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1 **A multiparameter investigation of Syngas/diesel Dual-Fuel Engine performance and**
2 **emissions with various syngas compositions**

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6 **Abstract**

7 Syngas, also known as producer gas or wood gas, is a gaseous biofuel produced by
8 gasification of biomass. It is mainly composed of hydrogen and carbon monoxide with a
9 smaller share of methane, all diluted by nitrogen and carbon dioxide. Despite having carbon
10 in its composition, since it is made from biomass, it is considered low to zero-carbon and
11 being so makes it one candidate for reducing carbon emissions of internal combustion
12 engines. This work focuses on the effect of different syngas compositions on the performance
13 and the exhaust emissions of compression ignition engine with decane pilot injection as a
14 diesel surrogate. Results showed that thermal efficiencies over 39% are possible with a
15 variety of syngas with less than 10% energy contribution of decane. NO_x and soot emissions
16 were generally lowered by increasing the syngas/decane ratio, whereas CO and Total HC
17 emissions increased. Additionally, relations between engine performance/emissions and
18 fundamental properties of varying Syngas compositions were established. Further
19 investigation on other combustion properties, such as stretch sensitivity of the syngas/air
20 flame, are needed in order to better predict optimum operability.

21 **Keywords:** Syngas-fueled compression engine, diesel pilot injection, Dual-Fuel, syngas
22 compositions, Performances, Emissions

23 **1 Introduction**

24 A considerable amount of pressure has been put on the energy sector to shift towards clean
25 and renewable energy. In fact, to achieve the goal set by more than 100 countries of net-zero
26 carbon emissions by 2050, all sectors of the economy will have to endure significant
27 change[1]. While it might appear to most that, the only solution to achieve this goal, is a
28 complete transition to a combustion-free energy sector, this might not be simple to
29 accomplish.

30 Given the context presented above the use of biofuels presents itself as an alternative that
31 would reduce global CO₂ emissions with more affordable costs and simpler technologies.
32 Syngas, also known as producer gas and wood gas, is a general classification given to
33 flammable mixtures produced by the gasification of biomass. Gasification is a process that
34 converts the molecules in the biomass (such as cellulose) to CO, H₂ and CO₂. It should not be
35 confused with biogas where the biomass is transformed mainly into CH₄ and CO₂ through
36 fermentation. As a waste-to-energy process, gasification competes with landfilling and
37 methanation, but the carbon footprint of the syngas scenario is higher than landfilling [2] and
38 can be in some case better than the biogas scenario [3]. The challenge when fueling an
39 internal combustion engine (ICE) with syngas is the inherent variability in composition that is
40 a result of several factors such as the biomass origin [4] and the gasification process [5].
41 Typical values for H₂, CO and CH₄ contents stay between 10-20%, 13-24% and 0-7% in
42 volume respectively[5,6]. Moreover, regarding dilution, air-fed gasifiers typically produce
43 syngas that contains from 45 to 60% N₂ content and 10-20% CO₂. If oxygen or steam
44 gasification is used, N₂ content can be close to zero but these methods tend to be more
45 expensive[6].

Nomenclature

SI	Spark Ignition	\dot{V}	Volumetric Flowrate
CI	Compression Ignition	\dot{m}	Mass Flowrate
HRR	Heat Release Rate	h	Heat Transfer Coefficient
η	Efficiency	LHV	Lower Heating Value
SOI	Start of Injection	P	Pressure
b	Cylinder Bore	T	Temperature
V_{cyl}	Displaced Volume	v	Piston linear speed
CAD	Crank Angle Degree	CAXX CAD	where XX % of the fuel is burned
IMEP	Indicated Mean Effective Pressure	IMEP _{cov}	Coefficient of IMEP variation
ATDC	After Top Dead Center	BTDC	Before Top Dead Center
MPRR	Maximum Pressure Rise Rate	LFS	Laminar Flame Speed
RPM	Revolutions Per Minute	THC	Total Hydrocarbons

46

47 Syngas can be used as fuel in ICE both in Spark Ignition (SI) [7,8] and Compression Ignition
48 (CI) Engine [9–14]. Studies in SI engine are mainly focused on the auto-ignition propensity of
49 the syngas. Sridhar et al. [7] showed that, due to the auto-ignition resistivity of syngas, it was
50 possible to increase the compression ratio of SI engine with minimum knock risk thus
51 improving the efficiency. Arunachalam and Olsen [8] studied the knock propensity as a
52 function of different syngas compositions. Their work is noticeable since it compares “real”
53 compositions containing all the main components of the syngas namely H₂, CO, CH₄, CO₂
54 and N₂. Regarding CI engines, Guo et al.[9] have investigated the effects of syngas energy
55 fraction, the reactive fuel injection timing and the load on emissions and efficiency for two
56 distinct simulated syngas compositions from air-fed gasifiers (48% N₂ and 13% CO₂
57 concentrations) and one oxygen-fed gasifier composition (6% N₂ only) in dual-fuel mode. The

58 effects of syngas substitution were a reduction in soot and NO_x emissions but higher CO
59 emissions for the two compositions with the highest N_2 content in syngas. Between these two
60 high-dilution compositions, the one with more CO and less H_2 produces more CO at the
61 exhaust and lower overall efficiencies. Some other studies used real syngas directly from a
62 gasifier. Rinaldini et al.[10] managed a maximum real syngas energy fraction of 60% at 50
63 N.m and 27% at 300 N.m of torque. Sharma and Kaushal[15] also tested real syngas from a
64 downdraft gasifier on a variable compression ratio CI engine. The result of increasing the
65 compression ratio from 12:1 to 18:1 was a reduction of CO and THC emissions with a
66 simultaneous increase in efficiency. Roy et al.[16] tested the effects of injection timing and
67 equivalence ratio on performance and emissions as a function of H_2 content in Syngas. Diesel
68 substitution levels of over 96 % under low or high H_2 content were achieved at an Indicated
69 Mean Effective Pressures (IMEP) of 14 bars but the highest H_2 content composition resulted
70 in a higher thermal efficiency. However, this also led to an increase in NO_x emissions.

71 The use of Syngas in a CI engine in dual-fuel mode has the advantage to have a flex-fuel
72 energy system, especially for off-grid stationary application. In dual-fuel mode, due to the
73 pilot injection of reactive fuel (as diesel fuel), there is the added complexity of the poorly
74 understood physicochemical interactions of the gaseous syngas combustion interactions with
75 the liquid pilot fuel spray. Currently, natural gas or methane dual-fuel operation are well
76 covered by the literature [17–21] but syngas less. Moreover, to correctly optimize dual-fuel
77 syngas CI engines, the effects of its composition should be well understood. The challenge,
78 addressed in the present paper, when studying the influence of syngas composition on dual-
79 fuel engine performance is not fed the engine with real syngas but to control the compositions
80 that are representative of what is possible to produce from gasification, as an input parameter
81 and, in parallel, identifying the impact of each gas component on performance and emission
82 parameters. The novel approach chosen for this study is to consider three compositions that

83 represent the typical production of three gasifier types: Fluidized Bed, Fixed-bed Updraft and
 84 Fixed-bed Downdraft (respectively indicated as Fluidbed, Updraft and Downdraft in
 85 following), detailed in Table 1, and originally defined by Bridgwater[5] as well as to keep a
 86 maximum syngas energy fraction(>60%). Indeed, the previous studies introduced above are
 87 mainly conducted with a unique syngas composition or are numerical studies [12–14,22]. As a
 88 new insight of syngas use in dual-fuel mode, the effect of syngas composition will be studied
 89 as well as the contribution of each component of the syngas experimentally on an engine test
 90 bench. It should be noted that the maximum laminar flame values for 3 Syngas compositions
 91 displayed in Table 1 have been determined previously[23–25].

92 **Table 1: Syngas Compositions.**

	H ₂ (% Vol)	CO (% Vol)	CO ₂ (% Vol)	CH ₄ (% Vol)	N ₂ (% Vol)	Stoichiometric Air/ Fuel ratio (mol/mol) (mass/mass)	LHV (MJ/m ³ of gas)	Maximum laminar flame speed at 298K and 1bar (cm/s)
Fluidbed	9	14	20	7	50	1.21 (1.25)	4.2	15.4
Updraft	11	24	9	3	53	1.12 (1.24)	4.4	30.7
Downdraft	17	21	13	1	48	1.00 (1.13)	4.8	36.7

93
 94 The global objective of this study is to identify what are the fundamental combustion and
 95 physical properties of syngas that determine engine performance and operating limits in dual-
 96 fuel mode. For that, the effects of the pilot fuel quantity and equivalence ratio of premixed
 97 syngas/air on engine performance and emissions are analyzed for each composition.
 98 Moreover, to highlight the contribution of CH₄ and CO₂ contents, an additional analysis is
 99 carried out with ternary mixtures of H₂/CO/N₂.

100 **2 Experimental Method**

101 In this section the engine characteristics, experimental method and the post-processing
102 method are described.

103 *2.1 Experimental Setup*

104 The experimental setup consists of a research PSA DW10 based engine test bench converted
105 to single-cylinder operation with 3 cylinders not fueled. The engine speed, driven by an
106 electric motor, is maintained at 1200 RPM. The engine speed for genset application is usually
107 1500 RPM. Unfortunately, it was not possible with our setup due to important vibrations of
108 the intake/exhaust pipes and bench. The engine characteristics are described in Table 2.

Table 2: Engine Characteristics.

Displaced Volume	499 cm ³
Bore	85 mm
Stroke	88 mm
Rod length	145 mm
Compression Ratio	17:1
Piston Bowl Type	“Mexican hat”
Firing TDC position	0 CAD
Intake Valve Opening	351 CAD ATDC
Intake Valve Closure	157 CAD BTDC
Exhaust Valve Opening	140 CAD ATDC
Exhaust Valve Closure	366 CAD ATDC
Oil and Coolant Temperature	85 °C
Max Brake Power (for the commercial multi-cylinder engine)	120 kW @ 3750 rpm
Max Torque (for the commercial multi-cylinder engine)	340 N.m @ 2000 rpm

110 In order to obtain the desired intake charge compositions a series of mass flow meters, as
 111 specified in Table 3, are used. The resulting uncertainty for the premixed syngas/air
 112 equivalence ratio, $\phi_{premixed}$ (eq. 1) of the intake charge is $\pm 2\%$. The mixing of the syngas/air
 113 charge is ensured by the intake plenum (visible in Fig. 1) which also enables to damper
 114 pressure oscillations at the intake port.

115

116

117

118

Table 3: Mass Flow Controllers.

Gas Type	Flowmeter / Controller	Full Scale	Uncertainty
Air	Emerson F025S	1100 NL/min	±0.5%
N ₂	Brooks 5851S	100 NL/min	±0.9%
CO	Brooks 5851S	100 NL/min	±0.9%
H ₂	SLA5850	50 NL/min	±1,0 %
CO ₂	SLA5850	37 NL/min	±1.0%
CH ₄	SLA5850	5 NL/min	±1.0%

120

121 The pilot injection is discharged by a Bosch CRI 2.2 six-holes common-rail injector operating
 122 at a reduced pressure of 200 bar to guarantee minimal injection quantities with sufficient
 123 injection duration. The injector was previously characterized by means of an IAV type-K flow
 124 rate analyzer to provide the injection rate profiles and injection quantities as a function of the
 125 injection duration. Decane (C₁₀H₂₂) was used as a surrogate for diesel fuel to facilitate future
 126 CFD simulations and kinetics one with Madison kinetic mechanism of Ren et al.[26] to
 127 determine fundamental combustion properties of syngas/decane/air mixtures.

128 The gaseous equivalence ratio, $\Phi_{premixed}$, is calculated as the O₂ volumetric flowrate required
 129 for stoichiometry divided by the real O₂ volumetric flowrate (Eq. 1). A global equivalence
 130 ratio (ϕ_{global}) can be also calculated as a function of the pilot fuel amount and the
 131 stoichiometric mass air/fuel ratio of decane (15.03) as indicated in Eq. 2.

$$\phi_{premixed} = \frac{0.5\dot{V}_{CO} + 0.5\dot{V}_{H_2} + 2.0\dot{V}_{CH_4}}{0.21\dot{V}_{Air}} \#(1)$$

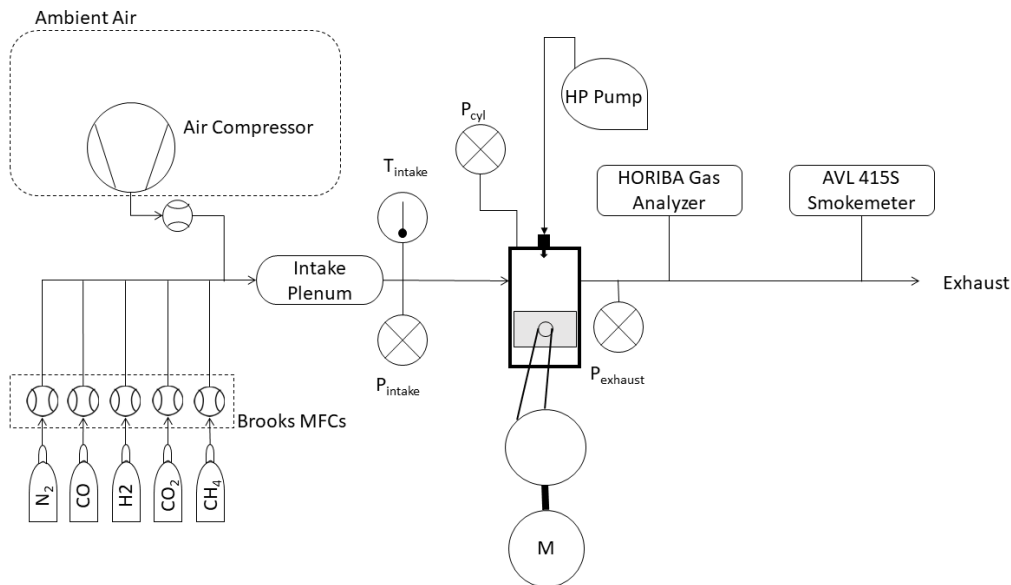
$$\phi_{global} = \phi_{premixed} + \frac{15.03}{\dot{m}_{air}/\dot{m}_{pilot}} \#(2)$$

132 Additionally, the energy share of the pilot fuel (decane) energy of the total supplied energy is
 133 defined as follows:

$$E_{pilot} = 100 \cdot \frac{\dot{m}_{inj} LHV_{C_{10}H_{22}}}{\dot{m}_{inj} LHV_{C_{10}H_{22}} + \dot{m}_{syngas} LHV_{syngas}} \quad \#(3)$$

134 A MEXA 7100D-EGR HORIBA gas analyzer is capable of measuring O₂ (magneto-
 135 pneumatic detector), CO and CO₂, (non-dispersive infrared absorption analyzer), NO_x
 136 (chemiluminescence analyzer) and total unburnt Hydrocarbons (THC) (flame ion analyzer)
 137 concentrations with a precision of 1 ppm for all gases. These concentrations are converted to
 138 specific emissions. Additionally, an AVL 415S smoke-meter, with a detection limit of 0.02
 139 mg/m³ is used to provide soot emission data. The full experimental setup is schematized in

140 **Erreur ! Source du renvoi introuvable..**



141

142 **Figure 1: Experimental Setup scheme.**

143 2.2 Post-processing method

144 From the averaged in-cylinder pressure, calculated over 100 consecutive cycles that are
 145 measured by a Kistler 6043A piezo-electric pressure transducer (accuracy of ± 2.0 %), the
 146 gross Heat Release Rate (HRR) is estimated with the following equations:

$$HRR (J/CAD) = \frac{\gamma}{\gamma - 1} P dV + \frac{1}{\gamma - 1} V dP + dQ_{wall} \#(4)$$

$$dQ_{wall}(J/CAD) = h.S.(T - T_{wall}) \#(5)$$

$$h (J.K^{-1}.m^{-2}) = 3.26b^{-0.2}P^{0.8}T^{-0.55}\nu^{0.8} \#(6)$$

147 The heat transfer coefficient h is determined using the correlation proposed by Woschni [27].

148 The integrated value of $dQ_{combustion}$ is used to determine the mass of fuel burnt (MFB).

149 Cylinder wall temperature, T_{wall} , is estimated at 423 K. The calculation is first done with a

150 constant heat capacity ratio, γ , to obtain a first MFB. Then γ is reassessed from the MFB with

151 the mole fractions of all six components (N_2 , O_2 , CO , H_2 , CO_2 , CH_4) for the unburnt gases

152 and with the emissions data for the burnt gases using NASA polynomials equation. Equations

153 4-6 are then recalculated with this variable γ and the definitive MFB value is obtained.

154 The thermal efficiency is calculated with the following equation:

$$\eta_{thermal} = \frac{IMEP * V_{cyl} * \dot{m}_{total}}{LHV_{CO} \cdot \dot{m}_{CO} + LHV_{H_2} \cdot \dot{m}_{H_2} + LHV_{CH_4} \cdot \dot{m}_{CH_4} + LHV_{C_{10}H_{22}} \cdot \dot{m}_{C_{10}H_{22}}} \#(7)$$

155 The combustion efficiency is calculated by doing the oxygen balance between intake and

156 exhaust related to the total equivalence ratio:

$$\eta_{combustion} = \frac{0.21\dot{m}_{air-intake} - \dot{m}_{O_2-exhaust}}{\dot{m}_{O_2-theoretically\ burning}} \#(8)$$

157 **3 Results and discussion**

158 *3.1 Effect of premixed equivalence ratio*

159 To study the effect of syngas/air equivalence ratio, the injection duration was kept constant at

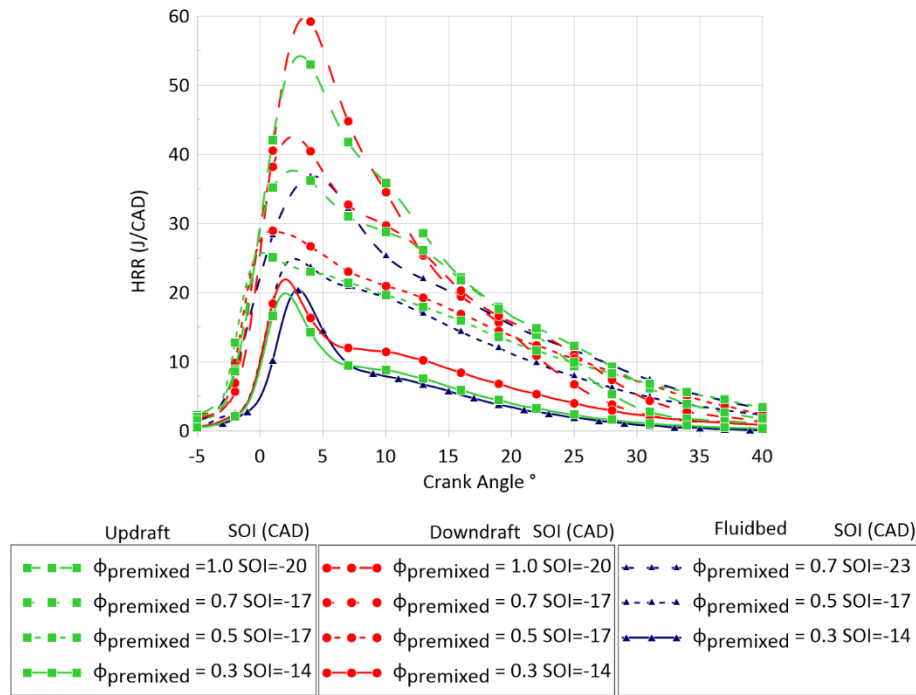
160 $500 \mu s$ (i.e. 0.61 mg) with an increase of syngas amount in the intake charge. The start of

161 injection (SOI) was optimized to guarantee maximum IMEP. Premixed equivalence ratio

162 $\phi_{premixed}$ was varied to 0.3, 0.5, 0.7 and 1.0 for all three compositions except for Fluidbed

163 for which $\phi_{premixed} = 1.0$ induced very unstable combustion, i.e. $IMEP_{cov} > 10\%$. In this

164 section, increasing $\phi_{premixed}$ leads to a syngas mass flowrate increase but an air mass
 165 flowrate decrease in order to keep a constant intake pressure (i.e. 1 bar).

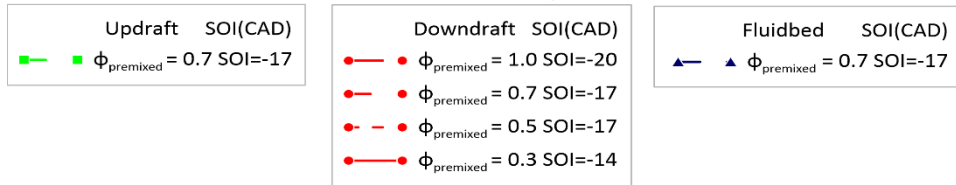
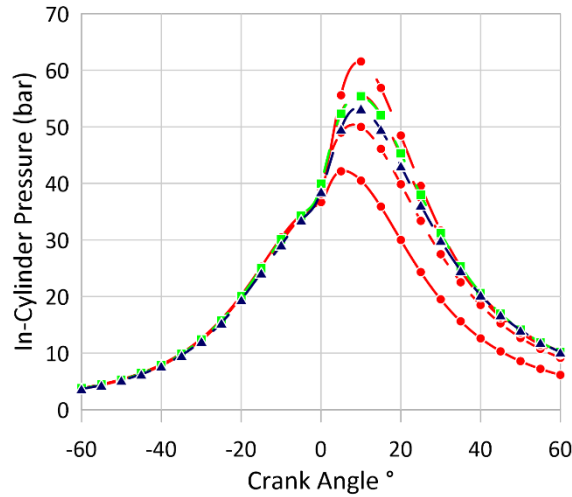


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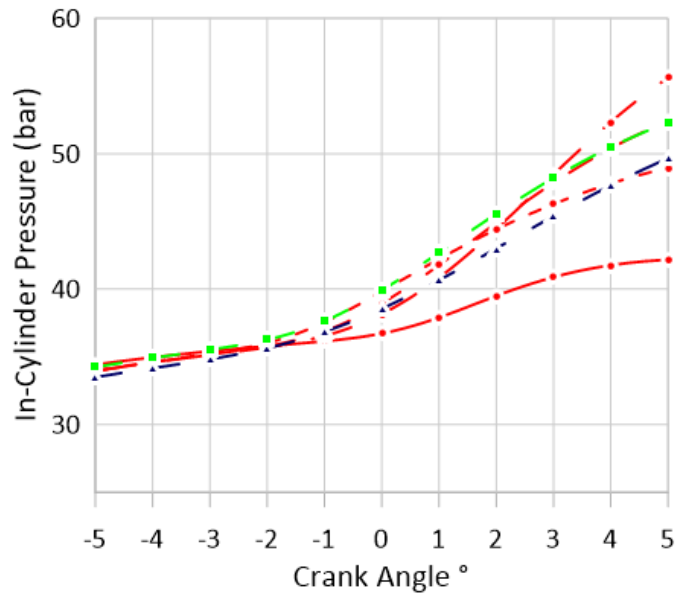
167 **Figure 2: Evolution of Heat Release Rate for all premixed equivalence ratios and the**
 168 **three compositions (1200 RPM, $P_{intake} = 1$ bar, $T_{intake} = 300$ K).**

169 In Figure 2 the HRR traces show that, for all compositions, the increase of $\phi_{premixed}$ induces
 170 a transition from a two-phase to a single-phase combustion evolution. This could be linked to
 171 a reduction in the ignition delay of the syngas/air mixtures with $\phi_{premixed}$ so, in practice,
 172 instead of having the first auto-ignition of the decane charge followed by a slow flame of
 173 syngas/air mixture, both fuels start burning simultaneously. When the pilot injection occurs,
 174 i.e 20 CAD BTDC, the liquid fuel is atomized and has enough time to mix with the nearest
 175 surrounding syngas/air premixed mixture. Therefore, the ignition of the liquid pilot spray will
 176 also ignite the surrounding premixed charge of syngas especially if the syngas is in sufficient
 177 quantity as for the stoichiometric syngas/air case. When $\phi_{premixed}$ is lower, the decane is
 178 introduced later, so less mixing with syngas/air, and less syngas is available. Therefore, the

179 decane will first ignite before the ignition of the premixed syngas charge. It should also be
180 noted that the maximum HRR increases with $\phi_{premixed}$ but the delay does not seem to be
181 affected after $\phi_{premixed} \geq 0.5$ for downdraft and updraft. Higher H₂ concentrations in the
182 syngas composition induce higher peak of HRR. This is consistent with the findings of Dhole
183 et al.[28] and Roy et al.[16]. For same equivalence ratio, the overall shape of the profiles is
184 not affected by the Syngas composition as also highlighted by the In-Cylinder Pressure in
185 Figure 3. The In-Cylinder Pressure shows that the $\phi_{premixed}$ increase leads to a higher peak
186 pressure and a longer combustion tail for downdraft. The major change is when increasing
187 from 0.3 to 0.5 after that the pressure traces show similar envelope. For the composition
188 effect, Updraft and Downdraft present the same pressure trace while the peak pressure is a bit
189 lower for Fluidbed as expected due to its lower energy content. The differences, between both
190 compositions, in terms of start of combustion are highlighted in Figure 3b (in-cylinder
191 pressure traces of Updraft and Fluidbed are available as supplementary materials). It can also
192 be noted from Figures 3 that SOI remains between -14 and -20 CAD for Updraft and
193 Downdraft and that the range is a bit wider for Fluidbed, i.e. down to -23 CAD. Moreover, in
194 order to get maximum IMEP with minimum IMEP_{cov}, the SOI is advanced with the increase
195 of $\phi_{premixed}$.



196

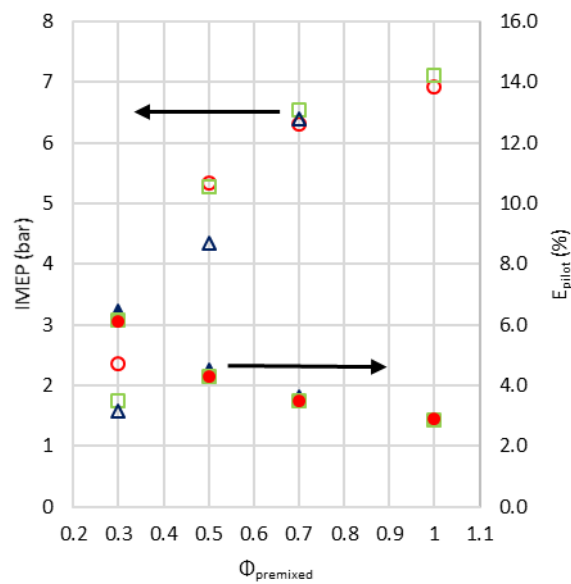


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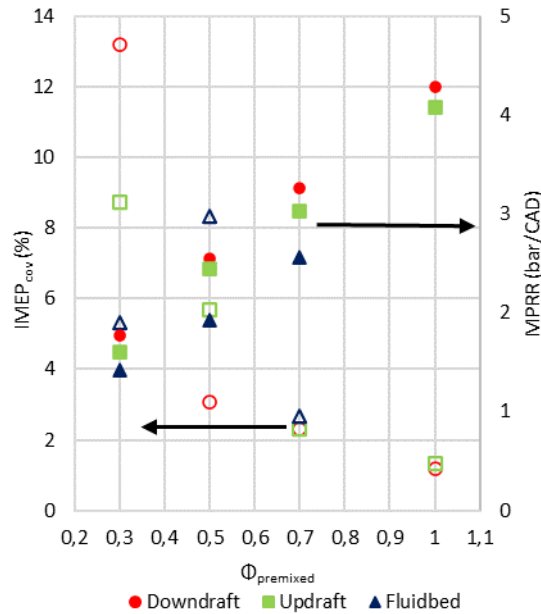
198 **Figure 3. (a) Evolution of In-Cylinder Pressure for all premixed equivalence ratio for**
 199 **Downdraft and only at $\phi_{premixed} = 0.7$ for Updraft and Fluidbed, (b) zoomed between**
 200 **-5 and 5 CAD. (1200 RPM, Pintake = 1 bar, Tintake= 300K)**

201 Figure 4a displays the corresponding IMEP and energy share of the pilot E_{pilot} . First, in
 202 agreement with HRR and in-cylinder pressure traces, IMEP increases with $\phi_{premixed}$ since
 203 more energy is introduced. Then it is worth noticing that, in all cases, the energy share of the

204 pilot stays below 21% of the total energy amount. Since the injected quantity of decane is
 205 maintained constant, the pilot energy share decreases with $\phi_{premixed}$. Figure 4b shows the
 206 IMEP_{cov} as well as the MPRR as a function of $\phi_{premixed}$. It can be seen that for premixed
 207 equivalence ratio greater than 0.5, the combustion is quite stable for all compositions, i.e.
 208 IMEPcov below 6%, except for Fluidbed (8% for IMEPcov). For $\phi_{premixed} = 0.3$, the
 209 combustion is more likely to be unstable (up to 13% of IMEPcov for Downdraft) but it
 210 remains possible to operate the engine. Regarding combustion noise, the maximum pressure
 211 rise rate (MPRR) increases with $\phi_{premixed}$ because of energy input increase and H₂ content in
 212 the syngas composition. The syngas compositions can be ranked, Fluidbed, Updraft,
 213 Downdraft from lower to higher maximum pressure gradient. For Downdraft and Updraft at
 214 stoichiometric premixed equivalence ratio, it should be mentioned that the MPRR is at the
 215 limit of excessive combustion noise (4 bar/CAD) [29].



216

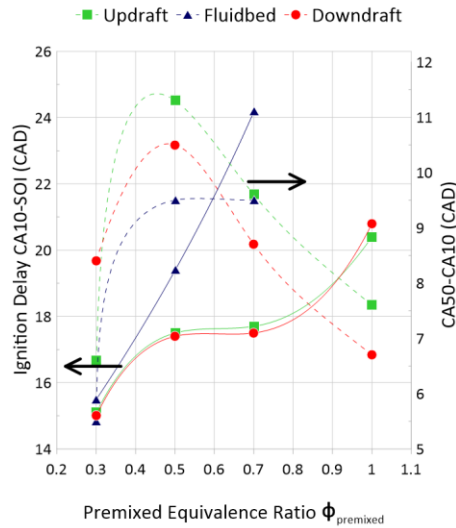


217

218 **Figure 4. a) IMEP (empty symbols) and Epilot (filled symbols) and b)IMEPcov (empty**

219 **symbols) and MPRR (filled symbols) as function of $\Phi_{premixed}$**

220 In Figure 5, both the ignition delays from the pilot injection timing and the first part of the
 221 combustion development are plotted as a function of the equivalence ratio. First, it can be
 222 noted that the increase in premixed equivalence ratio also increases the ignition delay. It is
 223 probably explained by the fact that the start of injection (SOI) is advanced with the increase in
 224 premixed equivalence ratio. Indeed, it should be reminded that SOI is advanced in order to
 225 keep a maximum IMEP and therefore a relatively constant CA50. This is especially verified
 226 for the Fluidbed composition, for which the increase is more linear and stronger than for the
 227 Downdraft and Updraft ones. This is probably explained by the higher CO₂ content (20%) of
 228 Fluidbed composition that contributes to delay the autoignition. Yet, the duration of the first
 229 half of the combustion, represented by CA50-CA10, strongly decreases from $\phi_{premixed} = 0.5$
 230 onwards. This is due to the increased reactivity of the premixed charge and the increase of the
 231 flame propagation speed.



232

233 **Figure 5: Effect of premixed equivalence ratio on ignition phasing (continuous lines) and**

234 **first half of combustion (dotted lines) (1200 RPM $P_{intake} = 1$ bar $T_{intake} = 300$ K).**

235 Figure 6 presents the thermal and combustion efficiencies and emissions as a function of

236 premixed equivalence ratio for the three Syngas compositions. Both combustion and thermal

237 efficiencies are bell-shaped reaching peak values around 98% and 39% respectively for

238 Downdraft and Updraft compositions. For Fluidbed, efficiencies continuously increase but the

239 curves start to bend. Since premixed stoichiometric equivalence ratio was not achievable, it is

240 not possible to forecast for which equivalence ratio efficiencies will start to decrease. The

241 lowest combustion efficiency, reached for the ultra-lean premixed charge, induces, as

242 expected, the highest CO and THC emissions. The minimum CO and THC emissions are

243 obtained when $\phi_{premixed}$ is between 0.5 – 0.7 and as expected where efficiencies are the

244 highest ones. Overall, this effect of the premixed equivalence ratio on the CO and THC

245 emissions confirms the ones observed by Roy et al.[16]. For NO_x emissions, also the lowest

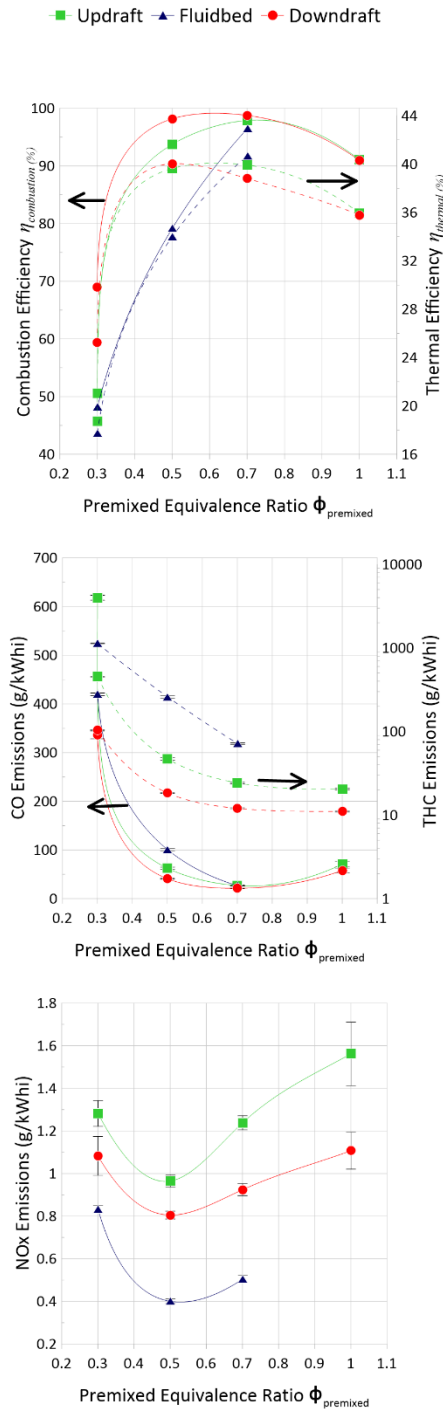
246 values are obtained at $\phi_{premixed} = 0.5$, with the highest ones reached at the stoichiometric

247 syngas/air mixture. This evolution is not expected as the NO_x emission peak is reached in

248 lean side in classical SI engine. It is indeed surprising to observe that minimum NO_x

249 coincides with minimum CO, but since syngas is a highly diluted fuel (about 50% N_2 , 10 to

250 20 %CO₂), its combustion temperature is very low leading to low NO_x levels even in lean
 251 mixtures where CO emission is also minimum. Similar trends were observed numerically for
 252 NO_x emission but not for CO one (Kousheshi et al. [30]). For all operating conditions, soot
 253 emissions were below the detection limit of the measurement device.
 254



255

256 **Figure 6: Efficiencies and exhaust gases emissions as a function of premixed equivalence**
257 **ratio for the three Syngas compositions (1200 RPM, $P_{\text{intake}} = 1$ bar, $T_{\text{intake}} = 300\text{K}$,**
258 **Optimum SOI).**

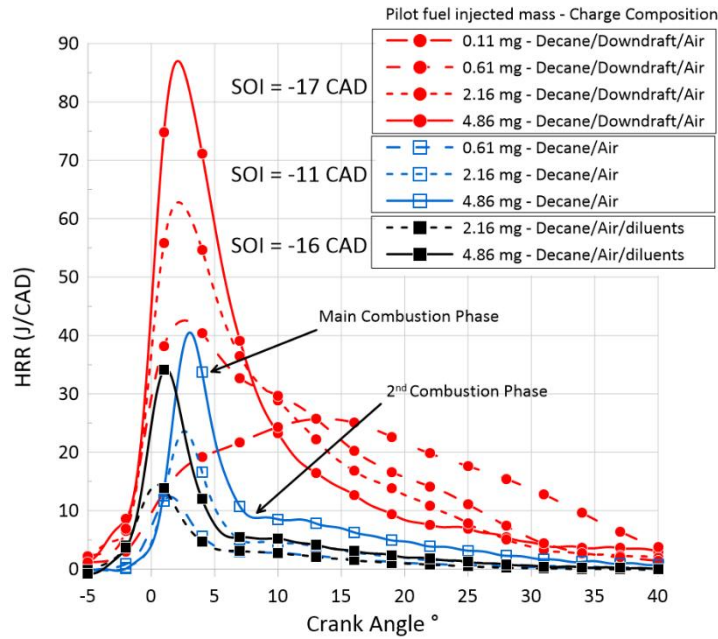
259 3.2 Effect of pilot fuel injection quantity

260 In the previous section, since the optimal premixed equivalence ratio was found to be around
 261 $\phi_{premixed} = 0.7$, the effect of the pilot injection was evaluated at this particular value, while
 262 the injection duration was varied from 250 μs to 1000 μs , i.e. corresponding to 0.11 to 4.86
 263 mg of decane injected per cycle (see Table 4). First, to evaluate the contribution of the pilot
 264 amount in the combustion development, the pilot fuel is first injected in air (without syngas)
 265 and then in air plus 5%_{vol} CO₂ and 20%_{vol} N₂ concentrations (equivalent charge dilution as the
 266 downdraft case).

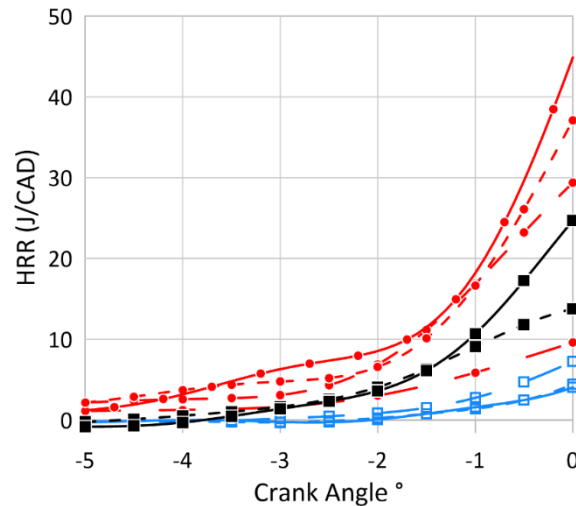
267 **Table 4: Experimental conditions to study the effect of pilot fuel injection quantity.**

Case	Injection Duration (μs)	Decane injected mass (mg)	ϕ_{global}	Pilot fuel energy share (%)	IMEP (bar)	SOI (CAD) ATDC
Downdraft/Air	250	0.11	0.71	0.6	5.7	-17
	500	0.61	0.74	3.3	6.3	
	750	2.16	0.83	10.9	6.8	
	1000	4.86	1.0	21.7	7.4	
Air	500	0.61	0.02	100	0.4	-11
	750	2.16	0.08		1.2	
	1000	4.86	0.17		2.8	
Air/Diluents	750	2.16	0.1	100	0.7	-16
	1000	4.86	0.22		2.0	

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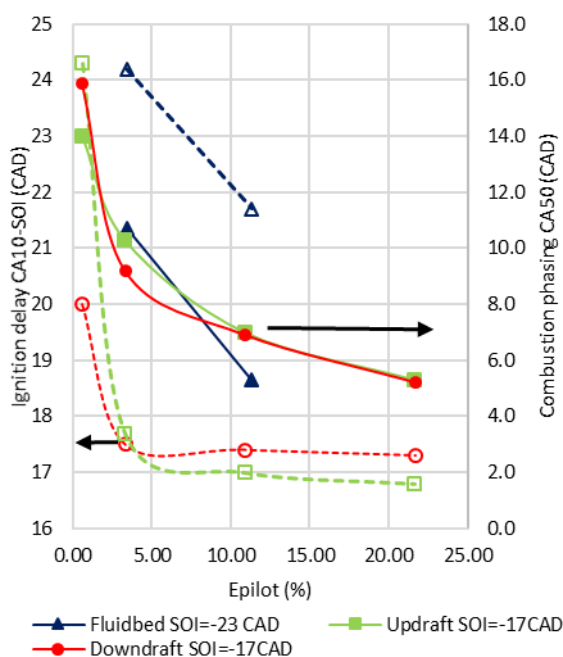


270

271 **Figure 7(a): Heat release rate from the fuel pilot injection in air and air with diluents**
 272 **compared to downdraft dual-fuel. ($\phi_{premixed} = 0.7$) and (b) zoom between -5 and 0**
 273 **CAD**

274 In Figure 7, it can be clearly seen that the ignition delay of the reactive fuel, decane from pilot
 275 injection, is similar in air with diluents as with the presence of syngas. However, it can be
 276 noted that for the highest quantity of liquid pilot injection, i.e. 4.86 mg, an earlier heat release
 277 can be observed between -5 and -2 CAD before TDC, smaller than the major rise in HRR that
 278 follows – when decane is injected in premixed syngas/air. This low-temperature heat release

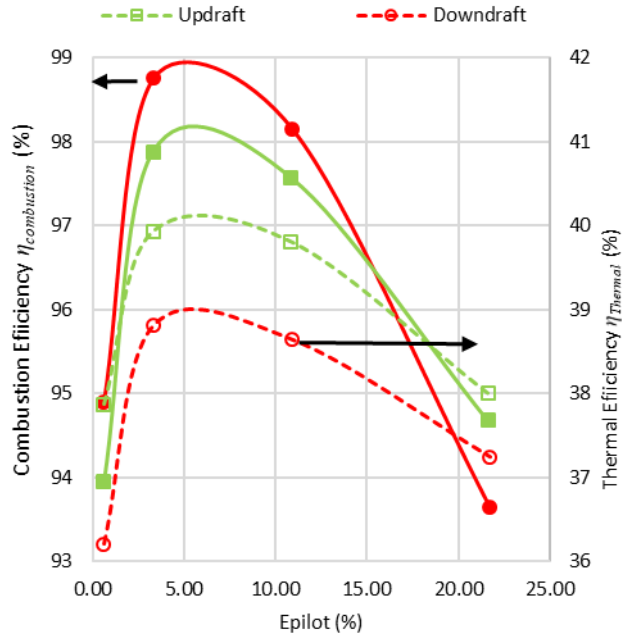
279 could indicate a two-stage ignition process that does not occur when the decane injection is
 280 done in non-reactive medium (i.e. air or air/diluent). In these cases, the combustion occurs in
 281 two phases: the main combustion phase due to the premixing of decane with air and a second
 282 one, slower due to the diffusion-controlled combustion. The distinction between the phases is
 283 less clear when syngas is premixed with the intake charge but there is still an inflexion point
 284 after the peak in HRR for 0.61 and 2.16 mg quantity injected at around 7 and 9 CAD ATDC
 285 respectively.



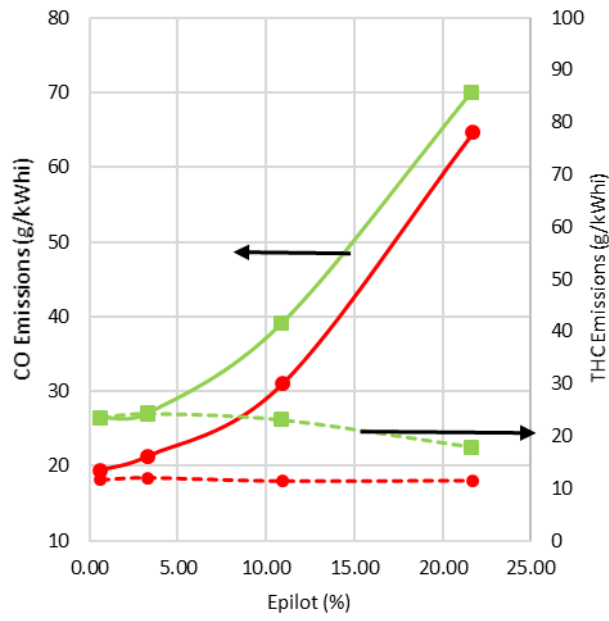
286 **Figure 8: Effect of pilot fuel energy share on ignition delay (empty symbols, dashed**
 287 **lines) and combustion phasing CA50 (filled symbols, continuous lines) for three Syngas**
 288 **compositions (1200 RPM, $P_{\text{intake}} = 1 \text{ bar}$, $T_{\text{intake}} = 300\text{K}$, $\phi_{\text{premixed}} = 0.7$).**

290 In Figure 8, the effect of decane addition on the ignition timing and the combustion phasing
 291 (CA50) is presented for the 3 syngas compositions. For the Fluidbed composition, stable
 292 combustion could not be achieved at the lowest and highest pilot fuel injection durations
 293 therefore only two data points are presented. This behavior can be attributed to the high CO_2
 294 concentrations of Fluidbed combined with the comparatively low H_2 and CO contents. For

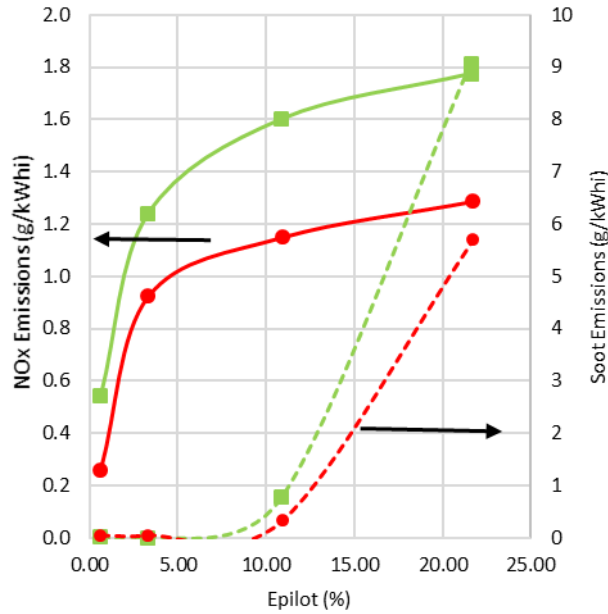
295 updraft and downdraft ones, the ignition delay seems to stabilize once enough decane is
296 injected (over 10% of the total available energy). But, the combustion phasing is monotonically
297 advanced with the addition of decane, as expected from the HRR profiles presented in Figure
298 7 for the Downdraft composition. Basically, increasing the energy share from the more
299 reactive fuel will reduce the ignition delay of the whole fuel charge as observed on CA10-
300 SOI, the decane being easier to auto-ignite. This will lead to a shift of the CA50 and globally
301 of the whole combustion earlier in the cycle. For Downdraft, $IMEP_{cov}$ decreases from 2.4
302 down to 1.08 % and MPRR increases from 1.2 up to 6.9 bar/CAD as E_{pilot} increase. For
303 Updraft, the trends and values are very similar to Downdraft. However, for Fluidbed, $IMEP_{cov}$
304 decreases from 2.6 down to 2 % and maximum pressure gradient increases from 2.6 up to 4.8
305 bar/CAD with E_{pilot} increases. Hence, and as expected, ranking in terms of combustion
306 stability and noise is the same as the one observed in the previous section.



307



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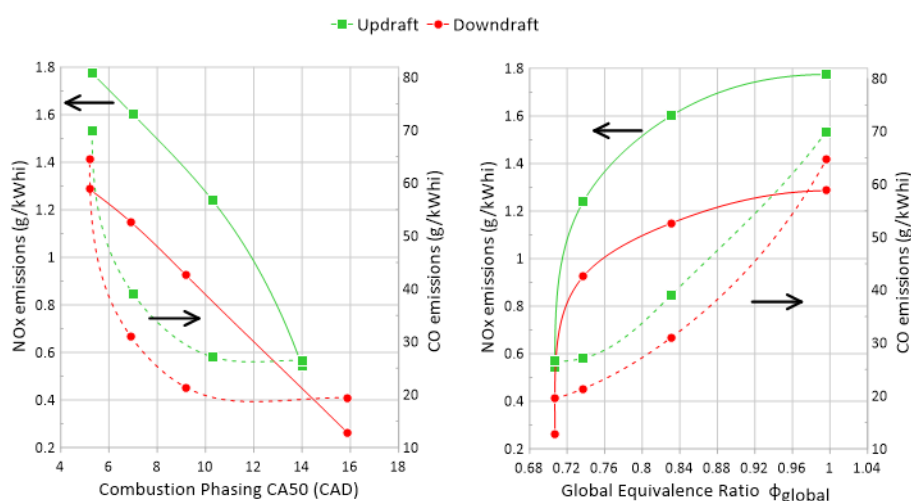


309

310 **Figure 9: Efficiencies and emissions as a function of decane energy share for the three**
 311 **Syngas compositions. Filled symbols/continuous lines : Combustion efficiency, CO and**
 312 **NOx emissions for a,b and c respectively. Empty symbols/Dashed lines: Thermal**
 313 **Efficiency, THC and Soot emissions for a, b and c respectively**
 314 **(1200 RPM, $P_{\text{intake}} = 1 \text{ bar}$, $T_{\text{intake}} = 300\text{K}$, $\phi_{\text{premixed}} = 0.7$).**

315 In Figure 9, for Updraft and Downdraft compositions, the combustion and thermal
 316 efficiencies are bell shaped with a maximum value, reached around 10% pilot fuel energy
 317 share. Fluidbed results are not plotted as only two conditions provide stable combustions. It
 318 has to be noted that the Updraft composition induces a lower combustion efficiency than
 319 Downdraft but a better thermal one. This is despite the fact that CA50 is very similar between
 320 the two compositions for the same pilot fuel amount (Figure 8). Due to the higher H2 content,
 321 Downdraft has a greater flame speed (Table 1) thus leading to a better consumption of fresh
 322 gases. On the other hand, this higher H2 content could lead to higher combustion temperature
 323 and therefore more heat losses thus depleting the thermal efficiency as highlighted
 324 numerically by Kousheshi et al. [30]. The emissions data show that CO and soot emissions are

325 negatively affected by the increase in decane quantity, without any bell or inverse bell shape:
 326 more diesel type fuel induces more unburnt carbonaceous exhaust gases except THC, i.e. a
 327 slight reduction seems to occur with decane addition for the updraft composition. The level of
 328 soot was so low than no value could be measured, for fuel amount lower than 12% energy
 329 share similarly to what was observed by Papagiannakis et al. [17] with methane/diesel dual-
 330 fuel. Yet when reaching 20% for E_{pilot} , soot emissions rise up to significant value of 6-9
 331 g/kWh. It is also clear that NO_x emissions strongly increase as a function of decane amount,
 332 due to the increase of in-cylinder temperatures. It is interesting to notice, both CO and NO_x
 333 are minimum for the same E_{pilot} and rises with E_{pilot} increase. The syngas is globally a low
 334 NO_x fuels, its combustion temperature is very low compare to other fuels. Moreover since the
 335 equivalence ratio stays poor in the whole study the CO and HC are also low. Yet, when
 336 increasing decane quantity both NO_x and CO rise simultaneously because it will induce a
 337 combustion temperature increase leading to higher NO_x and an increase of liquid quantity that
 338 leads to a poorer mixing and evaporation that leads to higher CO and HC. The effects of CO_2
 339 on NO_x emissions will be discussed further on the final part of this work.



340
 341 **Figure 10: Specific emissions of NO_x (continuous line) and CO (dashed line) as a**
 342 **function of combustion phasing (left) and global equivalence ratio (right)**
(1200 RPM $P_{intake} = 1$ bar, $T_{intake} = 300$ K, $\phi_{premixed} = 0.7$).

343 In Figure 10, NO_x and CO emissions are presented as a function of CA50 and ϕ_{global} .
344 Regarding the relationship between emissions and combustion phasing it is clear that, for this
345 premixed equivalence ratio, CO emissions reach a plateau for $\text{CA50} > 9$ CAD ATDC while
346 NO_x emissions decrease almost linearly with CA50, as the in-cylinder temperature is higher
347 for shorter combustion. The NO_x emissions as function of the global equivalence ratio
348 follows the decane share, and seems to reach a plateau when the global equivalence ratio
349 tends to 1. Meanwhile, the increase in CO emissions seems not to reach a plateau as usually in
350 SI engines: CO increases with the global equivalence ratio increase.

351 *3.3 Effect of CH_4 and CO_2 concentration*

352 To give further insight on the roles of CH_4 and CO_2 on performance and emissions,
353 complementary measurements were performed with the composition variations as in Table 5.
354 The variation consists of maintaining H_2 and CO volume fractions constant while adjusting
355 the N_2 volume fraction to compensate CO_2 or CH_4 variations. The variations are designated by
356 the composition (FB, UD, DD for Fluidbed, Updraft, Downdraft respectively), from which the
357 H_2 and CO content is kept, followed by an index that refers to the CO_2 or CH_4 content. The
358 variation FB-20 CO_2 is greyed out as no stable operation could be obtained. The Madison
359 kinetics mechanism[26] was selected in combination with the PREMIX and EQUIL
360 CHEMKIN ANSYS PRO codes to estimate laminar flame speed and flame temperature
361 respectively, by considering initial conditions equal to those in the cylinder at the start of
362 injection (864 K and 30 bar, $\phi = 0.7$). This mechanism was validated for this purpose in a
363 previous study[25]. Premixed equivalence ratio was kept constant at 0.7 and the injection with
364 a duration of 400 μs (i.e. 0.32 mg corresponding to $E_{pilot} \approx 1.65\%$) started at -18 CAD BTDC.
365

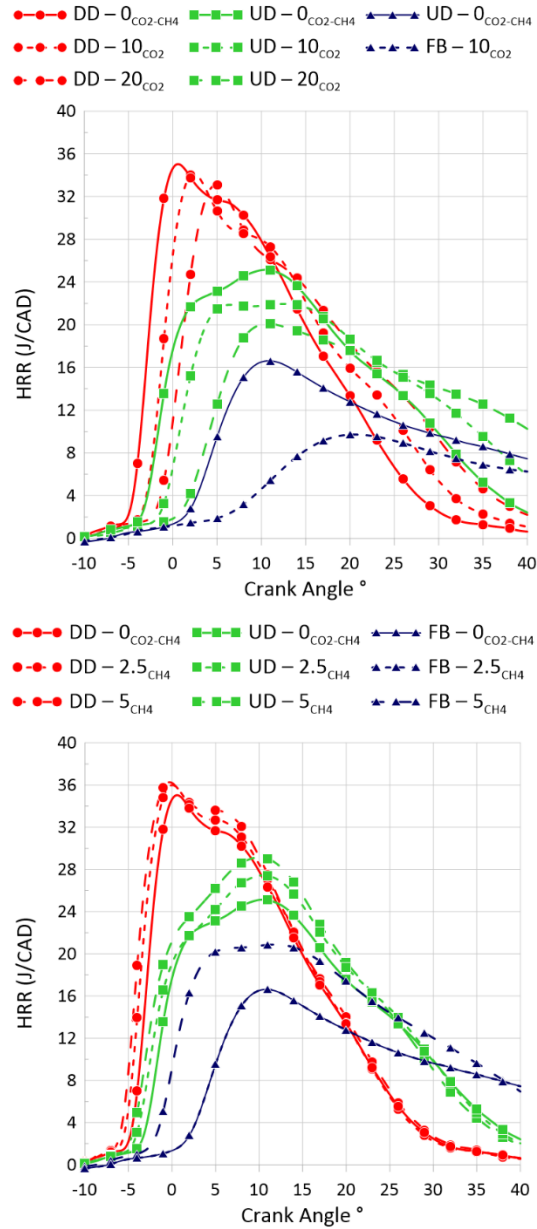
Table 5: Variations on the original Syngas compositions.

Variation	H2 (% vol)	CO (% vol)	CO2 (% vol)	CH4 (% vol)	N2 (% vol)	Adiabatic Equilibrium Flame Temperature (K)	Laminar Flame Speed (cm/s)
FB – 0 _{CO2-CH4}	9	14	0	0	77	1868	32.3
FB – 10 _{CO2}			10	0	67	1834	24.3
FB – 20 _{CO2}			20	0	57	1802	14.9
FB – 2.5 _{CH4}			0	2.5	74.5	1955	33.0
FB – 5 _{CH4}			0	5	72	2016	35.0
FB - Reference			20	7	50	2004	26.4
UD – 0 _{CO2-CH4}	11	24	0	0	65	2092	61.5
UD – 10 _{CO2}			10	0	55	2059	51.1
UD – 20 _{CO2}			20	0	45	2028	41.9
UD – 2.5 _{CH4}			0	2.5	62.5	2131	59.5
UD – 5 _{CH4}			0	5	60	2160	58.2
UD - Reference			9	3	53	2112	51.1
DD – 0 _{CO2-CH4}	17	21	0	0	62	2120	83.0
DD – 10 _{CO2}			10	0	52	2088	69.1
DD – 20 _{CO2}			20	0	42	2057	57.9
DD – 2.5 _{CH4}			0	2.5	59.5	2154	75.4
DD – 5 _{CH4}			0	5	57	2178	71.2
DD – Reference			13	1	48	2095	62.7

367 In Figure 11, the effect of CO₂ and CH₄ content on HRR is highlighted. CO₂ addition to

368 Syngas delays the onset of combustion and extends the combustion duration. This effect has

369 been well described by Xiang et al.[31] and Halter et al.[32] for CH₄/CO₂/Air mixtures where
370 the dilution, thermal and chemical contributions of CO₂ to the reduction of laminar flame
371 speed have been quantified. Since the total dilution amount, i.e. N₂ + CO₂ quantity, is kept
372 constant, the effect seen here is both related to the thermal (increased heat capacity of the
373 charge → reduction of charge temperature) and chemical effects. Moreover, the two
374 combustion stages present for downdraft and updraft without any CO₂ (DD – 0_{CO₂-CH₄} and UD
375 – 0_{CO₂-CH₄} respectively), are less evident with CO₂ addition. On the other hand, the addition of
376 CH₄ advances the start of combustion and makes it easier to distinguish the two combustion
377 phases. This could indicate that the H₂ in the syngas might be consumed first, contributing to
378 the initial rise in HRR, followed by the slower-burning CO and CH₄.



379

380 **Figure 11: Heat Release Rate profiles for varying CO₂ (top) and CH₄ (bottom) contents**

381 **(1200 RPM $P_{\text{intake}} = 1 \text{ bar}$, $T_{\text{intake}} = 300\text{K}$, $\phi_{\text{premixed}} = 0.7 \text{ SOI} =$**

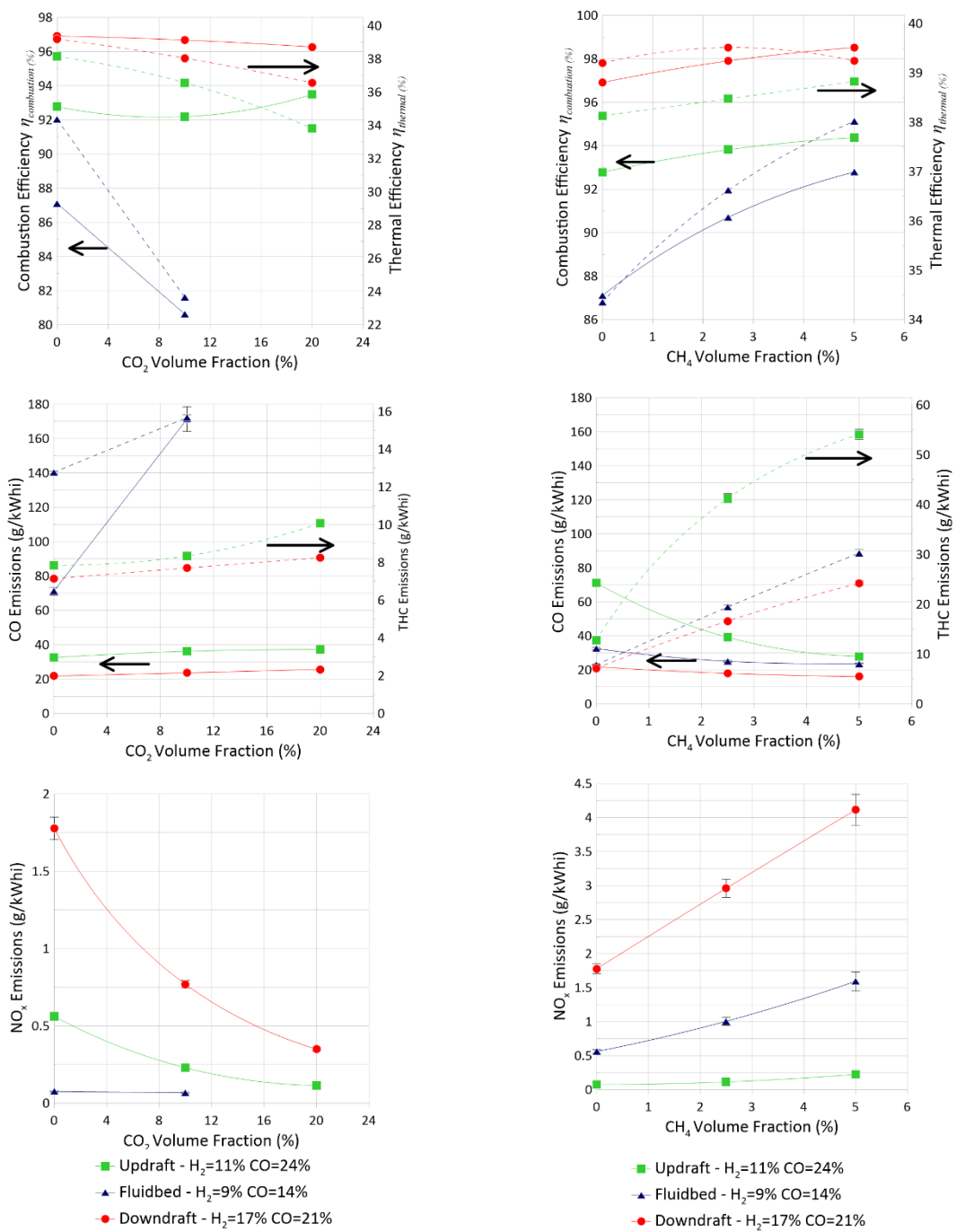
382 **-18 CAD BTDC).**

383 The resulting efficiencies and emissions from the variations tested are presented in Figure 12.

384 Soot emissions are not presented because they are always under the detection limit. By

385 replacing N₂ with CO₂, the decrease of combustion efficiency induces CO and THC increase

386 but a reduction of NO_x emissions, due to the delay of the combustion phasing as the start of
387 injection was maintained constant and not optimized.



a) Effect of CO₂ content

b) Effect of CH₄ content

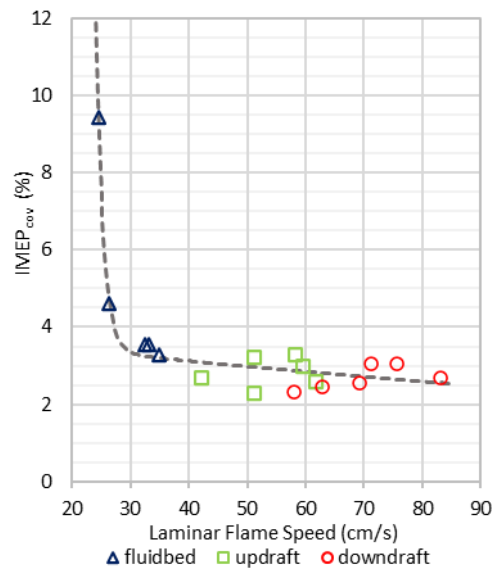
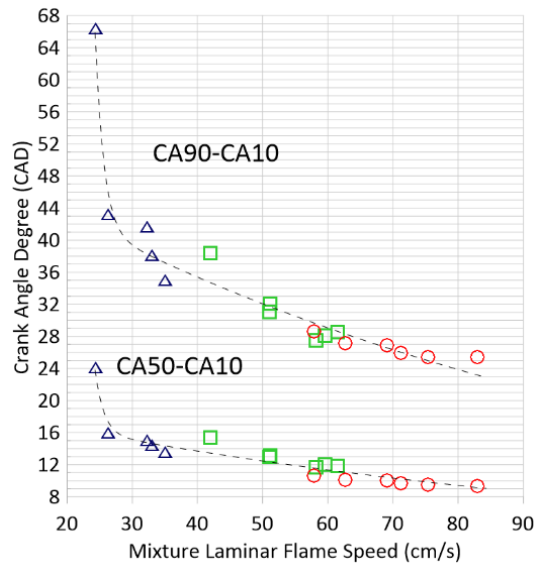
388 **Figure 12. Effect of Syngas components a) CO₂ and b) CH₄ on engine efficiencies and**
 389 **exhaust emissions (1200 RPM, $P_{intake} = 1 \text{ bar}$, $T_{intake} = 300\text{K}$, $\phi_{premixed} =$**
 390 **0.7 , $SOI = -17 \text{ BTDC}$).**

391 Figure 12 b) indicated that CH₄ addition increases both thermal and combustion efficiencies
392 resulting in lower CO emissions. Despite the overall higher combustion efficiencies, THC
393 emissions increase with CH₄ addition due to the increase of unburned CH₄ itself. Even if the
394 amount of CH₄ added remains low, the increase of CH₄ % induces an increase of NO_x
395 emissions, mainly due to higher in-cylinder temperatures, as predicted the higher adiabatic
396 temperature values in Table 5. Due to the higher H₂ content, Downdraft provides a greater
397 combustion development speed thus leading to a better consumption of fresh gases. On the
398 other hand, this higher H₂ content could lead to higher combustion temperature and therefore
399 more heat losses thus depleting the thermal efficiency.

400 *3.4 Relationship between fundamental composition properties and engine operation*

401 In order to predict the effect of syngas composition, it is important to highlight the
402 relationship between the fundamental properties of the composition (such as laminar flame
403 speeds, LFS, or adiabatic flame temperature, T_{ad}) and the resulting engine performance and
404 emissions. For that, empirical correlations are suggested in Figure 13 and 13 to identify the
405 effect of properties variations in Table 5 to the combustion durations and stability and NO_x,
406 THC and CO emissions.

407



408

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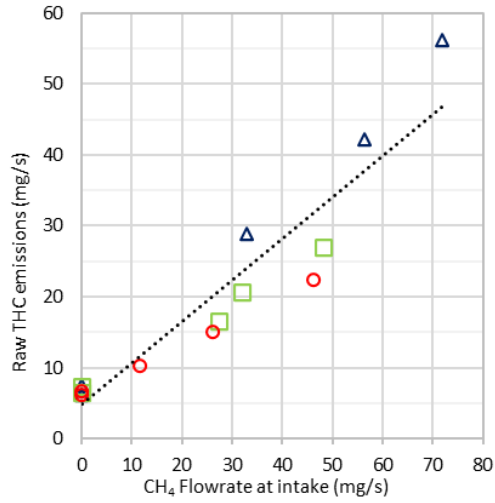
410 **Figure 13: Relationship between combustion duration and stability (IMEP_{cov}) as a**
 411 **function of syngas Laminar Flame Speed. (1200 RPM, P_{intake} = 1 bar, T_{intake} =**
 412 **300K, $\phi_{premixed} = 0.7$ SOI = -18 CAD BTDC).**

413 First flame development stage duration (CA50-CA10) and total combustion duration (CA90-
 414 CA10) clearly decrease with the laminar flame speed with a clear transition when the flame
 415 speed goes under a certain level probably due to the combustion instabilities linked to the low
 416 value of LFS in the case of fluidbed. A similar behavior was observed by Lhuillier et al.[33]
 417 for NH₃/H₂ mixtures in a SI engine. Nevertheless, while the trend is clear for the whole of the
 418 17 compositions tested, locally, the experimental points seem to group together as a function

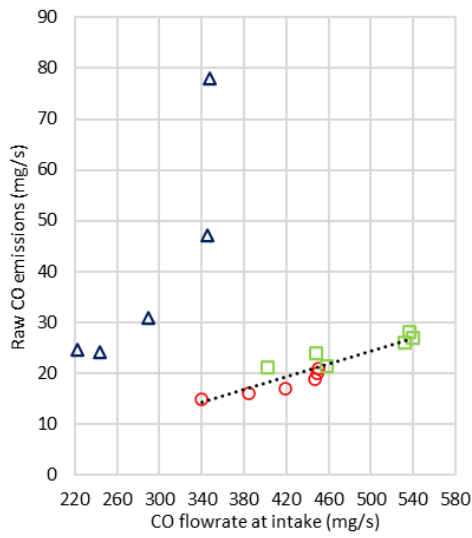
419 of H₂/CO contents. In Figure 13b, one can note that when the composition of a syngas/air
420 mixture induces a laminar flame speed lower than 40 cm/s, as it is for fluidbed composition,
421 IMEP_{cov} rises sharply. Yet, for LFS > 40 cm/s, the stability is not affected by any laminar
422 flame speed change.

423 In Figure 14a, total hydrocarbon (THC) emissions increase with the addition of CH₄, as the
424 number of HC increase, indicating that the part of intermediate CH due to the decane
425 oxidation (or to crevice trapping) is lower. In the case of CO emissions (Figure 14.b), same
426 linear dependency can be noted of Downdraft and Updraft compositions but the exhaust CO
427 values are less than 10 times the CO quantity introduced, due to the oxidation of the CO
428 during the combustion process. Yet, the high IMEP_{cov} for Fluidbed induces higher combustion
429 instabilities leading to high CO emissions even if the CO flowrate at the intake is lower.

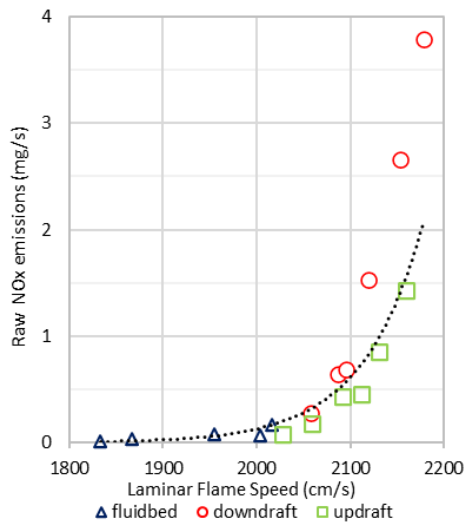
430 As the main source of NO_x for these fuels is due to the thermal mechanism, NO_x production
431 rate increases exponentially with the adiabatic flame temperatures as shown in Figure 14.c.
432 The increase of H₂ contents as in Downdraft induces higher NO_x emissions: exponential
433 evolution as a function of adiabatic temperature is accurate but with different coefficients,
434 dependent to the syngas compositions. Notably, for very similar adiabatic flame temperatures,
435 the Downdraft compositions produce more NO_x than the Updraft compositions. Last, as
436 highlighted by Rakopoulos et al. [34], the oxygen content has a significant effect on
437 performances and emissions. When comparing updraft and fluidbed, they exhibit very similar
438 H₂ content but CO and therefore oxygen content is much higher for updraft. Rakopoulos et al.
439 showed that NO emissions increase with the degree of oxygenation which could explain the
440 higher NO_x levels for updraft mixtures compared to fluidbed.



441



442



443

444

Figure 14: Relationship between THC emissions and intake CH₄ (a), Exhaust and

445

Intake CO (b), NO_x and T_{ad} (c).

446 (1200 RPM $P_{\text{intake}} = 1 \text{ bar}$ $T_{\text{intake}} = 300 \text{ K}$, $\phi_{\text{premixed}} = 0.7 \text{ SOI} =$
447 -18 CAD BTDC).

448 **4 Conclusion**

449 In this study, the effects of the syngas composition on engine operation parameters and
450 emissions are presented and discussed as a function of the syngas/air equivalence ratio in the
451 intake charge and the more reactive fuel pilot injected mass. The main conclusions from these
452 results are the followings:

- 453 • With minimal tuning and no engine geometry optimization, indicated thermal
454 efficiencies of over 38% were obtained with all compositions with syngas
455 representing almost 90% of the total energy supplied to the engine.
- 456 • Heat release rate profiles showed a strong influence of syngas H_2 content on
457 combustion duration and phasing.
- 458 • CO_2 , present on most of syngas compositions, plays an important role in reducing
459 NO_x emissions in dual-fuel operating mode. While this can be interesting for
460 complying with emission regulations, too much CO_2 on Syngas can lead to poor
461 combustion efficiency requiring more reactive fuel in the pilot injection in order to
462 ensure stable engine operation but increase of soot emissions is the consequence.
- 463 • The development of the in-cylinder combustion can be empirically predicted based
464 only on known fundamental properties of the syngas composition as the laminar
465 flame speed. The emissions also can be predicted as a function of the different
466 components in the syngas. This could be useful for live tuning of the engine's control
467 strategy to as a function of the composition fluctuations of the gasifier product gas.
468 Accurate predictions would require a better knowledge of secondary chemical and
469 physical effects of varying syngas compositions such as stretch sensitivity or
470 chemical pathways and species rate of production.

471

472 Finally, further studies on optical engine would be necessary to give a better understanding on
473 different combustion steps (as diffusion phase, premixed or cool flame due to pre-ignition)
474 and flame propagation as it relates to the different compositions and their respective
475 fundamental combustion properties.

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