EGR successfully increased the maximum achievable Indicated Mean Effective Pressure from 2.5 bar at EGR = 0% up to 3.3 bar at EGR = 25%, through damping the maximum pressure rise rate and allowing higher equivalence ratios.

1. Introduction

Through biomass gasification, a large range of biomass or wastes can be converted into gaseous fuels to be used in boilers or Combined Heat and Power (CHP) plants. The raw “producer gas” or “syngas” from biomass gasification is composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2), water vapor, tars and other trace gases and impurities. Tars are hydrocarbons heavier than benzene that are liquid or solid in normal conditions, but are vapors in raw hot syngas (about 500–700 °C) exiting from the gasifier. Since the conventional Spark Ignition (SI) engine requires intake charge temperatures to be well below 100 °C for knock free operation [1], the hot syngas needs to be cooled down. The cooling process, while improving the volumetric energy density of the syngas, results in the syngas being saturated with condensible impurities, i.e. tars. Thus, to avoid tar deposition on the vital internal parts of engines and prevent damages, tar filtration becomes necessary. The tars and their filtration, together, pose some of the biggest challenges faced by biomass gasification power plants based on the use of Internal Combustion Engine (ICE) or gas turbines [2].

A novel “tar tolerant” piston engine is being developed at the authors’ laboratory as an alternative to the complex and maintenance prone conventional tar destruction/purification processes [3,4]. The principle is based on operating the systems downstream of the gasifier

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at temperatures above the tar dew point, so as to avoid the condensation of tars. The tar dew point of syngas depends on the concentrations of constituent tar classes, especially of those which condense at the highest temperatures and at low concentrations. As a conservative estimate, a tar dew point temperature of 250 °C has been chosen for the current approach, based on the assumption of syngas containing 1 g/N m^3 of Class V tars [5]. Since, as mentioned previously, the SI engine cannot be operated at this temperature, the Homogeneous Charge Compression Ignition (HCCI) mode has been chosen instead due to its adaptability to operate at high intake temperatures [6].

Syngas as a fuel for HCCI engines has been investigated only recently [7–13]. The main theme explored in these works was the study of HCCI combustion in response to the unavoidable variations in the syngas composition, which occur due to uncontrollable factors in the gasification process. The effects of the main combustibles in the syngas were investigated and the ratio of fast burning H_2 to the slow burning CO was found to have a significant impact. However, these studies were carried out in a gasification scenario which assumed production of cooled and purified syngas. In contrast, the objective of the current authors is to develop a system capable of using tar loaded syngas directly in a piston engine. We performed a first comprehensive study in this regard, exploring the effects of the variations in the syngas composition, tars, moisture and operational parameters on HCCI combustion carried out at the high intake temperature of 250 °C [3]. It has been further explored through a 24-h run using real unscrubbed syngas from a gasifier demonstrating the capability of operating such system without stability issues [4].

This novel concept raises some challenges associated with this particular class of engines [6]. HCCI combustion is driven by chemical kinetics which in turn is highly dependent on the thermal conditions inside the combustion chamber:

1. The thermal conditions during charge compression are influenced by the intake conditions of temperature, pressure, charge turbulence along with thermal as well as species inhomogeneities within the compressed charge. Additionally, non-uniform cylinder wall temperatures, which are a result of the charge flow dynamics and thermal characteristics of previous cycles, also have a significant effect. The end result of these effects is poor combustion stability of current and subsequent cycles, as well as high sensitivity of the combustion phasing to the often uncontrollable operating conditions.
2. When the equivalence ratio increases, the autoignition process accelerates due to the larger availability of heat, resulting in an advanced combustion. This results in increased pressure ringing, indicated by high values of Maximum Pressure Rise Rate (MPRR), which can damage the engine and also result in decreased thermal efficiency. Thus, power output is limited by the maximum equivalence ratio, resulting in a power derating. This effect is even more pronounced in the current case due to the high intake temperatures which reduces the volumetric energy density.
3. Syngas composition undergoes uncontrollable changes in the course of the gasifier operation. Since the HCCI combustion is highly sensitive to fuel properties, it leads to control challenges. As observed in [3], a weak syngas composition (with lower LHV) may result in a significantly delayed combustion leading to high CO emissions, low combustion efficiency and low power. On the other hand, a stronger syngas composition may advance the combustion leading to higher pressure ringing, lower thermal efficiency and higher NO_x emissions.

The objective of this study is to explore Exhaust Gas Recirculation (EGR) as a control method to damp the heat release rate, thereby increasing the equivalence ratio and the achievable Indicated Mean Effective Pressure (IMEP). This method can also be used to effect the combustion phasing in response to the varying syngas composition or other operating conditions so as to stabilize the engine output.

The effects of EGR in HCCI engines have been explored in many works [14–16]. In a HCCI engine, the use of a higher equivalence ratio advances the combustion phasing, leading to an increase of MPRR and the appearance of knocking. The main EGR effect of interest is its ability to delay the HCCI auto-ignition driven combustion, and thus variations in the EGR rate can be used as a control. Additionally, since the IMEP is directly linked to the equivalence ratio, the use of such a control technique increases the possibility of achieving higher performance than would have been possible in the absence of any control.

It must be noted that a control system for a real application cannot be complete without an associated closed-loop strategy and hardware implementations, which modulates the controllable parameter, in this case the EGR rate. As an example, Olsson et al. discuss a closed-loop HCCI control system which uses real-time estimated crank angle where 50% of the fuel heat is released position as a feedback to control the combustion phasing, by changing the fuel composition consisting of two fuels, each with different combustion characteristics [17]. Such a closed-loop control setup was not developed or used in the following results. Also, the syngas and EGR were simulated to study EGR effects and thus effects of compositional variations, tars, moisture, etc of a real scenario were not studied in this paper but their effects were studied in previous works [3,4].

This paper presents a comprehensive study of the effects of EGR in terms of the dilution, thermal and chemical effects. It addresses a current lack of analysis in the literature for HCCI operation with hot and tar loaded syngas. The following section begins with a discussion on the experimental setup and procedures. Thereafter, specific experimental results are discussed where the influences of dilution are eliminated so as to isolate and analyse the thermal and chemical effects. Based on these studies, the effects of EGR on the overall experimental range is discussed.

2. Experimental setup and methodology

This section first presents the test bench and the experimental uncertainties. It then introduces the definition of EGR and its impact on the HCCI operation. Finally, it describes the characteristics of the syngas.

2.1. Test bench settings

The schematic of the experimental setup is shown in Fig. 1. The setup is similar to the one described in [3]. Except for air, which is supplied from a compressor, all other gases are supplied from bottles to create mixtures of air, syngas and EGR. EGR gases were composed of N_2, O_2, CO_2 and H_2O in proportions detailed in the next section. The water component of EGR was injected at the additives port before the mixing drum using a calibrated peristaltic pump. The overall flow rate was controlled so as to maintain a constant intake pressure and temperature of $p_{in} = 1.2$ bar at $T_{in} = 250\,°C$ respectively. An electric motor, controlled by a variable frequency drive controller, acted as a brake/motor for the test bench which maintained a constant 1000 RPM. This speed was selected to be able to explore a large range of EGR ratios with the current Mass Flow Controllers (MFCs).

The specifications of the air cooled mono-cylinder engine are mentioned in Table 1. This was originally a diesel engine with its volumetric compression ratio modified from 19.3 to the current optimal value of 12, based on Computational Fluid Dynamics (CFD) simulations where parameters such as ϕ, MPRR, CA50, IMEP and others were evaluated within the current context [18]. The piston combustion chamber was modified from a bowl shape to a flat design in order to minimise the heat losses by minimising the surface area. The crevices were minimised to reduce the amount of unburnt fuel.

The in-cylinder pressure was acquired by an AVL GH15D pressure sensor coupled to an AVL FlexIFEM Charge Amplifier (CAmp). The