



Controlling HCCI Ignition Timing of Biogas by Direct Injection of Solid Biomass

Philippe Guibert, Mira Ibrahim, Frédéric Ségretain, Khanh-Hung Tran

► To cite this version:

Philippe Guibert, Mira Ibrahim, Frédéric Ségretain, Khanh-Hung Tran. Controlling HCCI Ignition Timing of Biogas by Direct Injection of Solid Biomass. *Journal of the Energy Institute*, 2022, 100, pp.33-46. 10.1016/j.joei.2021.10.007 . hal-03552152

HAL Id: hal-03552152

<https://hal.sorbonne-universite.fr/hal-03552152>

Submitted on 2 Feb 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Controlling HCCI Ignition Timing of Biogas by Direct Injection of Solid Biomass

Philippe Guibert^{a,*}, Mira Ibrahim^{a,*}, Frédéric Ségretain^a, Khanh-Hung Tran^b

^aInstitut Jean le Rond d'Alembert (CNRS UMR 7190), Sorbonne Université, Saint Cyr-l'Ecole, 78210, France

^bLaboratoire Energétique, Mécanique Electromagnétisme, Université Paris Nanterre, Ville d'Avray, 92410, France

Corresponding author at: Institut Jean le Rond d'Alembert (CNRS UMR 7190), Sorbonne Université, Paris, E-mail address: philippe.guibert@sorbonne-universite.fr

Abstract

The reduction of pollutant emissions from internal combustion engines, and in particular greenhouse gases, must be achieved by optimizing the combustion process and choosing fuels with a low carbon impact. Heterogeneous mixture combustions such as Diesel induce a difficulty in managing of the pollutants formation even if in its principle the output efficiency remains favorable. Therefore, it is necessary to distinguish this last point, which refers to the compression ratio, in order to move towards homogeneous combustion with a high compression ratio. We then speak generically of HCCI combustion (Homogeneous Charge Compression Ignition), whose process takes place in the context of auto ignition.

An important challenge of this combustion is the control of the ignition timing. This paper presents a concept to control the initiation of combustion of a reactive gas mixture with low susceptibility to auto-ignition, which meets the expectation of high efficiency, via the introduction of biomass particles. From a schematic point of view, these particles will play the role of spark plugs distributed throughout the combustion chamber, and should have an auto ignition time much lower than that of the fuel.

For this purpose, a particle injector was conceived to directly inject a controlled quantity of biomass powder into the reactive mixture directly. This part is a challenging point. The reproducibility and viability of the particle injector were qualitatively validated by image analysis acquired at high frequency and high resolution. Thus, the system was integrated into an RCM (Rapid Compression Machine) chamber, allowing diphasic gas/solid biomass combustion study. This preliminary test was investigated by high-speed video on a lean diluted biomass enriched with hydrogen mixture ($\text{CH}_4/\text{CO}_2/\text{H}_2$) at low fuel-air equivalence ratio ($\Phi=0.6$), with different auto-ignition delays in the condition of experimentation. It was shown that the direct injection of a small amount of biomass particles was able to promote its reactivity and initiate the combustion process. This study highlights the promising effects of the injection of powder to control the beginning of homogeneous combustion, by bringing locally a spot of energy, distributed in the whole chamber. The control given by a global contribution of weak energy is distinguished from the process of combustion by auto-ignition of the fuel mixture whose properties of equivalence air-fuel ratio or dilution will complete the optimization of the process.

Keywords: Auto ignition combustion control, biomass and biogas optimal fuels, greenhouse gas reduction, duals diphasic fuel mode.

1. Introduction

Presently, the world knows of an unprecedented climate change due to global warming caused by anthropogenic activity. Industrial, Residential and transportation activities are the principal causes of carbon dioxide emission. The fossil resources still represent the principal energy

source for these sectors of activity. However, world citizens, policy makers have become aware of the crucial need to modify individual and collective behavior in the face of the climate crisis. The renewable energies seem to be a decarbonize solution to replace the massive fossil energy use. The combustion process continues to take an important place in the energy conversion system for industry, transport and residential. The renewable energy derived from biomass seems to have a high potential to meet the challenge of the energy transition. The global biomass resource is quite important, and we can estimate a reduction by five or even ten times of the GHG emissions. Integrated biomass as biofuel is relevant in the current energy conversion system for all activity sectors. The biofuels can be derived from several biomasses such as agriculture and forestry wastes, sewage sludge, or also microalgae. Indeed, the biomass diversity and its disponibility represent a real advantage for security supply and energy independence for countries. Combustion of biofuels under all its physical phases (solid, liquid and gas) is able to facilitate its integration in current conversion energy systems such as industrial burner, combustion chamber, furnace, internal engine. Combustion of biomass powder emerged in scientist work as an innovative and alternative combustion process. Previous studies have investigated the ignition and combustion of biomass particles. Riaza et al. [1] investigated the combustion behavior of several single particles of in biomass (sugarcane bagasse, natural and torrefied pine sawdust, olive residue, in a drop tube furnace and found significant differences between biomass fuels.

Whereas Mock et al. [2] investigated the burning behavior of single particles of torrefied wood and sewage sludge, coffee waste in an entrained flow reactor with cross particle injection in combustion products at 1090 K and 1340 K and O₂ concentrations ranging from 10 vol% to 40 vol%. This experimental setup was similar to those of industrial furnaces. Using high-speed photography, they observed the evolution of ignition delay time, flame volatility, soot formation tendency, char oxidation compared to different chemical and physical properties of each biomass particles. Simões et al. [3] study the ignition behavior of single particles of wheat straw, branches of kiwi, vine, sycamore and pine bark in optical McKenna flat flame burner. They concluded that ignition of the biomass particles generally occurred in the gas-phase, and that their ignition delay time decreased as the gas temperature increased. Carvalho et al. [4], examined the effects of potassium (K) and calcium (Ca) on the early stages of combustion of grape pomace pre-treated with demineralization and impregnation processes. The authors used the same experimental and measuring technique of Simões et al. [3] to conclude that the demineralization pre-treatment increased both the ignition delay time and the volatiles combustion time of the single particles. Recently, Weng et al. [5], study the combustion behavior of several single pulverized biomass particles (pine wood, wheat straw, rice husk and grape pomace) from ignition to the early stages of the char oxidation. The authors acquired temporally and spectrally resolved images of the single burning particles in a McKenna flat flame burner equipped with a biomass feeding unit and air/methane feeding system under conditions close to those encountered in real furnaces. The authors obtained data for CH*, C₂*, Na* and K* chemiluminescence, and thermal radiation from soot and char burning particles. They reported an important difference between the ignition delay time, combustion time and soot formation propensity of the four biomass residues, which are mainly affected by their volatile matter content.

These previous studies reported essentially qualitative information on the ignition behavior and volatiles and char combustion of single pulverized biomass particles under conditions similar to some industrial processes such as industrial burners, combustion chambers, furnaces. But it reveals a growing interest in the use of biomass particles in energy conversion systems.

Also, for the transport sector, there is a major challenge in the use of fuels from biomass [6-8]. Biogas can be used as a renewable fuel in internal combustion engines. However, variety in raw

materials and process of biogas production results in different components and percentages of various elements, including methane, CO₂. These differences make it difficult to control the combustion, effectively, in internal combustion engines. Therefore, it is common to use the dual fuel mode in CI and SI engine. This allows to intake a wide range of gaseous fuels. A pilot fuel is necessary to control the ignition. [9], [10] However, HC and CO emissions are very high and the thermal efficiency is quite low in dual fuel mode using biogas due to its high CO₂ content [11], [12].

Auto-ignition lean homogeneous combustion (HCCI) appears as an alternative solution to face these problems. Indeed, HCCI engine is a clean technology that reduces emissions by inhibiting NO_x and soot formation while maintaining appreciable thermal efficiency due to its high combustion rate [15], [16]. It allows higher thermal efficiencies than the SI engine because it operates at the fuel-lean condition with high compression ratios (>15) comparable to diesel engines. It can also operate with a wide range of fuels. Hence, this combustion process must face low reactivity, and it is necessary to have a well understanding of fuel behavior and adapt it in this operating range.

Therefore, using a mixture composed of fuel from biomass and H₂ is the best compromise between a very low environmental impact and engine efficiency from a carbon balance point of view. Nevertheless, HCCI combustion, to become an alternative solution, must meet several challenges, such as combustion and auto-ignition phase control, operation range [17], weak cold-start capability [18], homogeneous charge preparation [19], and higher emission rate of unburned hydrocarbons and CO [20]. The range of operating conditions in HCCI mode is usually constrained to a relatively small regime [21],[22]. Misfire is one factor that restrains the operation of HCCI engines [25]. It should be detected as early as possible to avoid engine damage and ensure stable engine operation. Engine misfire can be defined as the absence of combustion [24], the missing or incomplete combustion [25], the irregular combustion [26], and combustion failure [27]. Misfires are environmentally harmful, and modern vehicle standards require that misfires are detected and moderated in a driving cycle time frame [28]. However, among all the presented challenges, the control of HCCI combustion timing constitutes a crucial problem in homogeneous combustion. It has an essential role in determining efficiency and emissions. Thus, the principal HCCI benefits and challenges are directly linked to HCCI ignition timing.

Several strategies with various success levels have been investigated in the literature to control HCCI combustion timing and extend the load range. Most of these strategies can be grouped into two main aspects: active and passive control.

The passive control strategies do not require any energy input. Generally, it corresponds to a modification of the system, such as geometry change or fuel composition. This can include the changing of fuel properties, dual-fuel technology, exhaust gas recirculation, variable compression ratio (VCR), or variable valve timing (VVT) to increase the compression ratio [29]. The required time and conditions needed for auto-ignition vary between fuels, so changing the fuel properties in an HCCI engine effectively controls combustion timing [30].

As for SI [10, 12] or reactivity controlled compression ignition (RCCI) engines [8, 13], dual-fuel technology can be used in HCCI engine. Recently, Mahmoodi et al. [6] investigated dual fuel (reformed biogas/ diesel fuel), numerically on the combustion behavior, performance and emission characteristics of a reactivity controlled compression ignition (RCCI) engine. They show beneficial results on reduction in NO_x emission by enhancing the reformed biogas substitution ratio. The dual-fuel technology consists of creating a fuel mixture with an intermediate octane number by mixing fuels with a high/low octane number simultaneously. This has the effect of increasing fuel reactivity. However, some high-octane fuel does not

participate in oxidation reactions due to its low self-ignition tendency, increasing the hydrocarbon emissions.

Very recently, Feroskhan et al. [13], studied the operation of a Homogeneous Charge Compression Ignition (HCCI) engine using simulated biogas and diethyl ether (DEE) as the primary and secondary fuels respectively. Performance, emission and combustion parameters are measured for various biogas flow rates, composition (50 to 100% methane), intake temperatures and loads, and they investigated two ways to inject DEE at the intake port and by manifold injection. They demonstrated among others results that knock limits in HCCI mode can be extended by using augmented biogas flow rate and/or methane fraction with normal intake temperature. Nevertheless, the combination of high biogas flow and intake heating may result in misfire if DEE is injected at the intake port. At high flow rates and low engine loads, biogas can supply up to 60% of the fuel energy input, thus reducing the secondary fuel consumption.

Spark Assisted Compression Ignition (SACI) is another practical approach to bridge the gap between HCCI and SI engines [31]. Self-controlled HCCI by injection of IGR contained in an auxiliary chamber [32] or direct fuel injection into the cylinder at different stages of the engine cycle can help control HCCI combustion. It allows the combustion timing to be advanced by improving mixture ignitability or retarded by increasing fuel stratification while expanding the low and high load operating limits [30]. Although these proposed solutions can control the ignition timing of the lean homogeneous combustion, each of them has some drawbacks. On the one hand variable intake temperature and pressure and variable coolant temperature have a slow response time, while VCR and VVT are somehow challenging to implement. Practicality and cost-effectiveness are the main concerns with most proposed options, such as water injection and modulating two or more fuels. The dual-fuel engine concept can be seen as a practical solution; moreover, direct injection depends highly on the type of fuel and the injection itself [18].

In the light of all the above considerations, we proposed in this work an innovative application of lean homogenous combustion of a mixture with CH_4 , CO_2 , and H_2 . The focusing point developed in this paper will be in the strategy for the auto-ignition control of the combustion process using biomass powder.

Hence, the solution proposed in this work is an active/passive strategy that consists of injecting biomass powder into the reactive mixture. It combines the benefits of direct injection and dual fuel strategies. The ignition timing control can be assured by both the injection timing and the ignition properties of the injected particles.

Most studies in the literature as described above, are limited to the solid particle's combustion in a hot gaseous mixture, and very few consider the interaction of particles with the reactive gas mixture [35].

Based on a gaseous reactive mixture, the quasi-homogeneous species concentration will provide the optimal conditions for the non-production of soot. The injection of particles carried by gaseous vectors will introduce turbulence during the initiation and development of combustion, improving gas homogenization. The suspended particles may control and stabilize the lean homogeneous combustion of the reactive mixture and ignite it simultaneously in different combustion chamber zones, which can offset the thermal heterogeneities.

Using solid biomass as a fuel in an internal combustion engine (ICE) could be of great interest because it could combine the ICE's versatility with the large availability and the CO_2 -neutral impact of biomass fuels [14,33]. Only a few existing programs consider using dry biomass

powder in internal combustion engines [34], [35]. However, for these studies, the particles were fueled directly or indirectly to the combustion chamber and not with a controlled injection system. This method of introduction of powder is not ideal for efficiency and engine wear. On the other hand, the ability for direct injection of particles can reduce residual powder losses in the oil and improve combustion phasing, which leads to the possibility of reaching traditional engine efficiencies.

The first consideration for the development of this engine concept is to propose a controlled particle injection solution. For this purpose, an innovative solid particle injector system was designed and conceived at Sorbonne University. Its main objective is to introduce solid particles (micronized cornstarch particles are used in this work) into the combustion chamber of a rapid compression machine (RCM).

In the first section, the conceived experimental setup used for the biomass particle injection is described. In the second section, the injection system is fixed with the Sorbonne University RCM. Finally, the first particle injection effects on lean homogeneous combustion are highlighted on different mixtures corresponding to particular CH_4 , CO_2 , and H_2 proportion so as to obtain different ignition delay times. The qualitative effects of particles in controlling the ignition timing and increasing the operational range are discussed.

2. Particle injection system

2.1. Description of the injection system

The particle injection system is majorly composed of a particle suspension chamber in high pressure, a carrier gas, a hydraulic system to control the injection valves, and the particle injector. A simplified scheme describing the injection system is presented in Figure 1. The injector is based on a very high-speed needle control.

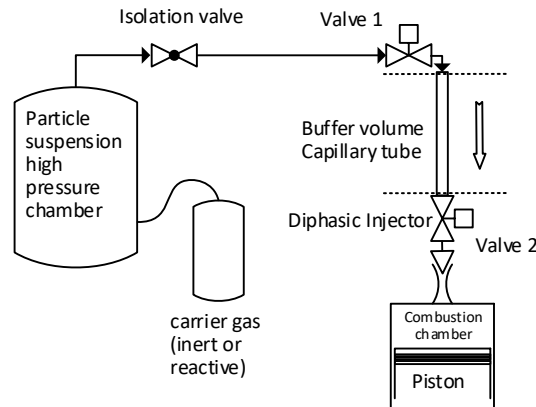


Figure 1: experimental setup of the particle injection system

Figure 2 gives a detailed 3D drawing of the particle's suspension chamber and its principal scheme. The particles are suspended in a closed chamber that is pressurized. The carrier gas flow is set in motion by a high-powered fan in a kind of closed wind tunnel. The carrier gas can be inert (nitrogen in the following application) or reactive (hydrogen, for example). This flow passes through a converging section used to accelerate the carrier gas to the minimum cross-section. The contraction rate is adjusted according to the type of particles. A divergent section allows this gas and the entrained particles to be progressively slowed down by widening the section. A sampling tube of the adapted section will take the suspended particles from this zone, which will be in homogeneous concentration, and carry them into the combustion chamber via an injection circuit. The blower circuit is of the "return" type and includes deflectors (rotation

baffles) to pre-rotate the carrier gas and particles flow. The adjustment of the pressure of the chamber must allow injection into the combustion chamber, whose pressure can be between a vacuum (cleaning process) and a pressure that must reach the maximum combustion chamber. The enclosure shall be filled beforehand with a number of particles or powders (by weighing or other means).

The pressure of the carrier gas, as well as the number of particles introduced, will define the dilution rate of the injected particles.

The suspension chamber can admit different types of particles whose physical or chemical properties, size distribution, shape, and composition will be adapted to the purpose of the applications and will allow them to control their ignition delays. In this paper, we used micronized cornstarch to an average particle size of 15 μm . Its chemical formula, similar to cellulose, is $(\text{C}_6\text{H}_{10}\text{O}_5)_n$. The melting point is reached around 257°C (530K) and 673K for the auto-ignition temperature.

The system includes a procedure for drying particles containing moisture harmful to the application process or leading to undesirable agglomeration, especially when using biomass particles.

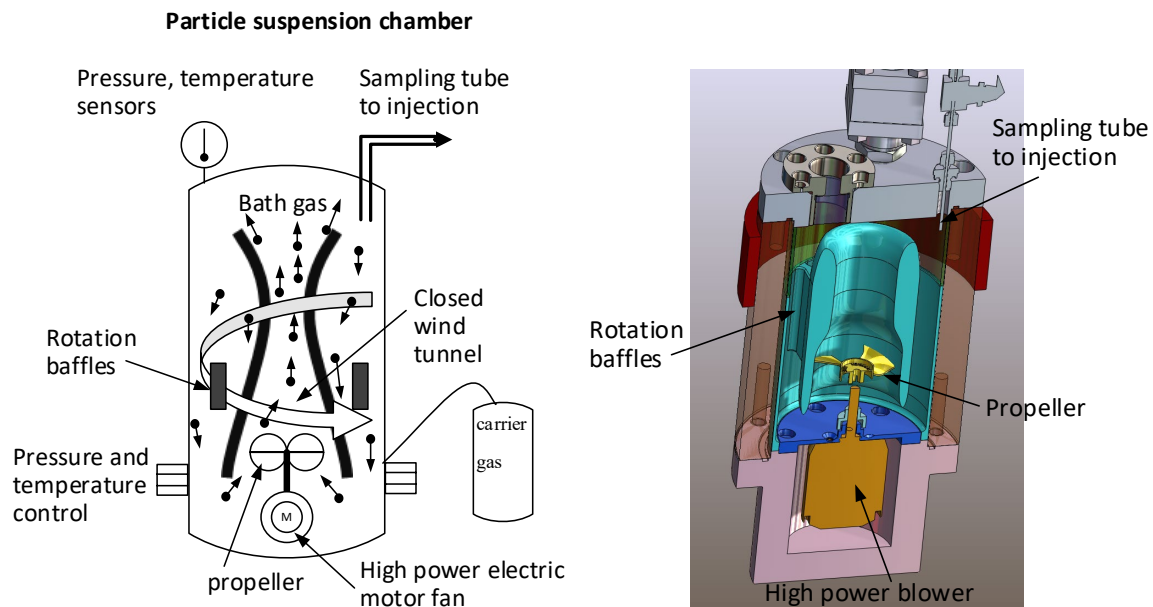


Figure 2: Detailed scheme describing the particles suspension chamber

A pressure sensor is used to measure the carrier gas pressure in the vessel, and a thermocouple to measure the suspension chamber's heating temperature. A hydraulic group is used to command the two valves 1 and 2 necessary for the particle injection. The injected volume can be defined as the volume of particles occupying the line between these valves (valve 1 and valve 2) (buffer volume).

Three modes of injection can be determined: Continuous and discontinuous injection. The first mode can occur when both valves are open simultaneously for a certain period (continuous mode). In the second mode, valve 1 must be opened first to fill the buffer volume (figure 1), while valve 2 is closed for the latter mode to happen. Once filled, valve 1 is closed, and valve 2 is opened to allow the charged volume injection into the porthole. The last mode runs as a classic liquid injector (valve 1 always open) with a valve 2 opening, closing diagram suitable to the necessary injected quantity.

The shape of the injection nozzle will be a control parameter allowing (figure 3), in particular, to obtain the angles of jet, penetration, turbulence resulting from the gas/particles injection. It will be able to homogenize the distribution of particles throughout the chamber or locate them in a particular zone to promote, as many ignition sites, combustion initiation in a specific volume of the combustion chamber.

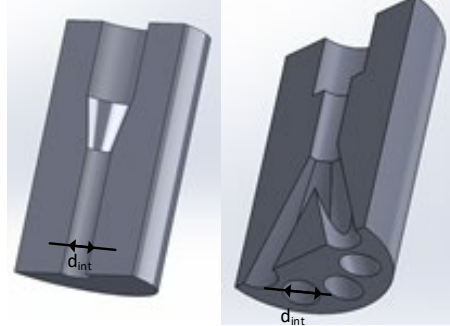


Figure 3: Two injection nozzle configurations

The first injection nozzle will be a simple tube with an internal diameter of $d_{int}=1.7$ mm. The second injection nozzle involves eight titled holes of internal diameter $d_{int}=1.125$ mm.

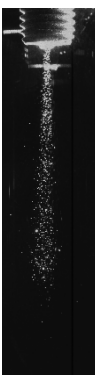
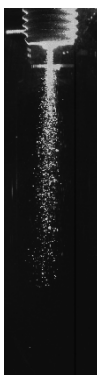
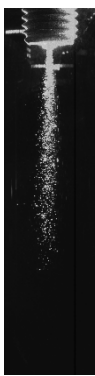
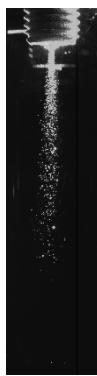
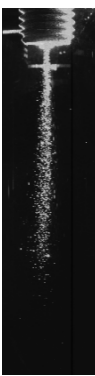
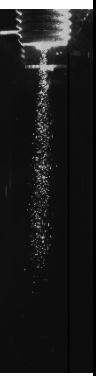
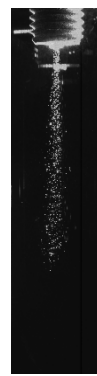
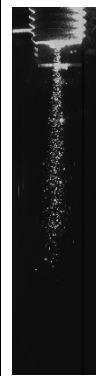
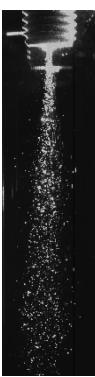
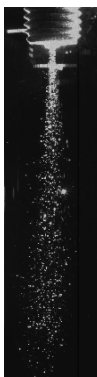
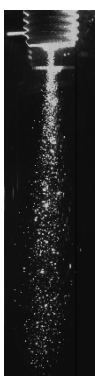
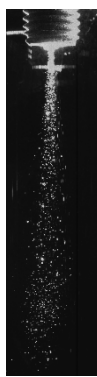
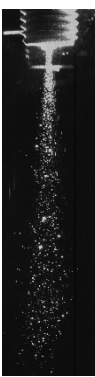
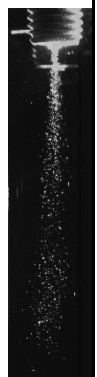
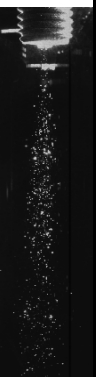
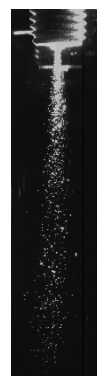
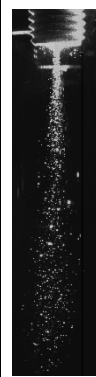
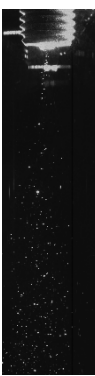
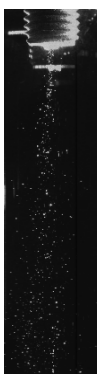
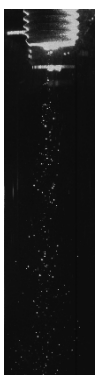
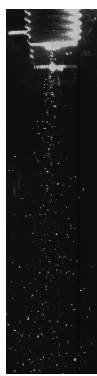
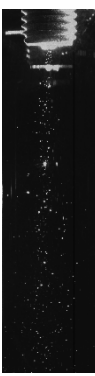
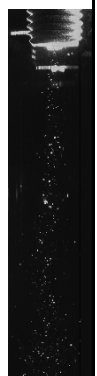
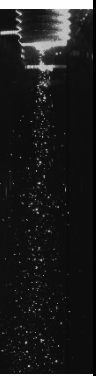
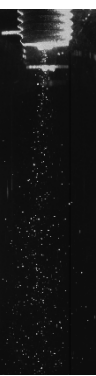
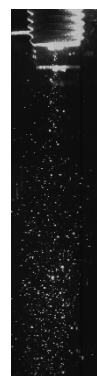
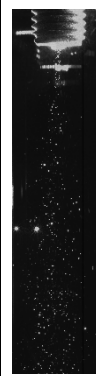
2.2. Characterization methodology

Several manufacturers conducted practical works of dry coal dust engines in pre-war Germany over the last century. Rudolf Diesel first investigated the use of dry coal dust in a compression ignition (CI) engine in 1892 but stopped due to the difficulties involved in handling a powered fuel and the subsequent fouling of the piston rings and lubricating oil [33]. R. Pawlikowski [36] then improved the engine feed system by adding a co-chamber to pre-ignite the solid fuel before injecting it into the combustion chamber. Several German companies developed low-speed engines utilizing solid fuel dust, operating between 100 and 1000 rpm due to coal dust's slow-burning rate [33]. However, the significant technical advances in coal dust engines were overshadowed by fuel delivery issues, leading to the implementation of coal slurries with liquid carriers (up to 50% coal loading) to facilitate the injection of solid fuel particles [37], [38], [39]. This technology of implementing solid and liquid fuel into the combustion chamber represents most studies in the literature related to solid fuel dust in an internal combustion engine. Recent developments of coal slurry engines have adopted several technical advancements while improving slurry development and injection for higher concentrated slurries (60– 65% coal) [35]. Some of these developments considered using dry biomass powder in engines instead of coal [33] [35]. Therefore, these works introduce an alternative method of utilizing the energy content of biomass particles by aspirating biomass suspensions directly into the intake air of an internal combustion engine.

However, in this work, the biomass powder will be directly injected into the combustion chamber. To verify the reproducibility of the injection tests, injection experiments have been conducted under atmospheric conditions. Thus, particle injection pre-tests were performed with imaging particles illuminated by a laser sheet (PIV based system). Images were registered with tens images to evaluate reproducibility with different delays generated between the command of the injection valve 2 and with the laser shot (camera is synchronized with the laser). Table 1 shows ten images registered 1 ms, 2 ms, and 4 ms after the start of injection t_0 . In the following

study, the start of injection t_0 refers to the opening of the injector (i.e., valve 2) and the mode 2 injection protocol was chosen (§3.1). The injection process lasts less than 7 ms.

Table 1: Ten registered images at three times after the start of injection. Injection (20bars) in a cylinder of stagnant air at ambient pressure

	Reproducibility tests									
Time after the start of injection (ms)	1	2	3	4	5	6	7	8	9	10
$t_1 = t_0 + 1 \text{ ms}$										
$t_2 = t_0 + 2 \text{ ms}$										
$t_4 = t_0 + 4 \text{ ms}$										

According to the registered images, the injection process is qualitatively reproducible. For the experimental fitting specific to atmospheric injection, the injection is visible 24.5 ms after the injection electric valve's command, defined by t_{SOE} (instant of the start of energizing, see Figure 6).

Many study parameters could have been discussed such as injection pressure and counter-pressure, control timing, injection mode, particle properties (shape and diameter), shape of the injection nose but it will be the subject of a specific development.

To quantify the process, Figure 4 represents the cone angle and the average vertical velocity 2-4-6 ms after the start of injection for 19 tests repeated at the same conditions. The measured parameters are shown to vary slightly from one test to another.

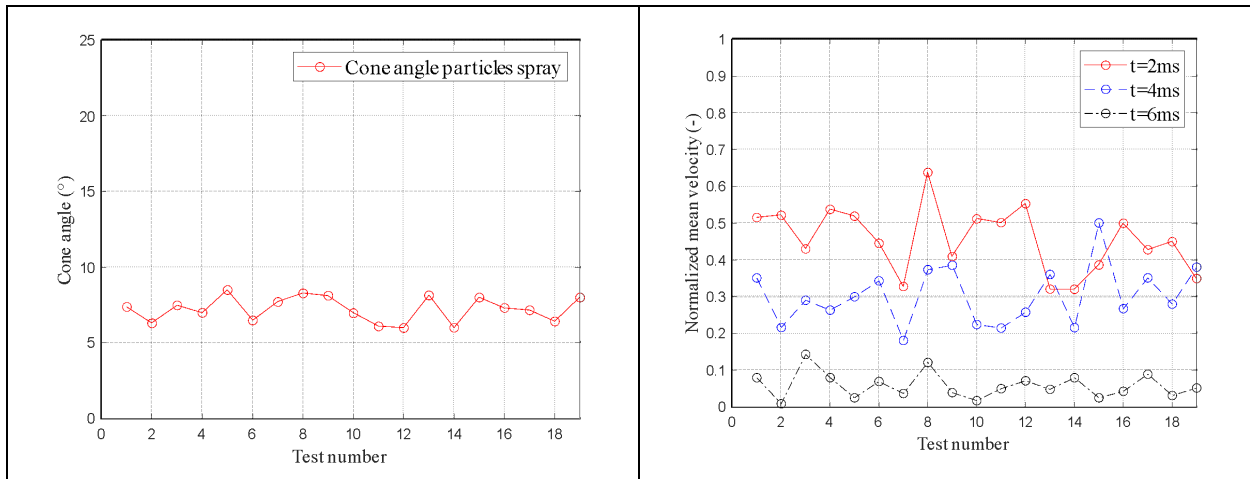


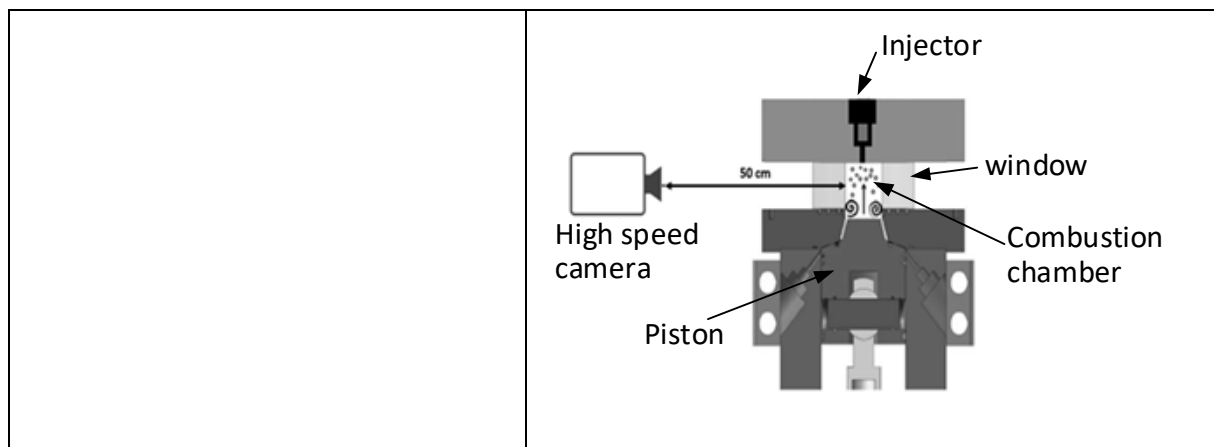
Figure 4: the reproducibility of cone angle and vertical velocity for three different times after the start of injection

3. Experimental conditions

3.1. Combustion study using a rapid compression machine

RCMs are single-shot, piston-based machines usually used to study auto-ignition phenomena at controlled conditions. Moreover, auto-ignition processes in RCMs represent those that occur within combustion engines, where these evolve through multiple thermo-chemical regimes.

Figure 5. shows a schematic diagram of the Sorbonne University rapid compression machine.



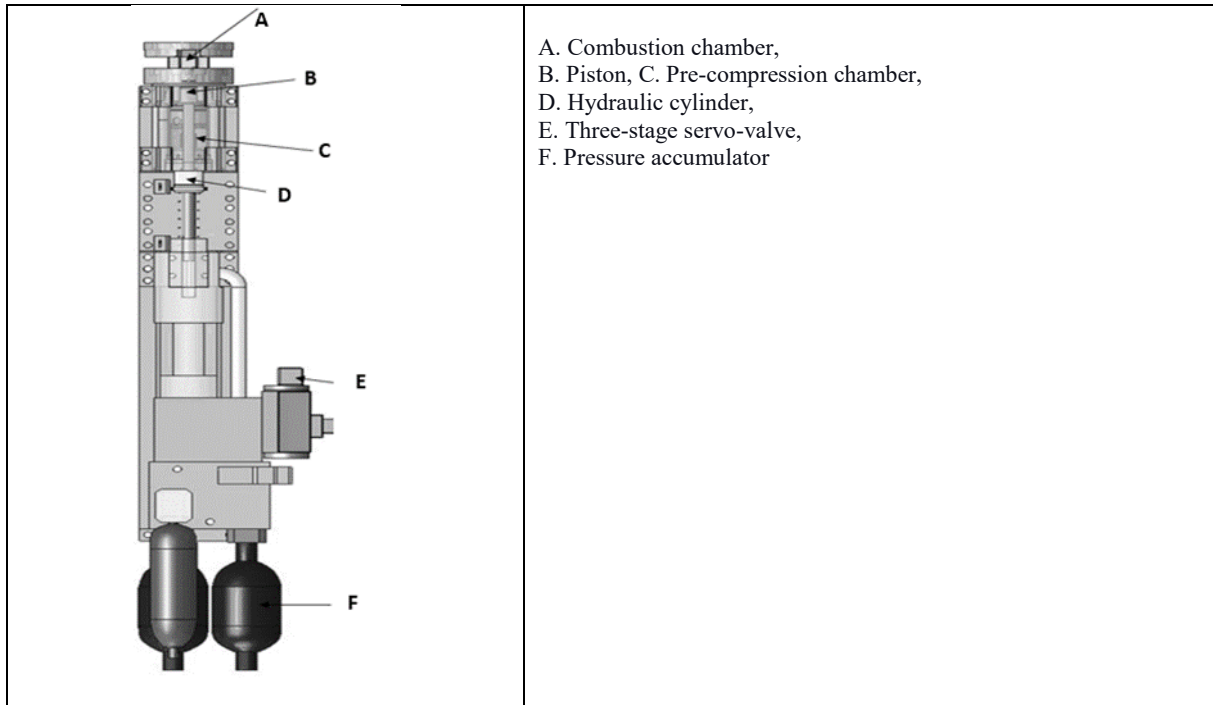


Figure 5: Schematic diagram of the SU rapid compression machine and schematic diagram of the experimental setup

The machine consists of four main components: the hydraulic system, the single-piston moving inside the pre-compression chamber, the combustion chamber, and the control and acquisition system. The hydraulic system consists of a hydraulic power unit, five oil pressure accumulators, a three-stage servo valve, and a hydraulic cylinder. This system controls the movement of the piston and allows it to compress the gas mixture in the pre-compression chamber. In its final position, the piston is locked at the top dead center (TDC), keeping the compressed gas in the combustion chamber to maintain high pressure and temperature for a longer time.

An ASM micrometer-scale, equipped with a sensor, examines and measures both the position and the speed of the piston. This type of control makes it easy to change the stroke, thus the compression ratio and the compression profile of the piston motion. The experiments in this work were conducted with a 150 mm long-stroke, leading to a compression ratio of 15. The piston velocity and dock characteristics were chosen to have a relatively short compression time of 30 ms to avoid chemical reactions in the compression phase. The converging section between the combustion chamber and the pre-compression chamber provides adequate volume for the turbulence grids set. A detailed technical description of the machine can be found in Ref.[41].

The combustion chamber is made of quartz for large optical access with a 40 mm diameter and a 40 mm height. The injection system described earlier in this paper was implemented into the combustion chamber center to allow the direct injection of solid particles. The combustion process is studied by direct visualization using an intensified camera, Phantom Fastcam.

The images provided by a high-speed camera were acquired with a resolution of 640x480 pixels, with 8 bits of depth. Along with the acquisition frequency, the exposure time must be chosen wisely [42]. Thus, all images were registered with 10 kHz and an exposure time of 99 μ s. The studied mixture is prepared manometrically inside a large vacuum tank of 30 liters to allow dozens of shots with the same load. It is equipped with a propeller to make the mixture homogeneous and a capacitance diaphragm manometer for measuring partial pressures. The

vacuum is made inside the whole test section through the exhaust port before the mixture admission.

Once the gaseous mixture is prepared, it is fed into the RCM pre-compression chamber via a heat-insulated Teflon tube and kept at 55°C (328 K) using heating fibers. The piston is then fired to compress the mixture into the combustion chamber and start the combustion process. The experimental procedure is kept the same for all studied tests to ensure the reproducibility of the process.

The main technical characteristics of the experimental setup are summarized in Table 2.

Table 2: Technical characteristics of the presented experimental setup

Stroke length (mm)	150
Compression ratio	15
Compression time (ms)	28-30
Pressure measurement	Piezoelectric pressure transducer Kistler 601 A range
Maximum allowed pressure (bar)	40
Heating system	Cylinder head and cylinder liner heated to 328K. The piston is also heated indirectly from the liner.
Chamber diameter and height (mm)	40 x 40
Transparent chamber material	Quartz

3.2. Studied mixture

The effects of solid particles on the combustion of gaseous mixtures are studied in this section. Some preliminary observations on the interaction of solid particles on the ignition and combustion processes of a reactive gas mixture can be underlined.

The idea is to take a mixture that does not burn for a high compression ratio or a mixture with a high auto-ignition delay. Increasing the compression ratio leads to an interesting rise in cycle efficiency. The particle injection timing then completes the management of the combustion cycle.

The search for an ideal composition (biogas, syngas, H₂) is not presented in this paper but remains the goal of this research. The general concept is presented in order to achieve the following objectives

- an ideal fuel which emits at the source few polluting emissions,
- a sustainable CO₂ balance,
- management of diluted (lean or not) combustion thanks to an addition of H₂ allowing a favorable reactivity and low pollutant emission,
- Multiple spot combustion (several spots of auto ignitions thanks to the injection of biomass particles).

This study will show whether the particles initiate the combustion of the gas mixture, how the gaseous mixture starts to ignite, and the interaction of the combustion propagation subsequently finishes to burn the particles.

The dilution rate controls the temperature of the compressed load by changing the proportions of diluted gases [43] [44]. In order to achieve homogeneous combustion, a significant amount of charge dilution must be present [19].

The studied mixture is a biogas CH₄/CO₂ enriched with 12.3% hydrogen and diluted with 70% Ar/N₂/CO₂. The equivalence air-fuel ratio is maintained at 0.6. As the objective being to be able to visualize the combustion process, the mechanical strength of the windows requires limiting

the pressure in the chamber. Thus, an end of compression pressure of 8 to 11 bars was chosen, with a low to an intermediate temperature of 940 - 990 K, mainly chosen to reduce NO_x emissions.

The experimental conditions are presented in Table 3.

Table 3: Biogas/syngas mixtures studied with solid biomass particles

Mixtures	Biogas enriched with Hydrogen			Diluents			O ₂ (molar fraction)	Φ (-)	Pressure (bar)	Tempe. (K)
	CH ₄ (molar fraction)	CO ₂ (molar fraction)	H ₂ (molar fraction)	Ar (molar fraction)	N ₂ (molar fraction)	CO ₂ (molar fraction)				
1	0.043	0.035	0.011	0.616	0	0.084	0.211	0.6	8	940
2	0.043	0.035	0.011	0.587	0.113	0	0.211	0.6	8	990
3	0.043	0.035	0.011	0.65	0.015	0.035	0.211	0.6	11	990

Each of these mixtures has its particularity in terms of combustion in such a way that they cover three different combustion behaviors which will be discussed in paragraph 5.

The particles will be injected into the reactive biofuel mixture compressed at an injection pressure of 20 bars.

4. Solid biomass particles ignition and combustion process

The combustion process of biomass particles is carried out in four steps: heating and drying (water vaporization), devolatilization (pyrolysis), combustion of gases, and char burning [45]. Lignocellulosic material is primarily composed of macromolecular substances (cellulose, hemicellulose, and lignin) with smaller amounts of low molecular weight substances: extractives and inorganics (salts or minerals). Biomass has a porous structure and consists of cells [46]. The process of biomass combustion involves several physical and chemical aspects of high complexity.

Drying and pyrolysis/gasification will always be the first steps in a solid fuel combustion process. The importance of these stages will depend on the combustion technology implemented, the biomass properties, and the combustion process conditions. Unlike gaseous fuels, which react with an oxidizer agent through well-studied mechanisms, solid fuels pyrolyze first before the occurrence of any subsequent ignition. Pyrolysis can be defined as thermal degradation (devolatilization) in the absence of an externally supplied oxidizing agent. When the dry biomass temperature reaches between 200°C and 350 °C, the volatile gases (CO, CO₂, CH₄) and high molecular weight compounds (tar) are released.

Similar to gas combustion, the ignition temperature and delay time are key parameters in studying solid combustion. Generally, particle ignition requires reaching the auto-ignition temperature of particles to trigger the chemical reactions.

Three modes of ignition can be identified for biomass or coal particles according to the timing of the ignition onset [47]:

- Homogeneous ignition characterized by sequential combustion of volatiles and char. The ignition first occurs in the gas phase (volatile matter) around the particle, resulting in a flame envelope formation preventing oxygen from reaching the surface of the particle. This results in a delay in the char ignition till the end of the devolatilization stage.
- Heterogeneous combustion where the ignition first occurs in the solid residue (char) at the particle's surface, resulting in simultaneous combustion of volatiles and char.

- Hetero-homogeneous ignition where the ignition first occurs in the gas phase near the particle surface without forming a flame envelope.

The ignition studies of biomass fuels are limited, while most of the experiments focused on coal [48], [49].

Several methods were identified in the literature to determine the ignition time of the solid combustion. However, methods based on optical diagnostic techniques are the most widely used. According to the study of Molina and Shaddix [50] on the combustion of bituminous coal diluted particle jets in an entrained flow reactor, the start of the ignition is defined based on the CH* chemiluminescence emissions. Yuan et al. [51] determined the ignition characteristics of diluted coal particle jets using the residence time when the intensity reached 10% of the maximum peak intensity value. More recently, Khatami et al. [52] and Riaza et al. [53] studied the ignition delay time of coal particles in a drop tube reactor under different conditions. They defined the ignition delay time as the time between the initial entrance of a particle in the reactor and the first appearance of luminous combustion.

Thus, the parameters influencing the ignition process of powder are in particular the temperature, oxygen concentrations, and the type and size of these particles. The ambient temperature has a significant effect on ignition and combustion. It was shown in the literature, that an increase in the temperature leads to a decrease in the ignition delay time of solid particles [54], [47], [55].

Oxygen content and particle size are also key factors that affect the combustion properties of solid particles. It was proved by several authors that the ignition delay times decrease with the increase of oxygen concentrations [52], [57], [60]. Oxygen can potentially impact ignition behavior by promoting the devolatilization process.

Simoes et al. [54] studied the ignition delay times of biomass samples on a McKenna flat flame burner for different thermal input, oxygen concentrations, and biomass properties. The ignition delay times of pine bark (13.9% moisture) and wheat straw (8.9% moisture) particles in size 224-250 micrometers were between 10-28 ms for gas temperature range 1500-1800 K, and oxygen concentrations 3.5-7.6 %. These delays are reduced to 8-18 ms for a smaller particle size of 80-90 micrometers.

Fatehi et al. [47] also conducted experimental studies on the ignition delay times of solid biomass. They showed that the ignition delay times of wheat straw 80 microns were 10-15 ms for gas temperature 1500-1800 K and oxygen concentrations of 6.5 %.

Li et al. [55] investigated the ignition behavior of biomass particles experimentally in a down-fire reactor for a lower temperature range. In this study, cornstarch particles were used to determine the effects of solid biomass on the reactive gas qualitatively. It is a polysaccharide comprising glucose monomers joined in α -1,4 linkages. Its chemical formula, similar to cellulose, is $(C_6H_{10}O_5)_n$. Many studies in the literature were conducted to determine the decomposition of cornstarch using thermogravimetric analysis (TGA) and differential thermal analysis (DTA). According to these tests, the ignition temperature of cornstarch for different initial conditions was around 550 K [59], [60], [61].

The studied temperature of the reactive gas is 940 K, and the mean size of particles is 15 μ m. An approximate polynomial fit was applied to the results of Li et al. [55], of the ignition delay time of softwood as a function of particle size for temperature 862 K. Hence, for this temperature, the ignition delay time of softwood (15 microns) can be estimated to 50 ms [56]. For a temperature of 940 K, the delay is estimated to be shorter, and thus, we expect an ignition delay time of a few milliseconds. The chronogram synthesizes the process observed during the tests on the rapid compression machine.

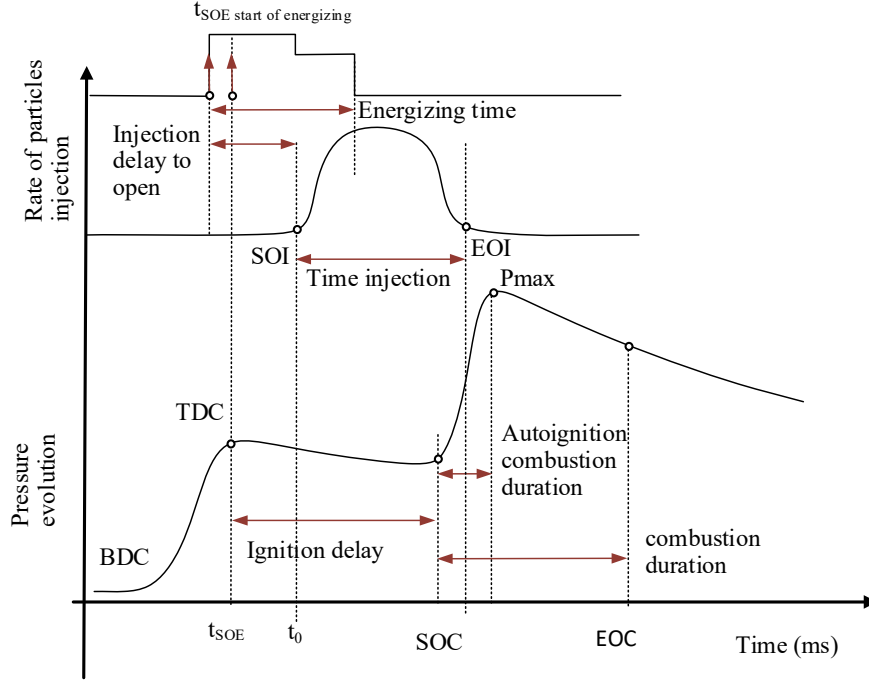


Figure 6: chronogram of the control of the injector (2), the needle lift and the pressure evolution

5. Results and discussion

5.1. Mixture 1

The experimental combustion of the three studied mixtures was performed more than ten times to verify the reproducibility of the combustion process. The injection timing t_0 (Figure 6) was performed at the top dead center (injection TDC) or 5ms before the TDC (injection BTDC). To illustrate the behavior of two-phase combustion, on the whole of the tests, we propose 2 illustrations whose behavior differs noted injection 1 and injection 2. The operating conditions remain however the same.

Figure 7 shows the pressure curves evolution for combustion with and without particle injection. The combustion occurs after a certain period of time for all of them (injection delay to open, particles self-ignition delay).

Mixture 1 was deliberately chosen not to burn under these experimental conditions. The results clearly show that it is the particles that initiate the ignition of the gas mixture. The auto-ignition delay of 38-42 ms (see table 4) is a long delay that leads to deviations in behavior (visible variability in the pressure curves). The thermodynamic conditions imposed by the RCM are outside the ideal conditions of adiabatic compression and involve temperature heterogeneity due to heat transfer to the walls. Beyond thermal transfer, the heating and drying processes (water vaporization), and devolatilization (pyrolysis) are also impacted by the thermal history.

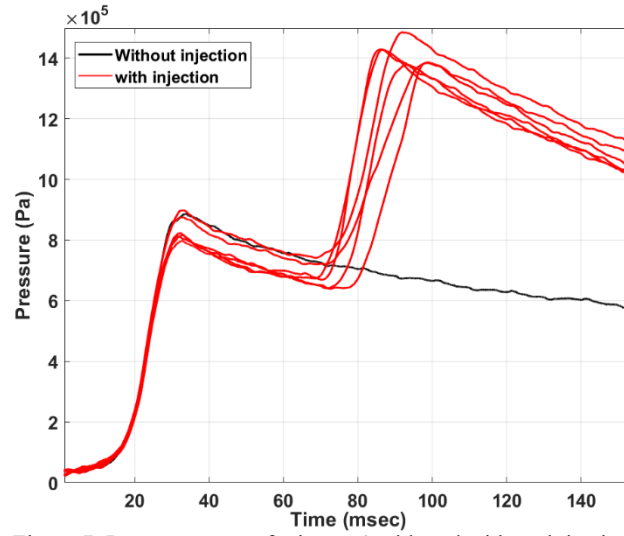


Figure 7: Pressure curve of mixture 1 with and without injection

Table 4: Combustion characteristics of the injection tests

Test	Auto-ignition delay times (ms)	Autoignition combustion duration (ms)	The velocity of pressure rises (MPa/ms)
Injection Tests	38-42	17-22	~0.036-0.047

Injection 1			
45 ms ATDC	45.6 ms ATDC	46.3 ms ATDC	48.1 ms ATDC
50.6 ms ATDC	51.9 ms ATDC	53.1 ms ATDC	54.4 ms ATDC
Injection 2			
40.5 ms ATDC	41.7 ms ATDC	42.9 ms ATDC	44.2 ms ATDC

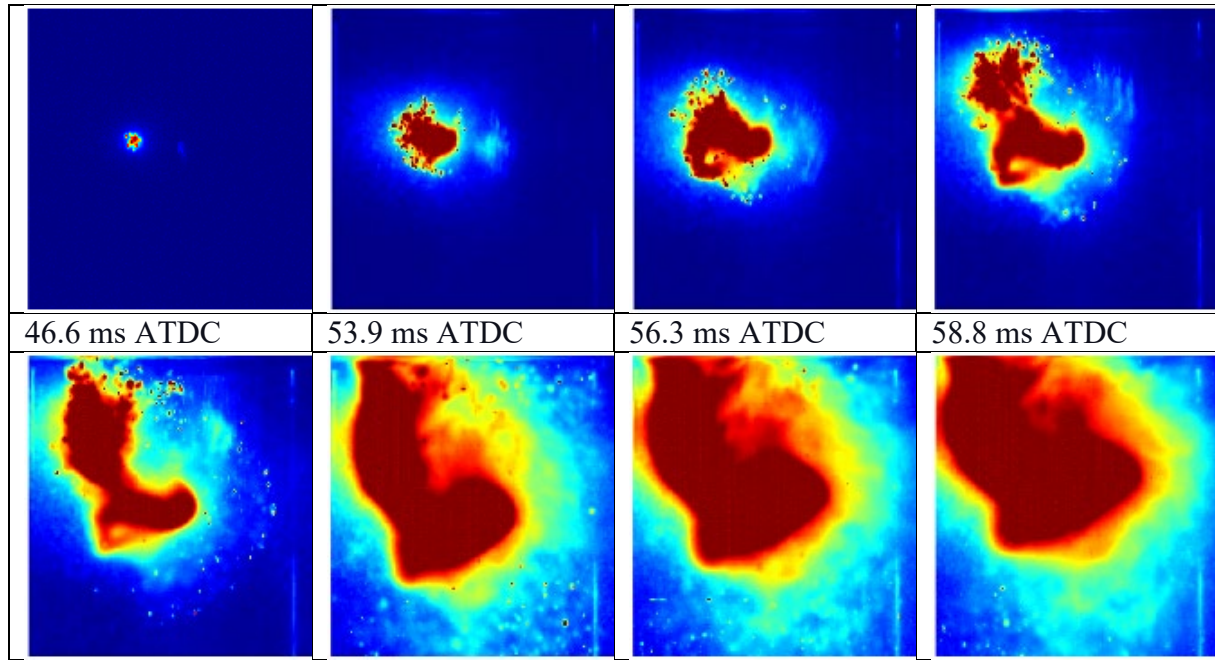


Figure 8: Combustion images of two different injection tests

According to these images, the combustion process (initiation and propagation) is influenced by the injection of a small amount of solid biomass. The difference in the combustion propagation is easily seen by comparing these images with the classic gaseous combustion of a reactive gas mixture. One must have in mind that the temperature in the chamber is not homogeneous and explain the localization of the start of the combustion [67].

For each injection test, the combustion is initiated by the ignition of one to several particles in the upper ‘injection 1), or center part (injection 2) of the chamber. The propagation of the combustion is highly dependent on the distribution of the particles in the chamber. For the first presented injection test, the particles located in the upper part of the chamber start to ignite and initiate the combustion of the gas mixture; the combustion then propagates throughout the chamber. For the second injection test, the combustion is initially initiated by particles in the center of the chamber. Other particles start to ignite after a certain time; then, the initiated sites are reunited and propagate in the chamber.

It is important to note that a particle that does not burn is not visible. In both illustrations (injection 1 and 2), after ignition, the propagating front initiates the particles surrounding the flame envelope. Many light spots are located around the most reactive area (red color)

5.2. Mixture 2

That time, the chosen mixture is reactive and gives an auto-ignition delay of 51ms without the injection of particles. The evolution of the pressure curve for combustion with and without particles is presented in Figure 9.

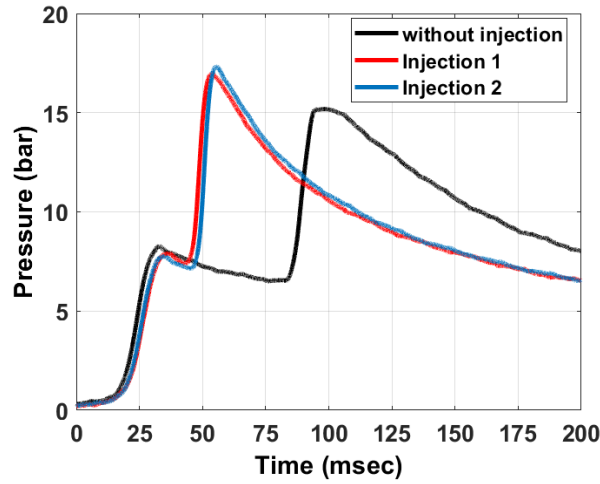


Figure 9: Pressure curve of mixture 2 with and without injection

Similar to mixture 1, the pressure curves indicate that the particle injection promotes the combustion of the gas mixture. With the injection of particles, the ignition delay time is significantly reduced from 51 ms in gas combustion to less than 15 ms in gas/solid combustion. Injection tests 1 and 2 exhibit quasi the same effects on pressure and heat release curves. Moreover, the pressure curve analysis shows that the combustion duration is reduced for the case with particle injection from 10.8 ms to 9ms (Table 5).

Table 5: Combustion characteristics of the mixture 14 with two injection tests

Test	Auto-ignition delay times (ms)	Auto-ignition combustion duration (ms)	The velocity of pressure rises (MPa/ms)
Without injection	51	10.8	0.08
Injection 1	11.4	9	~0.11
Injection 2	13	9	~0.108

Figure 10 show images of the combustion behavior of mixture 2 with and without particle injection.

Without injection			
50.1 ms ATDC	52.7 ms ATDC	54.2 ms ATDC	55.1 ms ATDC
56 ms ATDC	56.5 ms ATDC	57.7 ms ATDC	61.4 ms ATDC

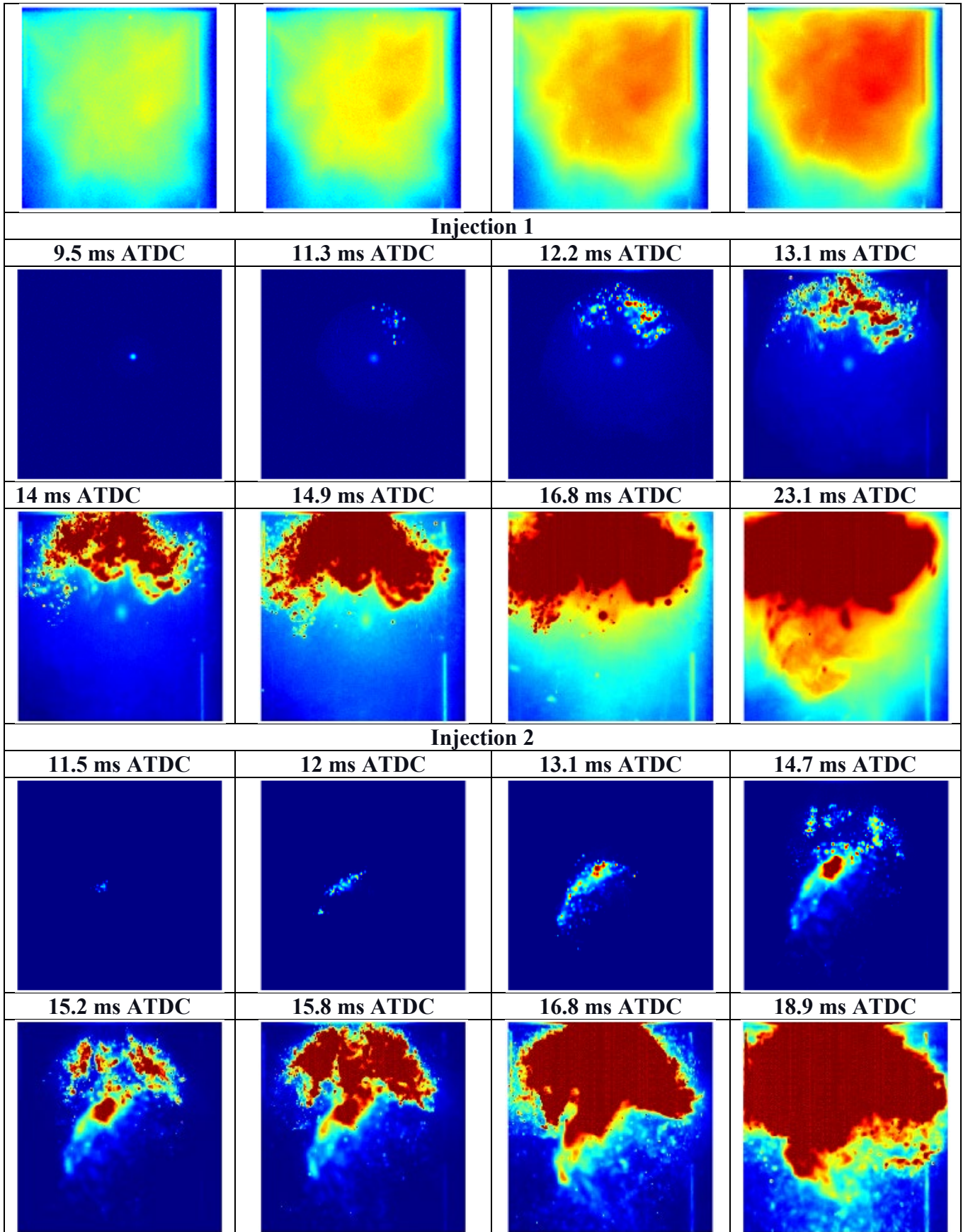


Figure 10: Combustion of mixture 2 with and without particle injection

For injection test 1, the first ignition site is initiated by a particle combustion 9.5 ms after the top dead center. Its produced energy, along with the thermodynamic conditions in the chamber are sufficient to start the combustion of the gas phase around the incandescent particle. This combustion behavior is similar to a flame front propagation from a spark plug ignition.

A spherical propagation with a pale blue colour is visible at 11.3ms. Then, at the passage of the flame front, several particles grouped towards the top of the chamber start to burn and initiate a mass self-ignition of the solid phase.

From image observation, the two modes of combustion seem to be present. The first initiated by a single particle propagates a spherical laminar flame of low intensity in the chamber and the second from multiple site particles in combustion that initiate a mass self-ignition towards the 14ms.

For injection test 2, the particles were ignited 11.5 ms after the top dead center.

The behavior is quite different than for the first injection, as it is not possible to distinguish a propagation front. Combustion takes place at multiple sites of self-ignition, linked to the location of the particles.

To summarize, the solid particles promote the ignition of mixture 2 and induce a change in combustion behavior. Without injection, the combustion was shown to ignite and propagate in the upper part of the combustion chamber, whereas, with particle injection, multi-sites combustion is favored for all the injection tests. The main difference occurs in the particle distribution in the combustion chamber one cycle to another and in the way of the combustion propagation which can suggest two possible behaviors (a dual case implies flame front and auto ignition of particles and gas, and an auto-ignition case where particles and gas produce combustion by mass self-ignition).

5.3. Mixture 3

The last case was chosen in order to give an example of a quasi-same time delay auto ignition of the particles and the gas. The evolution of the pressure curve for combustion with and without particles is presented in Figure 11.

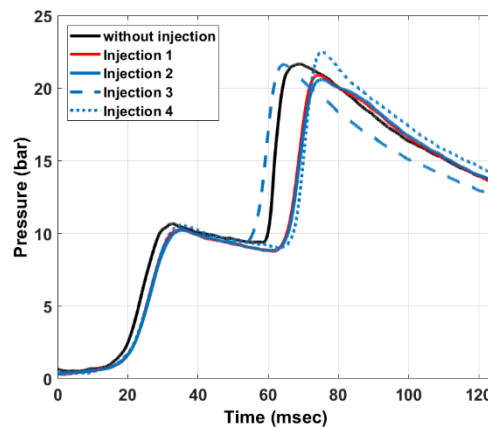


Figure 11: Pressure curve of mixture 3 with and without injection

Combustion data from Figure 11 are summarized in Table 6 below.

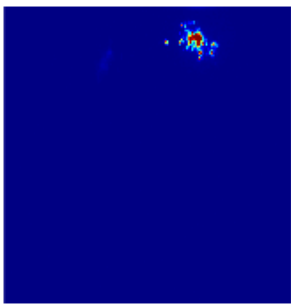
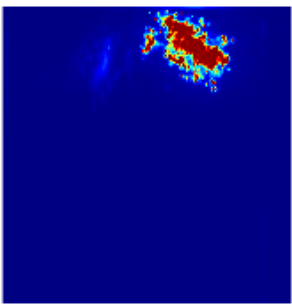
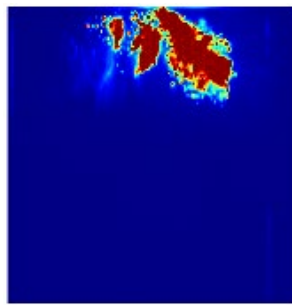
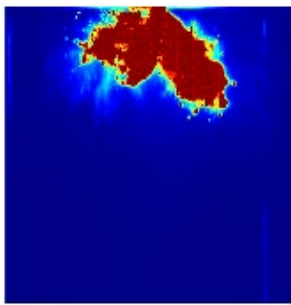
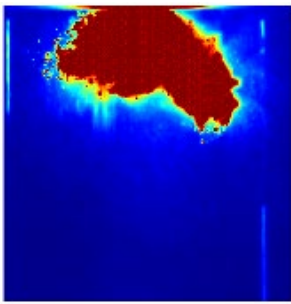
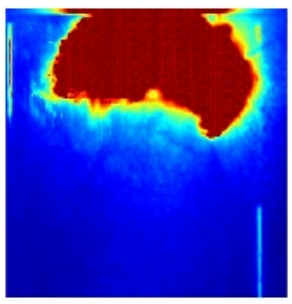
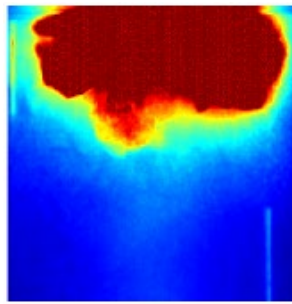
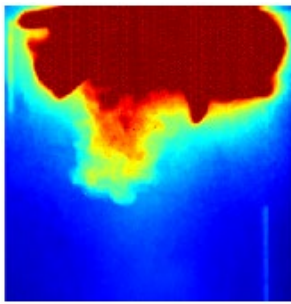
Test	Auto-ignition delay times (ms)	Auto-ignition combustion duration (ms)	The velocity of pressure rises (MPa/ms)
Without injection	28.6	9	~0.13
With injection	Injection 3= 21	9	~0.12
	Injection 1, 2, 4 ~30	11.5	~0.10

Table 6: Combustion characteristics of the mixture 3 with four injection tests

According to the pressure curves (Figure 11), two different observations emerge. First, the pressure curve of injection 3 indicates that the particles promote the combustion of the gas mixture. The ignition delay time is reduced from 28.6 ms in gas combustion to 21 ms in gas/solid combustion.

On the other hand, tests with injections 1, 2, and 4 have identical pressure evolution, and the ignition delay times are shown to be longer (~30 ms) than that of the gas mixture without injection (28.6 ms).

What is remarkable in these tests is that it shows a bifurcation of behavior, where we switch to a solid combustion initiation in one case, or to a gaseous combustion initiation in the other case. To better understand the process, it would be necessary to better master the whole chain that induces the combustion delays (temperature heterogeneity, particle size distribution and humidity and pyrolysis process, heat transfers...). The images of the combustion process of two injection tests are presented in Figure 12 to further explanation.

Injection 1			
28.2 ms ATDC	29.3 ms ATDC	30.3 ms ATDC	31.4 ms ATDC
			
33.5 ms	35.5 ms	40.8 ms	42.9 ms
			
Injection 3			

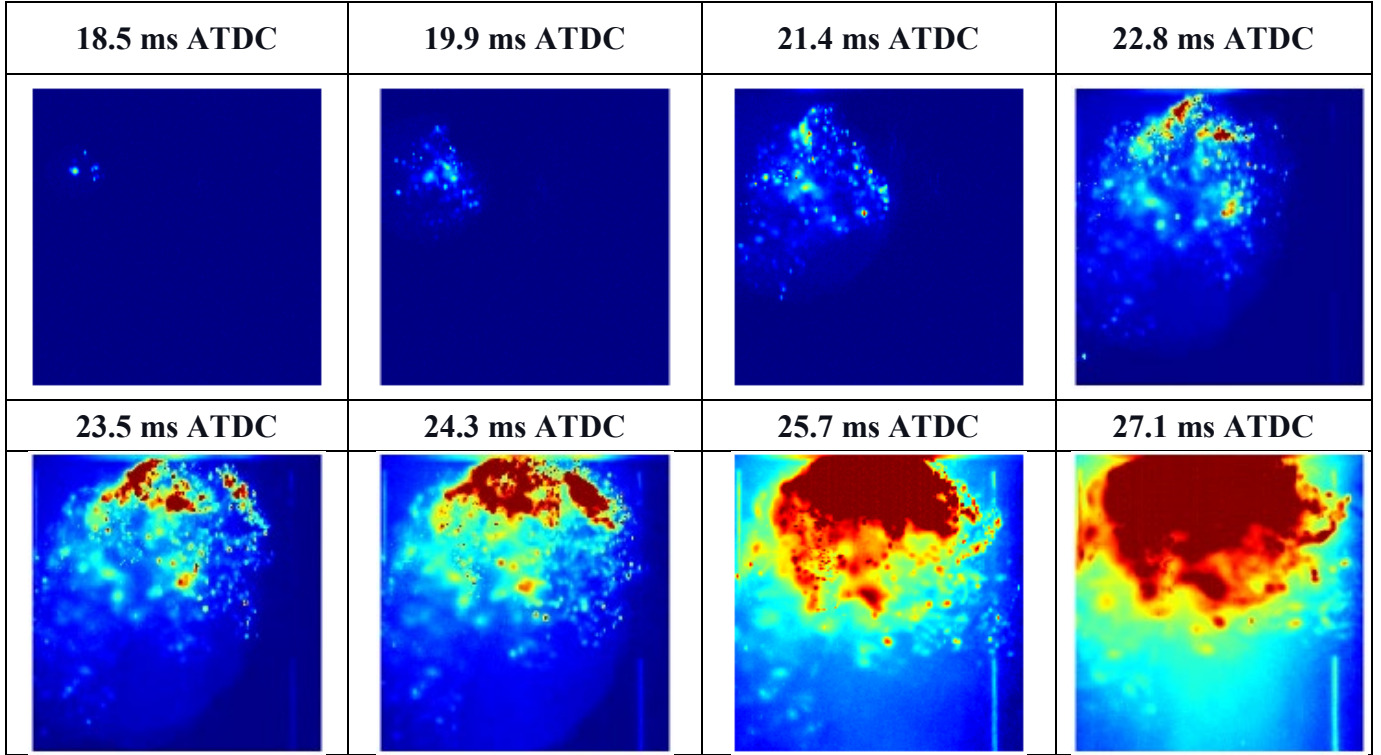


Figure 12: Combustion of mixture 3 with four-particle injection tests

Sets of images for injection 1 (also representative for injections 2 and 4) and 3 show the two combustion modes encountered above. The gaseous combustion takes over in a different way. For mixture 3 (injection 1), it is mass combustion that occurs between 33.5 and 35.5 ms, whereas, for mixture 3 (injection 3), we find a similar behavior compared to mixture 1 or mixture 2 (injection 1), with a spherical propagation of the flame in the chamber.

5.4. Discussion

Mixtures 2 and 3 have the same end of compression temperature (990 K). However, for the same injection timing, the particles ignite in mixture 2, about 8-19 ms earlier than in mixture 3. This can be explained by the difference in fuel composition; Mixture 3 is richer in carbon dioxide with higher heat capacity. This will cause a decrease in the thermal diffusivity of the mixture; the ignition delay of solid particles increases in mixture 3. This effect of the heat capacity of the ignition of the solid particle was validated by several authors in the literature. Molina and Shaddix [50] verified an increase in the ignition delay time of solid coal in O_2/CO_2 mixtures, claiming that such differences were due to the change in the heat capacity of the mixture gas, which leads to an increase the heat losses from the particle and delays ignition. Moreover, Zou et al. [66] studied the ignition of a single particle in a drop tube reactor and stated that the higher thermal capacity could reduce the rate of temperature increase of the particle, resulting in a higher delay of the ignition.

This result is very important as it highlights the dependency of solid ignition on the thermodynamic and transport properties of the reactive gas mixture.

As to summarize and explain the particles promoting effect, two configurations are possible:

- After the heating, drying, and devolatilization of the injected particles, the produced volatiles (mainly consistent with CO_2 , CH_4 , and CO) or char burn with oxygen. The combustion is exothermic, and it will provide the gas mixture with sufficient activation energy for the chemical reactions to occur.

- The produced volatiles changed the composition of the gas mixtures by creating locally rich mixtures, which will activate the chemical reactions and provoke the combustion of the mixture.

The most important points to be highlighted:

- The chemical and thermal effects of particles promote combustion.
- The ignition delay times of the gas/solid mixtures can be easily controlled but some more insight into the interaction gas-solid biphasic mixture must be explored.
- Direct injection of solid particles was shown to control the start of combustion and reduce the misfire region of the combustion.
- The ignition of solid particles depends on the transport properties of the gas mixture.
- Good optimization of the characteristics of gas/particles leads to a better combustion process.

In future studies, it would be interesting to study the different behavior related to different types of biomass, particle shapes, and size on the diphasic combustion gas/solid. Furthermore, a parametric study on the effects of the injection pressure, particle diameter, and fuel composition can be performed to understand under which conditions the two combustion modes appear

6. Conclusions

Around the world, C40 cities [68] are taking bold climate action, paving the way for a healthier, more sustainable future. Cleaning up the air that citizens breathe is a priority. To date, more than 40 of the 96 cities that make up the C40 have committed to implementing the commitments of the Paris Agreements (United Nations Framework Convention on Climate Change, 2015). 2024 is the starting point for banning diesel cars from the city center in Paris, and the same will happen a few years later for gasoline vehicles. Is this a sign of an irreversible local dynamic? It should be noted that the debate on the internal combustion engine is broader than the prism of the passenger car fleet. There is a whole industrial sector where the power involved, the applications, the weight constraints will not be able to find solutions in today's technological conditions in the all-electric engine (trucks, agricultural machines, cranes, airplanes ...). When we talk about the internal combustion engine, we think of its origins in 1897. With all due respect to Rudolph Diesel [69], internal combustion engines have become very mature and rather pragmatic in the meantime. The performances are the result of important technological innovations: direct fuel injection, developed as finely modulated multiple injection, variable valve timing, variable aerodynamics and turbulence control, mixture preparation, variable volumetric ratio, massive electronics, supercharging and downsizing, on-board management and 48V electrical power supply, post-treatment, fuel reformulation. The main objective of these developments was to reduce pollutant emissions (NO_x, particulate matter, CO, HC, etc.), although CO₂ was excluded.

Now, it would therefore be natural to switch to less carbon-intensive fuels, but in the best case to those that follow a virtuous life cycle (renewable carbon) or carbon-free fuels. The use of solid biomass (in the form of powders) is an interesting avenue. Biomass for fuels, biogas and chemistry would allow us to move away from fossil fuels and reduce greenhouse gas emissions. Moreover, the introduction of hydrogen as a fuel is an extremely interesting component.

Therefore, the characteristics of methane/hydrogen lean combustion were investigated in this paper in a new approach based on dual fuels with the use of biomass particles.

The proposed concept is based on two elements, one technological, the second operational. We propose a direct particles injection system for which we can control the particles density, the carrier fluid, the timing respecting the characteristic times of the combustion cycles and other parameters seen in paragraph 3.1. The second one refers to the use of a dual fuel where the gaseous fuel has an important auto-ignition delay while the second one (solid particles) is weaker. The innovation consists in the use of micronic particles of biomass which will play the role of multi spot of ignition. The penetration of these particles is unlike a liquid fluid, it is a lagrangian discrete dispersion and allows ignition of each particle independently.

The choice of a mixture of methane CH_4 , H_2 , CO_2 , O_2 , N_2 is an advantage as it would allow for increased compression ratio without generating knocking. We could consider other carbon-free fuels such as NH_3/H_2 which has similar properties. We could then keep the structure of diesel engines by making them work in homogeneous combustion mode with a multiple site ignition generated by biomass particles. The diesel engine would be transformed into a gasoline engine with a higher compression ratio than that of the spark ignition engine, which would promote efficiency.

From this work, it is believed that the characteristics of $\text{CH}_4/\text{H}_2/\text{CO}_2$ combustion with particles/gas injection can be widely understood, and this could lead to the development of an optimized fuel and combustion process. As further work, a real application of the concept on engine and not on RCM would be important. The concept could validate the problem of reducing NO_x , CO and CO_2 emissions.

The direct injection of solid biomass is a promising strategy in controlling the homogeneous ignition and reducing the misfire region. This could be a technological breakthrough for a new internal combustion engine. These results suggest an alternative technique to existing biofuels, it consists of modifying an engine to obtain low-refined fuels instead of converting solid biomass into liquid or gaseous fuels.

7. Nomenclature

HCCI: Homogeneous Charge Compression Ignition

RCCI: Reactivity Controlled Compression Ignition

R.BG: Reformed Biogas

RCM: Rapid Compression Machine

CCS: Capture Carbon and Storage

GHG: Green House Gas

TDC: Top Dead Center

BDC: Bottom Dead center

ATDC: After the Top Dead Center

BTDC: Before the Top Dead center

SOI: Start of Ignition

EOI: End of Ignition

SOC: Start of Combustion

SOE: Start of Energizing

VCR: Variable Compression Ratio

VVT: Variable Valve Timing

SACI: Spark Assisted Compression Ignition

ICE: Internal Combustion Engine

ASM: micrometer contactless Hall-based magnetic position sensor

8. References

- [1] J. Riaza , R. Khatami , Y.A. Levendis , L. Álvarez , M.V. Gil , C. Pevida , F. Rubiera , J.J. Pis , Combustion of single biomass particles in air and in oxy-fuel conditions. *Biomass Bioenergy* 64 (2014) 162–174. <http://dx.doi.org/10.1016/j.biombioe.2014.03.018>.
- [2] C Mock, H Lee, S Choi, V Manovic, Flame structures and ignition characteristics of torrefied and raw sewage sludge particles at rapid heating rates, *Fuel* 200 (2017) 467–480. <http://dx.doi.org/10.1016/j.fuel.2017.03.055>
- [3] G. Simões, D. Magalhães, M. Rabaçal, M. Costa, Effect of gas temperature and oxygen concentration on single particle ignition behavior of biomass fuels, *Proceedings of the Combustion Institute* 36 (2017) 2235–2242. <http://dx.doi.org/10.1016/j.proci.2016.06.102>.
- [4] A. Carvalho, M. Rabaçala, M. Costa, M.U. Alzueta, M. Abián, Effects of potassium and calcium on the early stages of combustion of single biomass particles, *Fuel* 209 (2017) 787–794. <http://dx.doi.org/10.1016/j.fuel.2017.08.045>.
- [5] W Weng, M Costa, M Aldén, Z Li, Single particle ignition and combustion of pulverized pine wood, wheat straw, rice husk and grape pomace, *Proceedings of the Combustion Institute* 37 (2019) 2663–2671. <https://doi.org/10.1016/j.proci.2018.05.095>
- [6] Reza Mahmoodi, Mortaza Yari, Jafar Ghafouri, Kamran Poorghasemi, Effect of reformed biogas as a low reactivity fuel on performance and emissions of a RCCI engine with reformed biogas/diesel dual-fuel combustion, *International Journal of Hydrogen Energy* 46 (2021) 16494–16512. <https://doi.org/10.1016/j.ijhydene.2020.09.183>.
- [7] M. Feroskhan, Saleel Ismail b, Shreyash Hemant Panchal, Study of methane enrichment in a biogas fueled HCCI engine, *International Journal of Hydrogen Energy*. <https://doi.org/10.1016/j.ijhydene.2021.02.216>.
- [8] Mior A. Said a, Ibrahim B. Dalha, Zainal A. Abdul Karim, Mohammed El-Adawy, Influence of biogas mixing parameters on the combustion and emission characteristics of diesel RCCI engine, *Alexandria Engineering Journal* (2021). <https://doi.org/10.1016/j.aej.2021.06.052>.
- [9] Swami Nathan S, Mallikarjuna JM, Ramesh a., An experimental study of the biogas-diesel HCCI mode of engine operation. *Energy Conversion and Management*, 2010, 51:1347-1353. <https://doi.org/10.1016/j.enconman.2009.09.008>.
- [10] Patel T, Dubey A, Feroskhan M. Investigation on the effect of intake air pressure in a biogas-diesel fueled dual-fuel engine. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 2020. <https://doi.org/10.1080/15567036.2020.1785592>.
- [11] Porpatham E, Ramesh A, Nagalingam B, Effect of hydrogen addition on the performance of a biogas fuelled spark ignition engine, *International Journal of Hydrogen Energy* 2007, volume 32, issue 12 ,2057-65. <https://doi.org/10.1016/j.ijhydene.2006.09.001>.
- [12] Park C, Park S, Lee Y, Kim C, Lee S, Moriyoshi Y., Performance and emission characteristics of a SI engine fueled by low calorific biogas blended with hydrogen,

International Journal of Hydrogen Energy, 2011, 36, 10080-10088.
<https://doi.org/10.1016/j.ijhydene.2011.05.018>.

[13] M. Feroskhan, Venugopal Thangavel, Balaji Subramanian, Ram Kishore Sankaralingam, Saleel Ismail, Abhishek Chaudhary, Effects of operating parameters on the performance, emission and combustion indices of a biogas fuelled HCCI engine, Fuel 298 (2021) 120799

[14] Ashraf Elfasakhany, Investigation of biomass powder as a direct solid biofuel in combustion engines: Modelling assessment and comparisons, Ain Shams Engineering Journal 12 (2021) 2991–2998

[15] TK Sharma, GAP Rao, KM Murthy, Homogeneous charge compression ignition (HCCI) engines: A review, Archives of Computational Methods in Engineering, 2016, 23, 623-657.
<https://doi.org/10.1007/s11831-015-9153-0>.

[16] M. Kraft, P. Maigaard, F. Mauss, M. Christensen, et B. Johansson, Investigation of combustion emissions in a homogeneous charge compression injection engine: Measurements and a new computational model, Proceedings of the Combustion Institute, 2000, vol. 28, no 1, 1195-1201. [https://doi.org/10.1016/S0082-0784\(00\)80330-6](https://doi.org/10.1016/S0082-0784(00)80330-6).

[17] S. Voshtani, M. Reyhanian, M. Ehteram, et V. Hosseini, « Investigating various effects of reformer gas enrichment on a natural gas-fueled HCCI combustion engine », International Journal of Hydrogen Energy, 2014, vol. 39, no 34, p. 19799-19809.
<https://doi.org/10.1016/j.ijhydene.2014.09.130>.

[18] M. Shahbakhti, Master of Science Thesis, Modeling and Experimental Study of an HCCI Engine for Combustion Timing Control, University of Alberta, 2009.
<https://doi.org/10.7939/R3PG8X>.

[19] M. Izadi Najafabadi et N. Abdul Aziz, Homogeneous Charge Compression Ignition Combustion: Challenges and Proposed Solutions », Journal of Combustion, 2013, p. 1-14, 2013. <https://doi.org/10.1155/2013/783789>.

[20] M. M. Hasan et M. M. Rahman, Homogeneous charge compression ignition combustion: Advantages over compression ignition combustion, challenges and solutions, Renewable and Sustainable Energy Reviews, 2016, vol. 57, p. 282-291.
<https://doi.org/10.1016/j.rser.2015.12.157>.

[21] J. Li, H. Zhao, N. Ladommatos, et T. Ma, Research and Development of Controlled Auto-Ignition (CAI) Combustion in a 4-Stroke Multi-Cylinder Gasoline Engine, 2001, p. 2001-01-3608, SAE 2001-01-3608. <https://doi.org/10.4271/2001-01-3608>.

[22] A. Fuerhapter, W. F. Piock, et G. K. Fraidl, CSI - Controlled Auto Ignition - the Best Solution for the Fuel Consumption - Versus Emission Trade-Off ?, 2003, p. 2003-01-0754, SAE 2003-03-03. <https://doi.org/10.4271/2003-01-0754>.

[23] R. K. Maurya, A. K. Agarwal, Experimental study of combustion and emission characteristics of ethanol fuelled port injected homogeneous charge compression ignition (HCCI) combustion engine, Applied Energy, 2011, vol. 88(4), pages 1169-1180.
<https://doi.org/10.1016/j.apenergy.2010.09.015>

- [24] H. Nareid et N. Lightowler, Detection of Engine Misfire Events using an Artificial Neural Network, 2004, p. 2004-01-1363, SAE 2004-03-08. <https://doi.org/10.4271/2004-01-1363>.
- [25] F. Ponti, Development of a Torsional Behavior Powertrain Model for Multiple Misfire Detection, J. Engine Gas Turbines Power, 2008, 130(2). <https://doi.org/10.1115/1.2770486>.
- [26] M. Sjöberg et J. E. Dec, Comparing late-cycle autoignition stability for single- and two-stage ignition fuels in HCCI engines, Proc. Combust. Inst., 2007, vol. 31(2), p. 2895-2902, <https://doi.org/10.1016/j.proci.2006.08.010>.
- [27] A. M. D. Silveira, D. Ramos, A. Castro, et S. C. Domahovski, Misfire diagnostic for flex vehicles - a case study, SAE 2009-36-0247. <https://doi.org/10.4271/2009-36-0247>.
- [28] J. Forster, A. Lohmann, M. Mezger, K. Ries-Müller, et R. B. GmbH, Advanced Engine Misfire Detection for Si-Engines, SAE 970855, 1997. <https://doi.org/10.4271/970855>.
- [29] X. Duan, M.-C. Lai, M. Jansons, G. Guo, et J. Liu, A review of controlling strategies of the ignition timing and combustion phase in homogeneous charge compression ignition (HCCI) engine, Fuel, 2021, vol. 285, p. 119 142. <https://doi.org/10.1016/j.fuel.2020.119142>.
- [30] M. N. Schleppe, Master of Science Thesis, SI - HCCI mode switching optimization using a physics based model, 2011, Alberta university. <https://doi.org/10.7939/R38K9M>.
- [31] L. Manofsky, J. Vavra, D. N. Assanis, et A. Babajimopoulos, Bridging the Gap between HCCI and SI: Spark-Assisted Compression Ignition, SAE 2011-01-1179. <https://doi.org/10.4271/2011-01-1179>.
- [32] Guibert P, HCCI auto contrôlé par injection d'IGR contenu dans une chambre auxiliaire. Patent number: WO2008139065 (A2), INPI-FR-2008, 2008-11-20.
- [33] B. Piriou, G. Vaitilingom, B. Veyssière, B. Cuq, et X. Rouau, Potential direct use of solid biomass in internal combustion engines, Prog. Energy Combust. Science, 2013, vol. 39(1), p. 169-188. <https://doi.org/10.1016/j.pecs.2012.08.001>.
- [34] Wei. X, Hellier P., Baganz F., Impact on performance and emissions of the aspiration of algal biomass suspensions in the intake air of a direct injection diesel engine, Energy Convers. Manag., 2019, vol 205, 112347. <https://doi.org/10.1016/j.enconman.2019.112347>.
- [35] L. Stover, B. Piriou, C. Caillol, P. Higelin, C. Proust, X. Rouau, G. Vaitilingom, Direct use of biomass powder in internal combustion engines, Sustain. Energy Fuels, 2019, Vol 3, 20763-2770. <https://doi.org/10.1039/C9SE00293F>.
- [36] R. Pawlikowski, Powdered fuel for internal combustion engines, 1927. patent DE510311C.
- [37] K. Nicol, The direct injection carbon engine, 978-92-9029-565-5. IEA Clean Coal Centre, december 2014.

- [38] J. A. Caton et B. D. Hsu, The General Electric Coal-Fueled Diesel Engine Program (1982–1993): A Technical Review, *J. Eng. Gas Turbines Power*, 1994, vol. 116, no 4, p. 749-757. <https://doi.org/10.1115/1.2906882>.
- [39] J. A. Galon, K. H. Rosegay, A Review and Comparison of Reciprocating Engine, SAE 831362, SAE Transactions Vol. 92, Section 3: 830693–831395 (1983), pp. 1108-1124.
- [41] P. Guibert, A. Keromnes, G. Legros, Development of a Turbulence Controlled Rapid Compression Machine for HCCI Combustion, 2007, JSAE 2007-01-1869. <https://doi.org/10.4271/2007-01-1869>.
- [42] L. Zheng, Y. Zhang, High Speed Digital Imaging for Flame Studies: Potentials and Limitations, *Energy Procedia*, vol. 66, p. 237-240, 2015. <https://doi.org/10.1016/j.egypro.2015.02.039>.
- [43] J. Würmel, E. J. Silke, H. J. Curran, M. S. Ó Conaire, et J. M. Simmie, The effect of diluent gases on ignition delay times in the shock tube and in the rapid compression machine, *Combust. Flame*, vol. 151, no 1-2, p. 289-302, 2007. <https://doi.org/10.1016/j.combustflame.2007.06.010>.
- [44] Haishen Di, Xin He., Peng Zhang, Zhi Wang, Margaret S. Wooldridge, Chung K. Law, Cuiping Wang, Shijin Shuai, JianxinWang, Effects of buffer gas composition on low temperature ignition of iso-octane and n-heptane, *Combust. Flame*, vol. 161, no 10, p. 2531-2538, 2014, <https://doi.org/10.1016/j.combustflame.2014.04.014>.
- [45] S. Sadaka et D. M. Johnson, Biomass Combustion », division of agriculture research & extension, Agriculture and Natural Resources, University of Arkansas, FSA1056.
- [46] S. V. Vassilev, D. Baxter, L. K. Andersen, et C. G. Vassileva, « An overview of the chemical composition of biomass », *Fuel*, vol. 89, no 5, p. 913-933, 2010. <https://doi.org/10.1016/j.fuel.2009.10.022>.
- [47] H. Fatehi, Numerical simulation of ignition mode and ignition delay time of pulverized biomass particles, *Combustion and Flame*, 2019, pp 400-410. <https://doi.org/10.1016/j.combustflame.2019.05.020>
- [48] Y. A. Levendis, K. Joshi, R. Khatami, et A. F. Sarofim, Combustion behavior in air of single particles from three different coal ranks and from sugarcane bagasse, *Combust. Flame*, 2011, vol. 158, no 3, p. 452-465. <https://doi.org/10.1016/j.combustflame.2010.09.007>.
- [49] J. B. Howard et R. H. Essenhigh, Mechanism of solid-partical combustion with simultaneous gas-phase volatiles combustion, *Symp. Int. Combust.*, 1967, vol. 11, no 1, p. 399-408. [https://doi.org/10.1016/S0082-0784\(67\)80164-4](https://doi.org/10.1016/S0082-0784(67)80164-4).
- [50] A. Molina et C. R. Shaddix, Ignition and devolatilization of pulverized bituminous coal particles during oxygen/carbon dioxide coal combustion, *Proc. Combust. Inst.*, 2007, vol. 31, no 2, p. 1905-1912. <https://doi.org/10.1016/j.proci.2006.08.102>.

- [51] Y. Yuan, S. Li, G. Li, N. Wu, et Q. Yao, The transition of heterogeneous–homogeneous ignitions of dispersed coal particle streams, *Combust. Flame*, 2014, vol. 161, no 9, p. 2458-2468. <https://doi.org/10.1016/j.combustflame.2014.03.008>.
- [52] R. Khatami, C. Stivers, et Y. A. Levendis, Ignition characteristics of single coal particles from three different ranks in O₂/N₂ and O₂/CO₂ atmospheres, *Combust. Flame*, 2012, vol. 159, no 12, p. 3554-3568. <https://doi.org/10.1016/j.combustflame.2012.06.019>.
- [53] J. Riaza, M. Ajmi, J. Gibbins, et H. Chalmers, Ignition and Combustion of Single Particles of Coal and Biomass under O₂/CO₂ Atmospheres, *Energy Procedia*, 2017, vol. 114, p. 6067-6073. <https://doi.org/10.1016/j.egypro.2017.03.1743>.
- [54] G. Simões, D. Magalhães, M. Rabaçal, et M. Costa, Effect of gas temperature and oxygen concentration on single particle ignition behavior of biomass fuels, *Proc. Combust. Inst.*, 2017, vol. 36, no 2, p. 2235-2242. <https://doi.org/10.1016/j.proci.2016.06.102>.
- [55] J. Li, M. C. Paul, et K. M. Czajka, Studies of Ignition Behavior of Biomass Particles in a Down-Fire Reactor for Improving Co-firing Performance, *Energy Fuels*, 2016, vol. 30, no 7, p. 5870-5877. <https://doi.org/10.1021/acs.energyfuels.6b01065>.
- [56] T. Matsuda, Y. Tsukioka, K. Benkiewicz, A. Hayashi, Measurements of ignition delay times in cornstarch dust-air mixture, *AIAA-2001-0479*. <https://doi.org/10.2514/6.2001-479>.
- [57] J. Riaza, R. Khatami, Y.A. Levendis, L. Alvarez, M. Gil, C. Pevida, F. Rubiera, J. J. Pisa, Single particle ignition and combustion of anthracite, semi-anthracite and bituminous coals in air and simulated oxy-fuel conditions, *Combust. Flame*, 2014, vol. 161, no 4, p. 1096-1108. <https://doi.org/10.1016/j.combustflame.2013.10.004>.
- [58] H. Zhou, Y. Li, N. Li, et K. Cen, Experimental investigation of ignition and combustion characteristics of single coal and biomass particles in O₂/N₂ and O₂/H₂O, *J. Energy Inst.*, 2019, vol. 92, no 3, p. 502-511. <https://doi.org/10.1016/j.joei.2018.04.008>.
- [59] X. Liu, L. Yu, H. Liu, L. Chen, et L. Li, Thermal Decomposition of Corn Starch with Different Amylose/Amylopectin Ratios in Open and Sealed Systems, *Cereal Chem. J.*, 2009, vol. 86, no 4, p. 383-385. <https://doi.org/10.1094/CCHEM-86-4-0383>.
- [60] Xingxun Liu, Yanfei Wang, Long Yu, Zhen Tong, Ling Chen, Hongsheng Liu, Xiaoxi Li, Thermal degradation and stability of starch under different processing conditions, *Starch - Biosynthesis Nutrition Biomedical*, 2012, vol. 65, no 1-2, p. 48-60. <https://doi.org/10.1002/star.201200198>.
- [61] P. Aggarwal et D. Dollimore, A thermal analysis investigation of partially hydrolyzed starch, *Thermochim. Acta*, 1998, vol. 319, no 1-2, p. 17-25. [https://doi.org/10.1016/S0040-6031\(98\)00355-4](https://doi.org/10.1016/S0040-6031(98)00355-4).
- [62] J. Yang, Expanding the operating range of homogeneous charge compression ignition-spark ignition dual-mode engines in the homogeneous charge compression ignition mode, *Int. J. Engine Res.*, 2005, vol. 6, no 4, p. 279-288. <https://doi.org/10.1243/146808705X30422>.

- [63] C. D. Blasi, Combustion and gasification rates of lignocellulosic chars, *Progress in Energy and Combustion Science*, 2009, pp 121-140. Vol 32(2). <https://doi.org/10.1016/J.PECS.2008.08.001>
- [64] R. Patton, P. Steele, et F. Yu, Coal vs. Charcoal-fueled Diesel Engines: A Review, *Energy Sources Part Recovery Util. Environ. Eff.*, 2009, vol. 32, no 4, p. 315-322. <https://doi.org/10.1080/15567030802612028>.
- [65] S. Pounkin, PhD Thesis, Paris 6, Etude des régimes de combustion initiés par auto-inflammation et des interactions de la turbulence avec la cinétique réactionnelle chimique.
- [66] C. Zou, L. Cai, D. Wu, Y. Liu, S. Liu, et C. Zheng, Ignition behaviors of pulverized coal particles in O₂/N₂ and O₂/H₂O mixtures in a drop tube furnace using flame monitoring techniques, *Proc. Combust. Inst.*, 2015, vol. 35, no 3, p. 3629-3636. <https://doi.org/10.1016/j.proci.2014.06.067>.
- [67] K.H. Tran, P. Guibert, C. Morin, J. Bonnet, S. Pounkin, G. Legros, Temperature measurements in a rapid compression machine using anisole planar laser-induced fluorescence. *Combustion and Flame*, 2015, Volume 162, Issue 10, Pages 3960–3970. <https://doi.org/10.1016/j.combustflame.2015.07.033>
- [68] Reinventing Cities, C40 cities, supported by EIT - Climate KIC, <http://www.c40reinventingcities.org>
- [69] Rudolf Diesel: Theorie und Konstruktion eines rationellen Wärmemotors zum Ersatz der Dampfmaschine und der heute bekannten Verbrennungsmotoren . Springer, Berlin, 1893, ISBN 978-3-642-64949-3