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Experimental Study of a Diesel Engine Incorporating a "KALAMA" Screw and Operating on Vegetable Oils

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Abstract: The vegetable oil is an alternative fuel that complements or substitutes for fossil fuels. However, its use in diesel engines gives rise to a number of difficulties, especially at low engine power levels. To resolve these problems, improving the thermal conditions in the engine's combustion chamber is one of the solutions being considered. This study presents the performance and combustion parameters of a LISTER type indirect injection diesel engine incorporating a KALAMA screw (an adaptation of the engine's pre-chamber screw with a "hot spot") and using vegetable oils. The results obtained were compared with those obtained by operating the engine on diesel and oil, this time without the KALAMA screw. The results show an improvement in engine performance (specific consumption, thermal efficiency and exhaust gas temperature), particularly at low load. The reduction in excess fuel consumption (with the KALAMA screw) is of the order of 12% at loads of 13% and 26% of maximum engine power. The ignition delay and combustion times of Jatropha oil are better than, or even similar to, those obtained with diesel. The combustion phenomenology is modified by the use of the KALAMA screw. On the heat release rate curves, there was no peak in the kinetic combustion phase during the tests with the modified screw. On the other hand, the diffusion phase was comparable for all the tests. Evaluation of cyclic dispersion using the COV_{IMEP} study shows an improvement in the regularity of combustion cycles in this type of engine incorporating the KALAMA screw.

Keywords: Indirect Injection, Pre-Chamber Screw, KALAMA Screw, Hot Spot, Jatropha Oil

1. Introduction

The vegetable oils are a renewable source of energy and are presented as an interesting alternative to fossil fuels, particularly in diesel engines. This has been described in various previous works [1-13]. However, their direct use in diesel engines gives rise to a number of difficulties, especially at low engine loads. These problems have been identified in the literature [3-9, 12-15]. Authors agree that carbon deposits on mechanical and sensitive engine parts are one of the major problems associated with the use of vegetable oils in diesel engines [3, 5, 8, 12]. The main causes of these problems are the physico-chemical nature of the oil (which does not favour rapid ignition) and the thermal conditions in the combustion chamber (jet of fuel on a cold surface). The literature is certainly full of technological solutions (diesel-oil blending, oil pre-heating, EGR, modification of engine parts, emulsions, etc.). However, these solutions are either too expensive and cumbersome (to encourage their widespread use) or less effective in minimising the problems associated with the use of vegetable oils in diesel engines, or they are unsuitable for low engine operating loads. An approach aimed at introducing a “hot spot” into the trajectory of the fuel jet has therefore been developed as part of a project (Local Agrofuels, Rural Territories and Energy (ALTERRE)). The project was led by the Non-Governmental Organizations (NGO) GERES, with technical support from the French Agricultural Research Centre for International Development (CIRAD), through the Biomass, Wood, Energy, Bio-products (BioWooEB) laboratory. The engine used in this work is a LISTER type diesel with indirect injection (with a pre-chamber and a combustion chamber), which is fairly widespread in Africa and has a wide range of uses (motor pump, mill, etc.). It is presented as one of the types of engine that can operate well using vegetable oils [1, 4]. However, there are still problems associated with the use of vegetable oils in this engine, especially at low loads. The aim is to improve the conditions for igniting the fuel when it hits a surface. Previous studies on the evaporation conditions of an oil droplet on a surface have shown that the macromolecules making up vegetable oils degrade more easily and completely when the temperature levels are close to 500°C [3, 10, 14]. In addition, field and laboratory measurements of the temperature within the engine's combustion pre-chamber have shown that this is less than 400°C at low loads and increases as the load applied to the engine increases, reaching 550°C at full power [11]. This finding indicates that the combustion of vegetable oils in this type of engine would lead to deposit problems at low loads, when fuel droplets settle on cold engine surfaces.

Based on this observation, various solutions have been tested in order to obtain a hot zone in the trajectory of the fuel jet, the temperature of which allows complete degradation of the vegetable oils (thus avoiding deposits) [8, 11]. The solution adopted at the end of the tests was an adaptation of the pre-chamber screw with a parabolic part (a dome) with a "head" at its center (Figure 2). This assembly is known as the "KALAMA screw" [11]. Laboratory and field tests have shown that using this adaptation reduces the amount of soiling on the various engine parts. However, there is no scientific work presenting the results and a detailed analysis of the performance and combustion parameters of this type of engine incorporating a KALAMA screw and running on vegetable oil.

The aim of this study is to compare the overall performance and combustion parameters of this type of engine running on vegetable oil, incorporating the KALAMA screw, with those of an engine operating on diesel and oil without adaptation.

2. Materials and Methods

2.1. Engine Test Bench

The system consists of an engine test bench and a system for acquiring and processing the measured data. It is located in the environmental physics and chemistry laboratory of Joseph ki Zerbo University (Ouagadougou, Burkina Faso). A LISTER diesel engine with indirect injection has been installed. It is water-cooled and develops a maximum power of 7.35 kW. It is then coupled to a generator producing an electric current. The characteristics of this equipment are detailed in Table 1. Halogen lamps of different powers (150W, 500W and 1000W) are used at the output of the generator to apply different load powers to the motor. The data acquisition system consists of various sensors that monitor parameter changes during engine operation. A Kistler type 61125C piezoelectric sensor measures the pressure inside the cylinder, a second KISTLER type 4067C3000A2 piezoresistive sensor measures the pressure in the fuel injection line. Both signals are received in a National Instrument NI 9215 unit. Type K thermocouples are also used to measure intake air, exhaust gas and engine lubricating oil temperatures. These thermocouples are connected to National Instrument's NI 9012 package. The signals are time-stamped using a KISTLER 2614C11 angle encoder with a resolution of 720 points per cycle.

LabVIEW software is used to acquire the measured data. The measured data is processed over 100 motor cycles, a number used in previous work because it provides good accuracy for the calculations.

Figure 1 is a synoptic diagram of the experimental set-up.

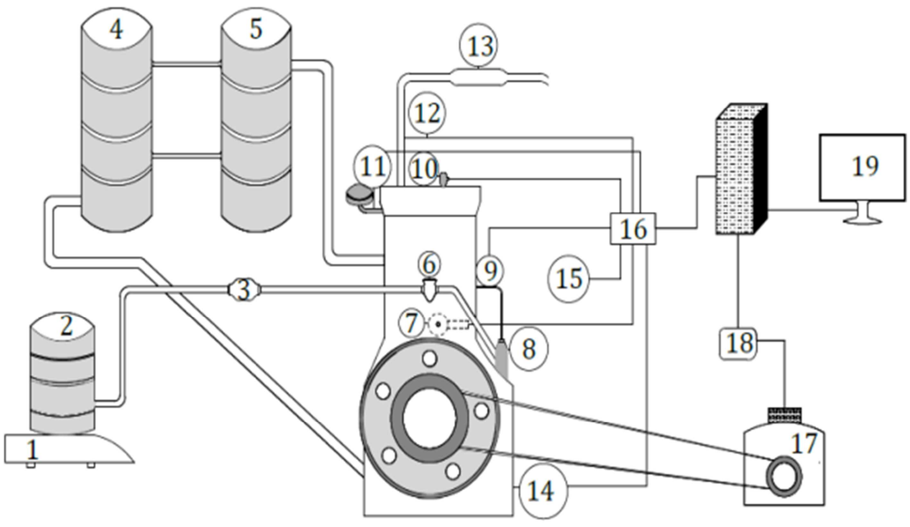


Figure 1. *Synoptic diagram of the experimental.*

(1) balance; (2) tank; (3) fuel filter; (4) hot water barrel; (5) cold water barrel; (6) fuel filter; (7) angle encoder; (8) injection pump; (9) injection pressure sensor; (10) cylinder pressure sensor; (11) Intake pressure sensor; (12) Exhaust thermocouple; (13) Exhaust; (14) Lubricating oil thermocouple; (15) Thermocouple for ambient temperature; (16) Acquisition rack; (17) Generator; (18) Power analyzer; (19) Computer

2.2. Description of the KALAMA Screw

Figure 2a, b show the KALAMA screw and the hot-spot insertion process [8, 11].

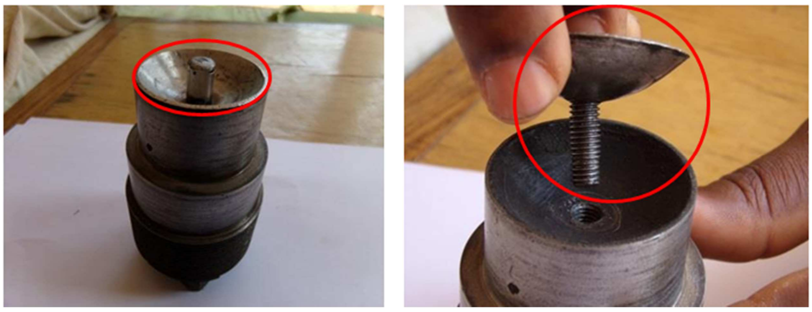


Figure 2. *The KALAMA screw and the hot-spot insertion process.*

The hotspot represents the assembly of the (parabolic) dome topped by a nipple (circled part in Figure 2b). This assembly is in contact with the screw over an area equivalent to the cross-section of the "nipple". A thin film of air separates the upper surface of the screw from the rear surface of the dome to limit heat exchange by conduction. The dome and nipple assembly is made of refractory steel, unlike the rest of the screw which is made of cast iron (higher thermal conductivity). The KALAMA screw is then introduced into the engine's pre-combustion chamber (Figure 3) and the hot spot opens up in the path of the fuel jet. Its role is to store the heat received from the combustion gases of the previous cycle and transfer it to the fuel to boost ignition of the next cycle.

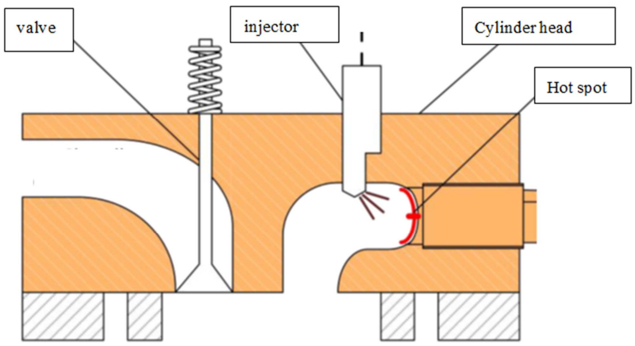


Figure 3. *Cross-section of the Lister engine cylinder head.*

2.3. Methods

Figure 4 illustrates the procedure for conducting an engine test.

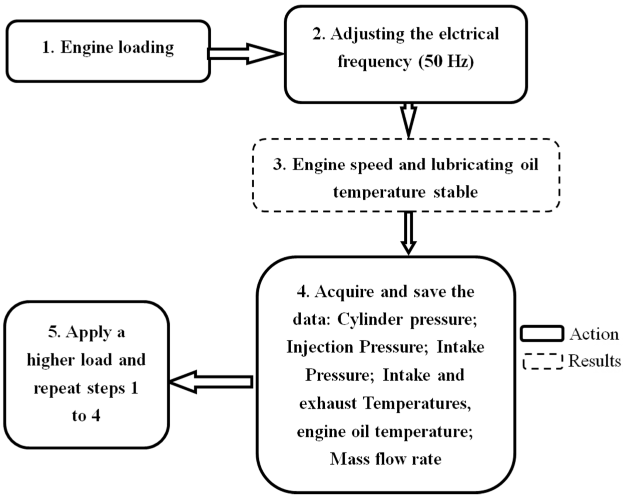


Figure 4. *The procedure for conducting an engine test.*

Table 1 shows some of the physico-chemical characteristics of diesel and Jatropha oil [9].

Table 1. *The physico-chemical characteristics of diesel and Jatropha oil.*

Characteristics	Methods	Diesel	Jatropha oil
Kinematic viscosity at 40°C (cSt)	ASTM D445	2.44	35.98
Density at 20°C (kg/m^3)	ASTM D 1298	850	917
Conradson residue (%)	ASTM D 189	0.1	0.8
Lower Calorific Value (kJ/kg)	ASTM D 240	42852	36974
Flash point (°C)	ASTM D 97	71	229
Cloud point (˚C)	ASTM D 97	−6	4

The parameters compared when the engine is operating on diesel and jatropha oil are: overall performance and combustion parameters. Specific fuel consumption, thermal efficiency and engine exhaust gas temperatures are the selected overall performance parameters. For the analysis of engine combustion parameters, the characteristic variables are fuel ignition delay, heat release rate and cyclic dispersion. The method used to evaluate these different parameters is the same as that used in previous work [9].

3. Results and Discussion

3.1. Results of Engine Performance

Figure 5. a and b show the results for specific consumption and thermal efficiency of the engine (with or without hot-spot) operating on diesel and vegetable oil at different loads.

D: Diesel; HS: Hot Spot; J: Jatropha oil; J-HS: hot-spot diesel engine operating on Jatropha oil

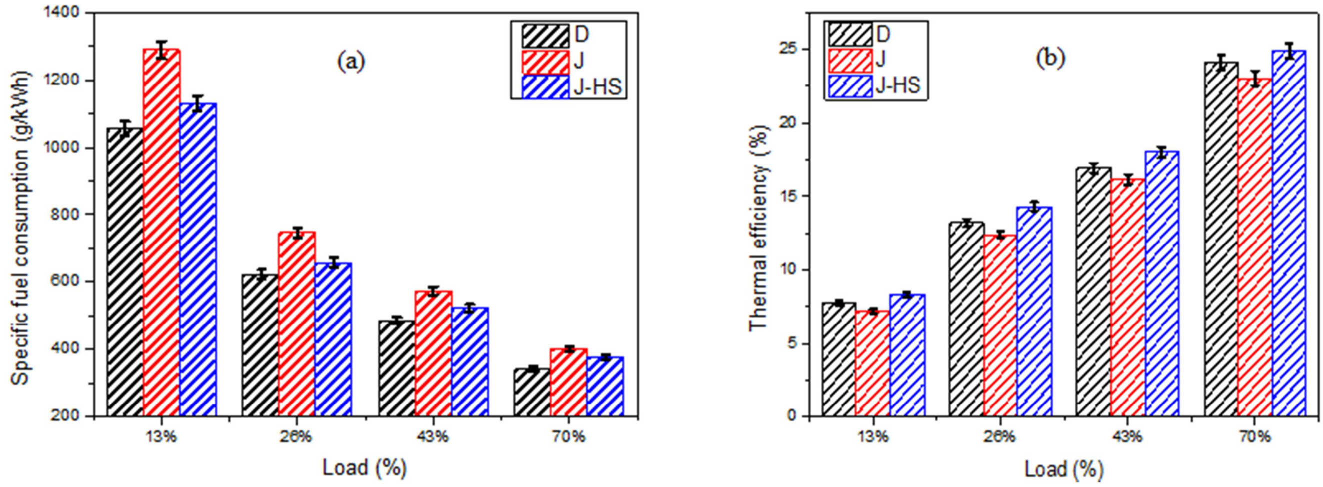


Figure 5. *(a) Specific consumption (b) thermal efficiency of the engine (with or without hot-spot) operating on diesel and vegetable oil at different loads.*

It can be seen that without the integration of the hot spot, the specific fuel consumption of the engine running on jatropha oil at all loads is the highest. However, this decreases with the inclusion of the hot spot, particularly at low engine loads. This drop in fuel consumption is around 12% at loads of 13 and 26% (with hot spot). This is because low loads are when the thermal conditions in the engine combustion chamber are most unfavourable to the thermal degradation of oils [7, 13, 14]. These are generally the loads where the problems associated with the use of vegetable oils in diesel engines are the most recurrent [8, 9, 11, 12]. The above observation therefore demonstrates the usefulness of the hot-spot in reducing the engine's excess fuel consumption when using vegetable oil. The injected fuel (jatropha oil) encounters a hotter surface (420 to 450°C from 13 and 26% of the load) than the head of the engine's pre-chamber screw (without a hot spot); this leads to heat gain by the droplets, then to the formation of micro-droplets of fuel which in turn vaporise and can easily ignite on contact with oxygen [12]. This phenomenon, highlighted by Jalinier (1988) [12] helps to promote the combustion of vegetable oils in this type of engine at low loads. For high loads (greater than 50% of the engine's rated power), the use of the "hot spot" is less relevant. The relative differences between the specific consumption of the different fuels are of the order of magnitude of the uncertainties.

Thermal engine efficiency increases with the load applied to the engine. It can also be seen that the thermal efficiencies obtained with vegetable oil (with the "hot spot") are substantially equal to or even greater than those obtained with diesel. In fact, with a lower calorific value than diesel, to provide the same effective power, the energy deficit of vegetable oil is offset by the over-consumption of the latter [14]. Thermal efficiency is calculated from the engine's specific fuel consumption, so when the engine's fuel consumption decreases, thermal efficiency increases.

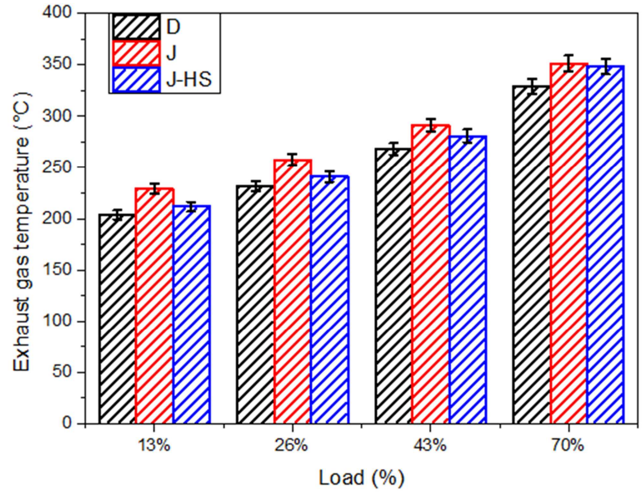


Figure 6. *The exhaust gas temperature as a function of load.*

Figure 6 show the exhaust gas temperature levels at the end of combustion in the engine.

Engine exhaust gas temperatures increase with load. In fact, an increase in load contributes to an increase in the temperature of the combustion chamber, which in turn improves combustion in the engine [7]. Regardless of the load applied, exhaust gas temperatures are relatively high with vegetable oil compared with diesel, especially at low loads.

However, a reduction in engine exhaust gas temperatures was observed during tests with the vegetable oil "hot spot" (of the order of 7% to 13% of load applied to the engine) compared with those carried out without it. This observed reduction in engine exhaust gas temperatures (with the addition of the 'hot spot') when operating on vegetable oil could be justified by the reduction in the engine's specific fuel consumption. The reduction in the engine's specific fuel consumption leads to a reduction in the quantity of fuel injected, so the exhaust gas temperatures are lower [8, 9].

In summary, the overall performance of the engine showed improvements with the 'hot spot' when vegetable oil was used. However, these quantities are only data on the macroscopic scale of the processes taking place within the engine. In this context, it would be appropriate to confirm these results with those of the combustion parameters in the engine.

3.2. Results of Engine Combustion Parameters: Ignition Delay, Heat Release Rate and Cyclic Dispersion

Figure 7a show the results of the ignition delay of the various fuels when used in the diesel engine (with or without a hot spot) at different loads. Figure 7b shows the combustion duration of the fuels in the engine with or without a hot spot.

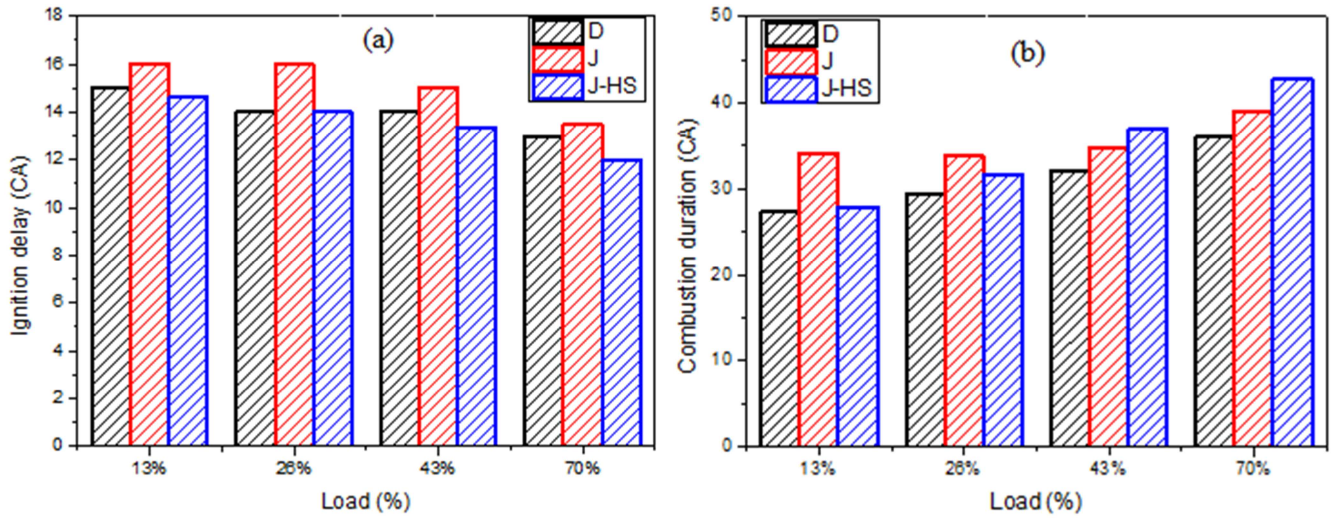
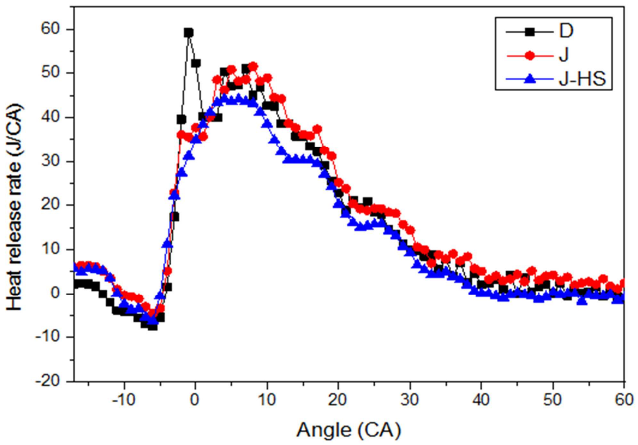


Figure 7. *(a) The results of the ignition delay (b) the combustion duration of the fuels in the engine with or without a hot spot.*

Analysis of the results shows a reduction in the ignition delay of jatropha oil when the "hot spot" is used. There was also a reduction in combustion duration in the engine when this fuel was used with this engine modification. These results could have several causes. Firstly, the increase in temperature of the injected fuel droplets encourages their vaporization and rapid ignition. Previous studies, [3, 5, 10, 13, 14] have highlighted the role of temperature in improving the physical and chemical processes involved in the degradation of vegetable oil macro molecules when they collide with the engine walls. When the oil droplets come into contact with the surface of the hot spot (at a temperature of around 420 to 450°C), the degradation processes are initiated and light, volatile compounds (alcohols, alkanes, alkenes, etc.) are released. As soon as they reach their auto-ignition temperature, these compounds vaporize and initiate combustion. This reduces the ignition delay of the fuel. Also, micro-droplets of fuel are formed as a result of the collision between the jet and the hot surface. These finer micro-droplets can vaporize and ignite more spontaneously. This rapid ignition of the fuel has the effect of reducing ignition delay in the hot-spot engine using Jatropha oil.

Figure 8 show the comparative heat release rate curves for diesel and vegetable oil when the engine is operating with or without a "hot spot".

The phenomenology of combustion with the hot spot is different from the classic phenomenology of diesel combustion. The shape of the curves with the hot spot clearly shows the virtual absence of a marked premix combustion phase (kinetic combustion peak). Combustion is mainly diffusive. The ignition of a small quantity of degraded and vaporised fuel during the delay phase allows a relatively rapid rise in the rate of heat released. The probable reason for this development must be linked to the fact that combustion is initiated earlier (as indicated by the delays obtained with the hot spot). The absorption of heat from the hot spot during the delay phase (between -19°V and -5°V) leads to rapid degradation of the oil droplets, whose degradation products quickly reach their ignition point. Droplets arriving at the hot spot, which has a temperature of around 420°C to 450°C, decompose in three stages: the expansion phase (expansion of the droplet and formation of gas pockets), the diffusion phase (where the gases formed within the droplet escape), a reduction in the size of the droplet with the formation of polymer residues (the size and persistence of which will depend on the ambient temperature) [10]. At this temperature, compounds such as light alkanes (Cyclohexadecane, Tetradecane, 2, 6, 10-trimethyl- etc.), alcohols and alkenes are produced as a result of the thermal degradation of the droplets [10]. The ignition of these light products provides the energy required for the degradation process and the evaporation of the rest of the injected fuel. The physical phenomena involved are mainly the diffusion of heat and the degraded materials that govern fuel combustion. This is confirmed by the performance results, which show that the use of the hot spot enables pure oil to give results comparable to those obtained with diesel.



CA: Crank Angle

Figure 8. *Heat release rate curves for diesel and vegetable oil when the engine is operating with or without a "hot spot".*

Figure 9 show the values of the coefficient of variation of the mean indicated pressure (COV_{IMEP}) as a function of load when the engine is running on diesel or vegetable oil (with or without a hot spot).

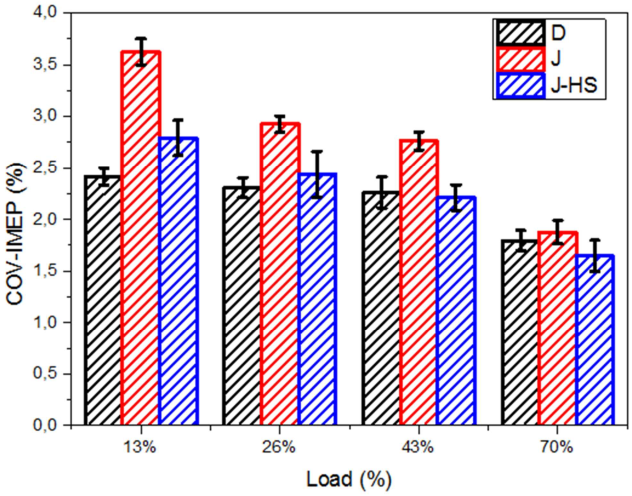


Figure 9. *The coefficient of variation of the mean indicated pressure (COV-IMEP) as a function of load.*

For all the tests carried out, the combustion cycles are regular because the values of the coefficient of variation of the mean pressure indicated do not exceed 10% for all the loads tested and independently of the fuel used (this limit is set by the literature) [16]. Previous work has shown that combustion in this type of engine is more stable than in direct injection engines [17]. This stability is an advantage for the use of vegetable oils in this type of engine (indirect injection), as the cycles are fairly stable for the combustion of vegetable oils.

Analysis of the results also shows that using the hot spot improves the stability of vegetable oil combustion. This finding is confirmed by the improvements in engine performance already observed when the "hot spot" is used. Indeed, previous studies have shown that regular combustion cycles in the engine lead to an improvement in overall performance [7, 9, 17–19]. In addition, it should be noted that increasing the temperature of the fuel jet (by collision with the "hot spot") could favour its vaporisation and rapid ignition, thus reducing delays and cyclic dispersion. Indeed, previous work has shown that the reduction in fuel ignition delay (due to the increase in the temperature of the fuel jet on a hot surface) results in lower values for the coefficient of variation of the indicated mean pressure [9, 20–22]. In the opposite case, a longer ignition delay increases the quantity of air-fuel mixture (significant kinetic combustion peak), but the phenomena that occur during this phase are random, stochastic and less repeatable [9, 19, 23, 24].

In summary, the analysis of combustion parameters (phenomena on a microscopic scale) provides support for the results obtained in terms of the engine's overall performance. It indicates the importance of the hot spot in improving the combustion of vegetable oils in this type of engine.

4. Conclusion

The aim of this work was to evaluate the performance and combustion parameters of a diesel engine with indirect injection and incorporating a KALAMA (hot-spot) screw. Analysis of the various data showed that:

1. Inserting the hot-spot into the device considerably reduces the engine's fuel consumption when using vegetable oils, especially at low engine loads. This in turn improves overall engine efficiency.
2. Low engine exhaust gas temperatures when using the KALAMA screw
3. Fuel ignition delays are also reduced by inserting the hot spot. Combustion phenomenology is modified with the KALAMA screw, and the heat release rate curves do not show a kinetic combustion peak. However, the diffusion phase remains the same for all the tests.
4. Cyclic dispersion is less important on this type of engine. However, the addition of the hot-spot improves the regularity of combustion cycles during tests with vegetable oil.

Globally, the results showed an improvement in engine performance and combustion parameters when the hot-spot was inserted into the engine pre-chamber screw. However, work is continuing to assess the composition of engine exhaust gases with this major modification.

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