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Effects of Temperature, Pressure and Physico-Chemical Characteristics on the Atomization and Disintegration of Jatropha Oil and its Formulations

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The physicochemical characteristics of vegetable oils, the atomization and the particle size of the spray are fundamental aspects for the simulation of their combustion on burners.
In this study, the influence of temperature and pressure on the disintegration of the jet of jatropha oil and its mixture with gas oil was simulated on a Riello Gulliver burner with power ranging from 22.5 to 35.6 KW. The disintegration and dispersion conditions of the droplets from the burner were determined using the average Sauter diameter by equations and mathematical functions. The results showed that there is a minimum temperature and pressure (130°C and 14 bar, respectively) from which it is possible to obtain an adequate disintegration of jatropha oil

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and its mixtures with diesel with suitable selected type of burner. These simulation results are consistent with results obtained experimentally and show satisfactory disintegration conditions at low pressure.

Keywords: Jatropha oil; gulliver burner; adequate disintegration; average diameter of sauter.

1. INTRODUCTION

The significant increase in energy demand that the world is experiencing will inevitably lead to increased consumption of fossil fuels. The estimated energy needs of developed and developing countries are more than 80% fossil fuels out of the total energy available in the world [1-4]. This high demand therefore poses a number of problems, notably the increase in greenhouse gases, the scarcity of conventional resources, and a high dependence on oil-producing countries [5-8]. Burkina Faso, like most countries in the South, remains vulnerable to these difficulties related to fossil fuels.

It is imperative to explore all existing and available sources of energy in order to find a sustainable energy solution. One of the solutions being considered is biomass, in particular agrofuels such as pure vegetable oils (PVOs), which offer interesting prospects: favourable CO2 balance, interesting energy balance, low cost, endogenous resources, etc. [1,8-10]. PVOs can potentially contribute to solving energy problems in various sectors, particularly in the agri-food industry, which has a high energy demand [1,11,12]. Indeed, Burkina Faso is experiencing an almost unprecedented development of food processing industries (AFI), which has led to an increase in its oil bill. In addition, some units use wood as an energy source (mainly boilers), which leads to strong pressure on the vegetation cover with all the consequences that this entails (deforestation, desertification, destruction of carbon sinks, etc.). Thus, the introduction of new biomass energy solutions such as the installation of burners consuming PVOs in the AFIs could lead to energy savings and a reduction in the pressure on the plant cover.

Pure vegetable oils can be used as alternative fuels in burners with interesting results [1,8,13]. In view of the thermal energy needs in the AFI and the alternative uses of PVOs in burners, it was considered in this study to evaluate the suitability of small burners (power less than 50 kW) to use pure vegetable oil in the AFI. The Riello GULLIVER burner, which is part of the small power range, is a burner that could be used in this context. Unfortunately, small burners are not very tolerant of PVOs. The use of HVP in these burners therefore requires specific conditions. Indeed, the use of HVP in burners encounters many technical difficulties such as rapid clogging of the furnace, clogging of the filters, rapid deterioration of the burner parts if certain conditions are not met [13].

The general objective of this study is to numerically determine the optimal conditions for the use of jatropha oil and its mixtures with diesel in a Gulliver-type REILLO burner, which is widely used in industry.

More specifically, the aim is to determine

- the properties of the fuel and the operating parameters of the burner for which the average diameters of the drops are lower than the acceptable critical threshold in the burners;
- the fuel properties and burner operating parameters for which the atomisation regime is reached;

Atomization, which is the most important mechanism of spray disintegration, is however not fully understood until now because of its chaotic process. Although many models have been developed for atomisation, none of them can be considered universal.

This work shows the comprehension of the different stages of atomisation and disintegration of liquid fuels, in particular diesel and jatropha oil and its formulations. The understanding of these phenomena is very important as they can have an influence on the evaporation and combustion of fuels in internal combustion engines.

2. DESCRIPTION OF THE METHOD FOR SIMULATING THE PARAMETERS OF JATROPHA OIL USE IN A RIELLO BURNER

The main parameters that determine the optimal use of HVP in a burner are

Reynold's number (Re), Ohnesorge number (Oh), Sauter's mean diameters (D32) [1,13]. These parameters are known from quantities such as kinematic viscosity, density, surface tension, temperature, spray pressure, nozzle hole diameter. This section gives the main characteristics used for the determination of the parameters and describes the methods for estimating these parameters.

3. PHYSICO-CHEMICAL CHARACTERISTICS OF JATROPHA OIL AND RIELLO GULLIVER BURNER USED FOR THE SIMULATION

The types of fuels used, the physico-chemical characteristics necessary for the simulation of their behaviour, as well as the technical characteristics of the burner are given in Tables 1, 2, 3 and 4:

Table 1. Type of fuels used

Denomination of samples	Name
Pure diesel	Pure diesel
J100	100% jatropha oil
JG1	20% jatropha oil and 80% diesel
JG2	30% jatropha oil and 70% diesel
JG3	40% jatropha oil and 60% diesel
JG4	50% jatropha oil and 50% diesel
JG5	60% jatropha oil and 40% diesel
JG6	70% jatropha oil and 30% diesel
JG7	80% jatropha oil and 20% diesel
JG8	90% jatropha oil and 10% diese

Table 2. Characteristics of the RIELLO GULLIVER burner

Type	RG01
Flow rate (kg/h)	1,9-3,0
Heating power (kW)	22,5-35,6
Fuel	Domestic oil, max viscosity 20°C : 6 mm2/s
Electrical power supply	Single phase, 230 V±10%-50Hz
Engine	0,85A absorbed-2750 g/min-289 rad/s
Ignition transformer	Secondary 8 kV-16 mA
Pump pressure (bar)	Pressure 8-15bars
Electrical power input (kW)	0,29

Table 3. Characteristics of pure jatropha oil [14]

Temperature (°C)	Density (kg/m^3)	Dynamic viscosity (Pa.s)	Kinematic viscosity (mm^2/s)
25	914,990	88,839.10^{-3}	0,097
30	911,294	63,553.10^{-3}	0,069
50	896,510	24,864.10^{-3}	0,027
70	881,726	13,400.10^{-3}	0,015
90	866,942	8,445.10^{-3}	0,009
110	852,158	5,841.10^{-3}	0,006
130	837,374	4,297.10^{-3}	0,005
150	822,590	3,304.10^{-3}	0,004
170	807,806	2,625.10^{-3}	0,003
190	793,022	2,140.10^{-3}	0,002
210	778,238	1,780.10^{-3}	0,002
230	763,454	1,5067.10^{-3}	0,001
250	748,67	1,292.10^{-3}	0,001
260	741,278	1,202.10^{-3}	0,001
270	733,886	1,122.10^{-3}	0,001
280	726,494	1,049.10^{-3}	0,001

Table 4. Characterisation of jatropha oil/diesel blends from 20 to 90% oil [15]

	HVP	Gazole	JG1	JG2	JG3	JG4	JG5	JG6	JG7	JG8
Density (kg/m3)	0,908	0,856	0,87	0,87	0,88	0,88	0,89	0,89	0,90	0,90
Value of viscosity (cSt) à 40°C	35 ,31	4,55	7,49	9,64	11,80	13,95	16,10	18,26	20,41	22,56

4. ATOMIZATION AND GRANULOMETRY ANALYSIS

The use of a liquid as a reagent in many energy applications (fuel testing in burners or engines) requires the formation of a mist of fine droplets to promote heat and mass transfer. The formation of the fine droplets, the fragmentation of the jets are a form of atomisation. As for the size of the droplets, their speed, it is evaluated thanks to a granulometric analysis.

4.1 Determination of the Atomisation Regime

Atomization is the process by which a volume of liquid is subdivided into multiple drops. The formation of drops at the outlet of an injector in a combustion chamber, the spraying of a liquid, the fragmentation of a jet into fine droplets, etc. are all situations or phenomena that involve atomization. The formation of these fine droplets is a complex process that can be broken down into two phenomena: primary atomization, which results from the disintegration of the jet, i.e. the droplets that come from the jet, and secondary atomization, which is governed by the interactions of the droplets with each other and with the external environment. In our study, we are interested in primary atomisation, which is a phenomenon dependent on physico-chemical parameters such as viscosity, surface tension, density, jet speed and nozzle diameter. To evaluate the relative importance of these forces, the Reynolds (Re) and Ohnesorge (Oh) numbers are often used [16-18]. They are defined by equations (E.1) and (E.2). They allow to characterise the decay regime of the fuel oil:

$$\mathrm{Re} = \frac{\rho_l V_j d_{tr}}{\mu_l} \quad \text{(E.1)}$$

$$Oh = \frac{\mu_l}{\sqrt{\rho_l \sigma_l d_{tr}}} \quad \text{(E.2)}$$

With ρl the density of the liquid, σl the surface tension of the liquid, μl the dynamic viscosity of the liquid, Vj the velocity of the jet and dtr the hole diameter. The different decay regimes of a jet as well as the transition criteria between these regimes are described in Fig. 2:

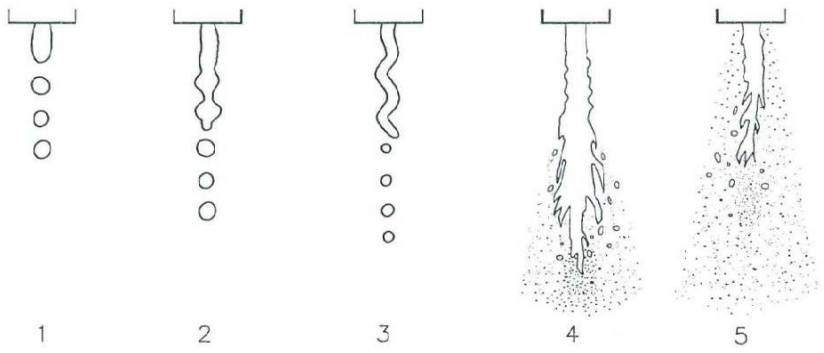

Fig. 1. Disintegration regime of a jet
1: Drop-by-drop regime
2: Rayleigh regime (RaM)
3: first aerodynamic interaction regime (First-wind-Induced (FWI) regime)
4: second aerodynamic interaction or incomplete spray regime (Second-Wind-Induced (SWI) regime). In this phase, atomization only starts at a certain distance from the jet exit
5: atomization regime or complete spray regime. During this stage, atomisation starts as soon as the jet exits

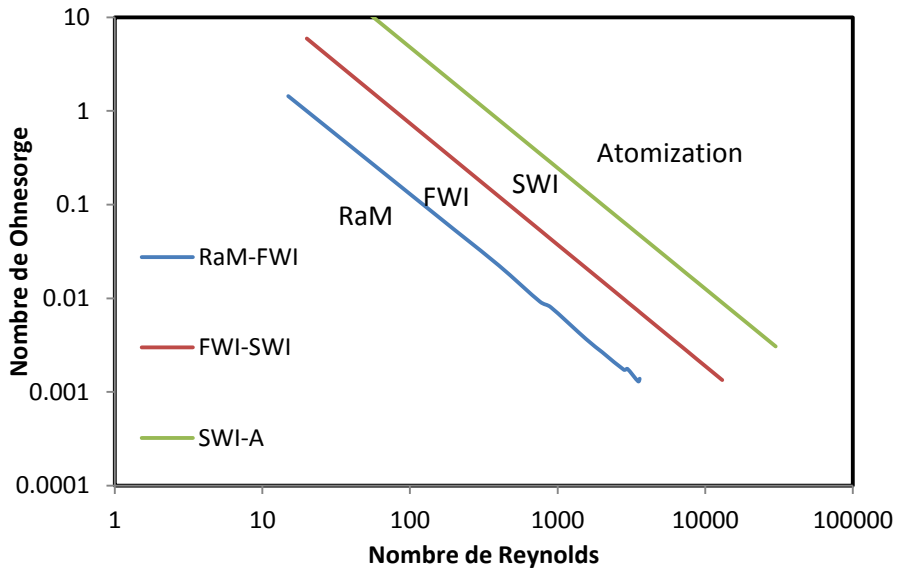

Fig. 2. Classification of different jet decay regimes and transition criteria [1,18]

The regime 5 corresponds to the desired regime. It is from this regime that fine droplets are observed, which allow a large exchange surface to be obtained. In this part, two main phenomena are observed: the beginning of the development of the spray and a high concentration of a liquid core (fuel) in this part. These phenomena give regime 5 its ideal character of good atomisation.

The determination of the decay regime of the different fuels is carried out on the basis of the curves giving the limits of the different regimes in an Oh=f(Re) diagram in logarithmic scale.

The Ohnesorge diagram is an important tool when determining the predominant mechanism in the decay of a spray. Later, Faeth [19] and Ranz [14] studied the transition between the different zones on the Ohnesorge diagram. Thus, a continuous increase in the injection velocity of the liquid allows a shift in the Ohnesorge diagram in a straight line from left to right parallel to the Reynolds number axis to pass through the different zones of the decay regimes experienced by the liquid.

4.2 Determination of Granulometry

The granulometry of a vegetable oil fuel spray gives the characteristics of the droplets that compose it, i.e. the size and dispersion of the droplet sizes, the velocity and position, etc. [1,14,20,21]. The size of the injected drops must be as small as possible (very small diameter) so that the exchange surface with the air is as large as possible and promotes fuel vaporization. To assess the granulometry of the spray it is important to determine the diameters of the drops. Two methods are generally used to determine the particle size of the spray: the diameter distribution function and the single average diameters characteristic of the drop size. Diameter distribution functions describe diameter distribution curves or velocities of drops and account for their dispersion, and single mean diameters are used to characterise the particle size of sprays and also account for diameter dispersion. Here the particle size is determined based on the Sauter mean diameter (D32[1]). This diameter was calculated using the ELKOTB correlation [17] translated into the equation:

$$D_{32} = 6156 \nu_{fl}^{\,0,385} (\rho_{fl}\sigma_{fl})^{0,737} \Delta P^{-0,54} \rho_a^{\,0,06} \quad \text{(E.3)}$$

With vfl the kinematic viscosity in m2/s, ρ_fl and ρ_a in kg/m3 respectively the density of the fluid and that of air, P the pressure in bar, σ_fl the surface tension of the fluid in N/m. We will use this equation to determine the different diameters of the drops that can be easily admitted. Thus, for the determination of the surface tensions of jatropha oil, we will use equation (E.4).

[1] *The diameter equivalent to that of a drop that has the same surface/volume ratio as the entire spray. It is widely used because it characterises both the penetration of the drops into the air and the heat and mass transfers.*

σ=28,1-0,0573*(T-373) (E.4)

Where: T the temperature in K; σ in mN/m.

The estimate of the surface tension of the jatropha/diesel mixture is calculated using the weighting law for volume mixtures. It is given by the equation below.

$$\sigma mélange = \frac{\%voljatropha}{100}\sigma\, jatropha + \frac{\%vo\lg azole}{100}\sigma gazole \quad (E.5)$$

With:

- $\%voljatropha$: Percentage by volume of pure jatropha oil
- $\%vo\lg azole$: Percentage by volume percentage of diesel oil

The average diameter of the jumper is less than 100 µm and the oil burns well in the Riello Gulliver burner [1,17,18].

5. RESULTS AND DISCUSSION

5.1 Atomization Conditions in the Burner

Fig. 3 shows the simulation results of the atomisation conditions of pure jatropha oil in the Riello Gulliver burner as a function of temperature.

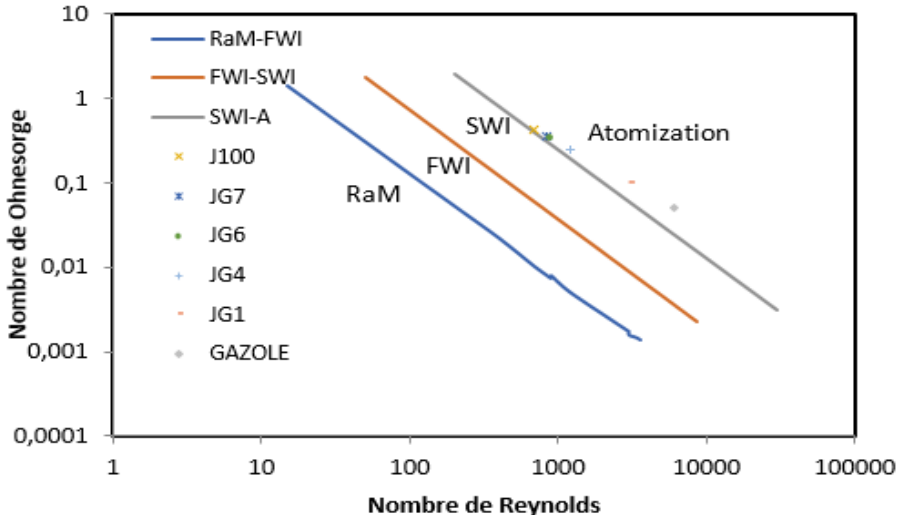

Fig. 3. Atomization conditions in an unmodified burner (mixture at 30°C)

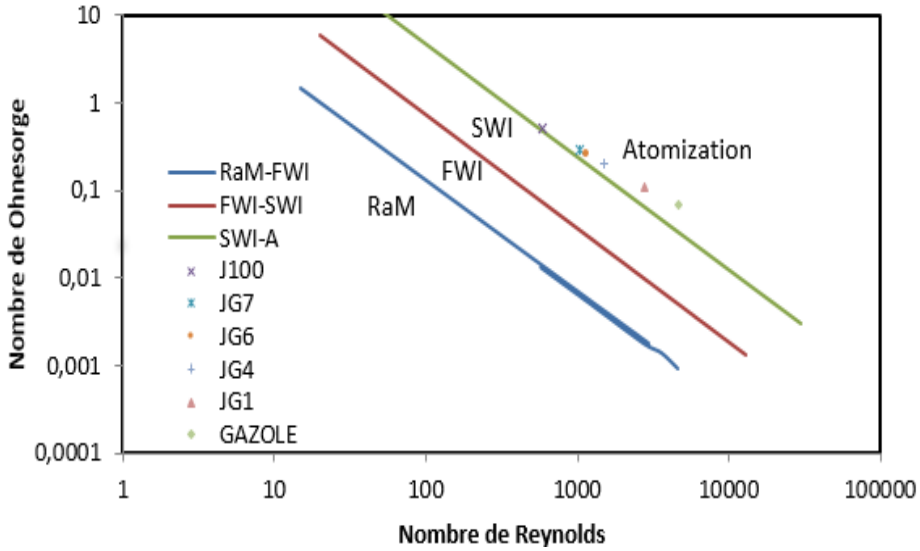

Fig. 4. Atomization conditions in an unmodified burner (mixture at 40°C)

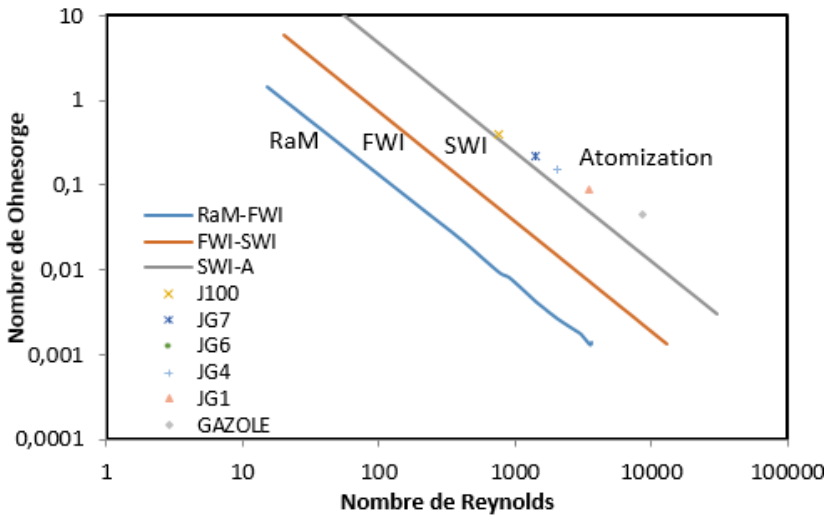

Fig. 5. Atomization conditions in an unmodified burner (mixture at 50°C)

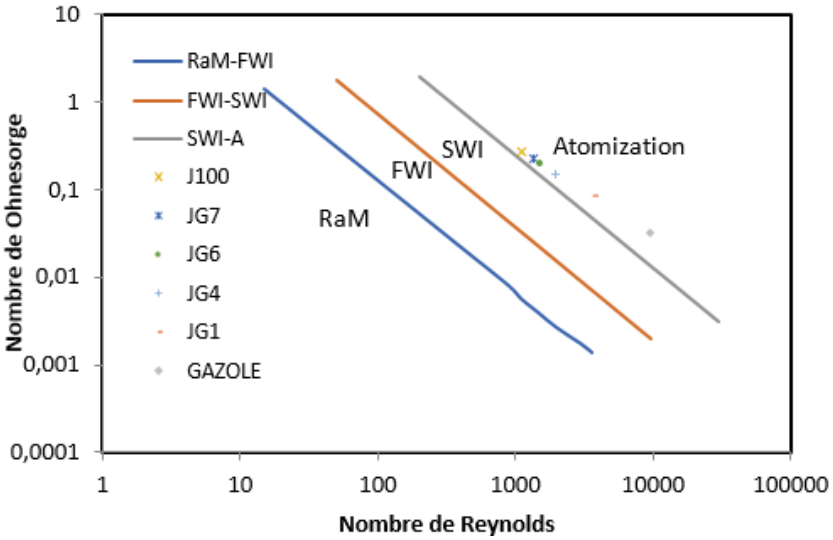

Fig. 6. Atomization conditions in an unmodified burner (mixture at 60°C)

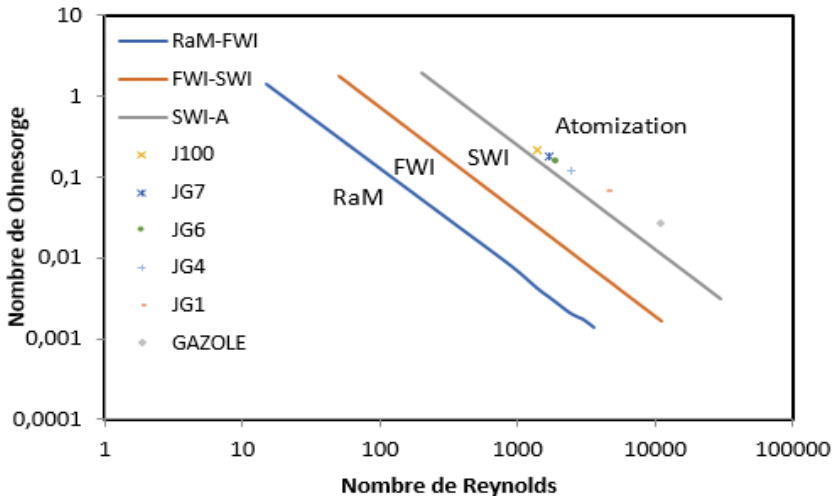

Fig. 7. Atomization conditions in an unmodified burner (mixture at 70°C)

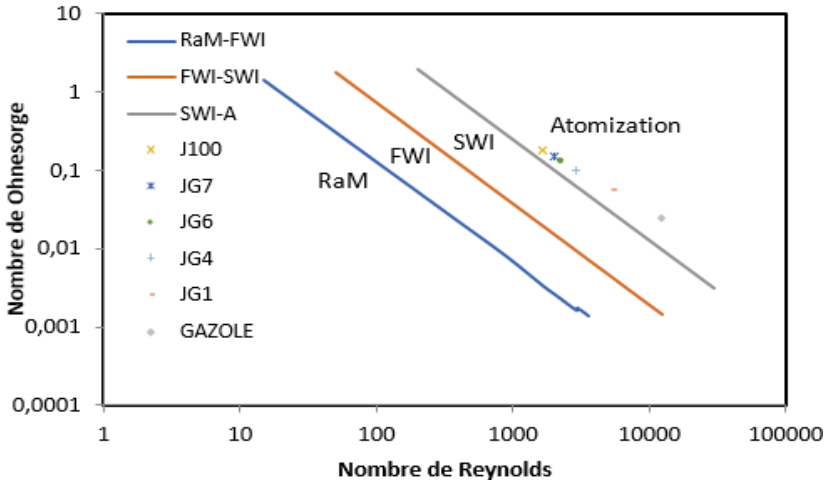

Fig. 8. Atomization conditions in an unmodified burner (mixture at 80°C)

It can be seen that for high proportions of diesel in the mixture, the atomisation zone is reached. The higher the percentage of diesel in the mixture, the further away from the atomization limit zone (SWI), i.e. the full spray regime is reached. We also notice that although the proportion of diesel in the mixture is high (Figs. 3 and 4), we do not move very far from the second dynamic interaction (SWI) regime. On the other hand, for the same proportions at different temperatures (Figs. 5 to 8), we are further away from it. This means that mixing is necessary for good atomisation due to the high viscosity of pure jatropha oil.

The high viscosity of jatropha oil has a negative impact on its use in burners. The high viscosity of jatropha oil has a negative impact on its use in burners. In view of the atomization conditions presented, it is essential to heat the oil to a certain temperature or to make a mixture in order to use it without damaging the burner.

5.2 Size Analysis of the Average Skip Diameters

In this part, to characterise the particle size of the sprays, the single average diameters were used and more precisely the Sauter average diameter. The results obtained are presented in Figs. 9, 10, 11, 12, 13, 14 and 15.

Fig. 9 shows the average Sauter diameter as a function of different temperatures. The oil used for the numerical simulation is pure jatropha oil. The average Sauter diameters of the drops

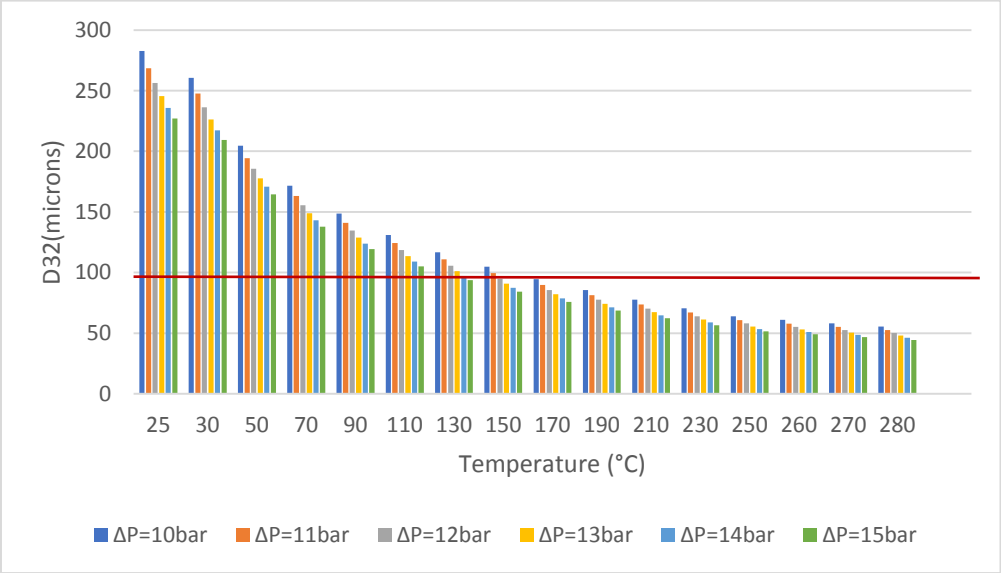

Fig. 9. Sauter's average diameter as a function of temperature

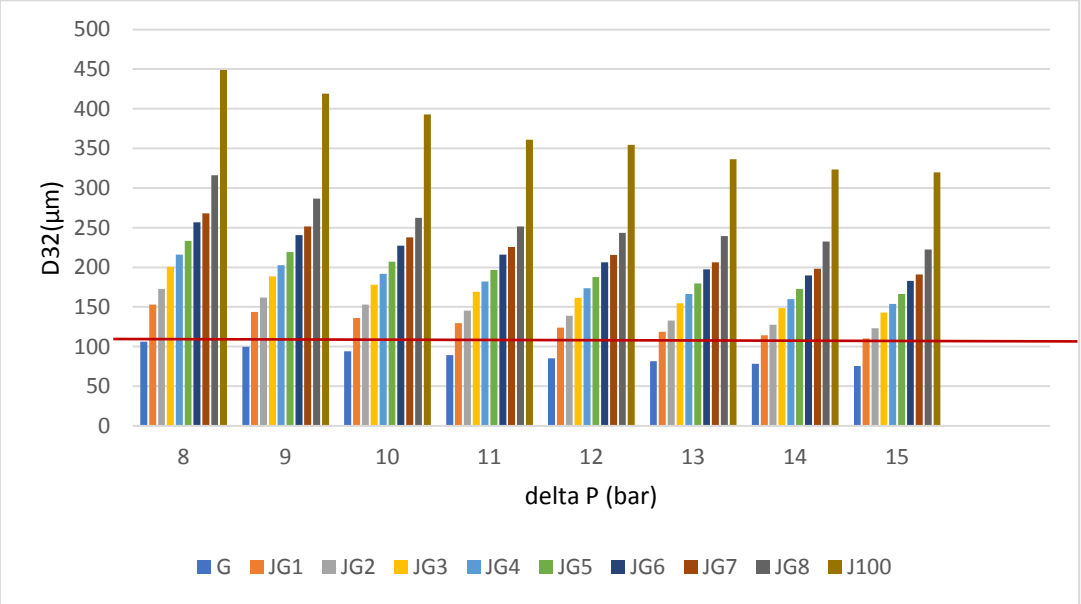

Fig. 10. Sauter's average diameter as a function of pressure difference (pure jatropha-gazole oil mixture) at 30°C

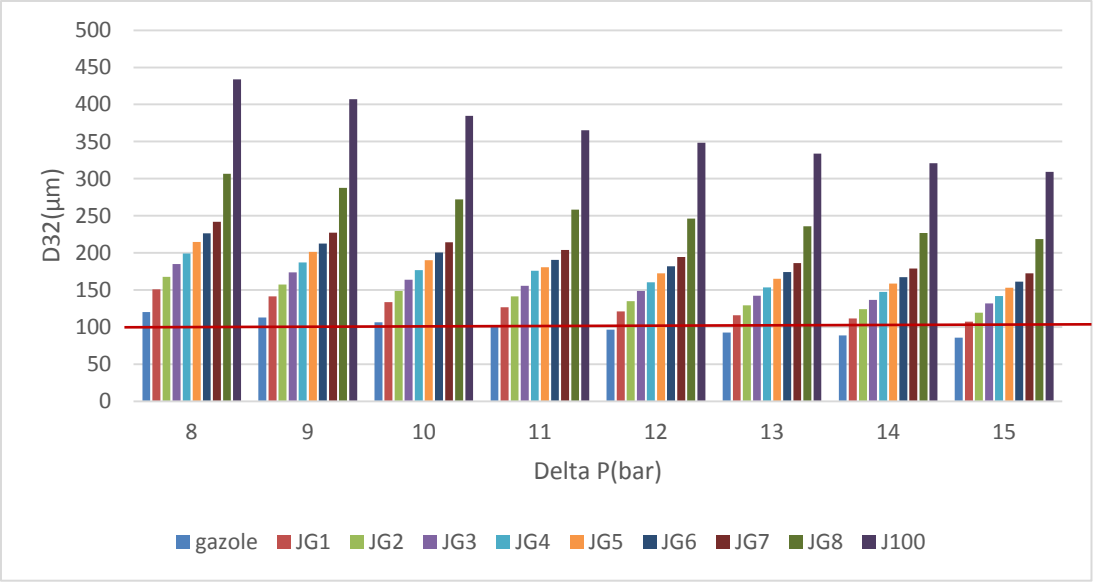

Fig. 11. Sauter's average diameter as a function of pressure difference (pure jatropha-gazole oil mixture) at 40°C

leading to good combustion vary between 50 and 100 µm [1]. Drops with Sauter mean diameters strictly above 100 µm constitute poor combustion. Fig. 9 shows that the Sauter mean diameter of less than 100 µm is achieved at different temperatures and pressures. For a temperature of 150°C under a pressure of 11 bar the average Sauter diameter is 99 µm and for a temperature of 130°C under a pressure of 14 bar it is 97 µm. These values compared to those obtained in the literature with cottonseed oil, show that those obtained with jatropha oil are better. Indeed, for cottonseed oil, a temperature of up to 115°C and a pressure of 27 bar are required to obtain a diameter of less than 100 µm [1,18,22]. Heating the oil to 130°C is therefore essential to obtain good disintegration of the jet at 14 bar.

The results show that an increase in pressure is necessary for good combustion. Our results were compared with other experimental results from

the literature. We note that the results are similarly successful. In Figs. 10 and 11 we can see that the higher the amount of diesel in the mixture, the lower the average diameter, but it is still below 100 µm. These values show that the mixture alone is not sufficient and that more heating is required (30°C and 40°C). On the other hand, for temperature values of 50°C, 60°C, 70°C and 80°C, average Sauter diameters of less than 100 µm are obtained (see Table 5). These results are satisfactory, and even better in some cases (for cottonseed oil and its mixture, the average Sauter diameter of less than 100 µm is reached for ΔP=19 bar) [1,13,23]. Furthermore, it is found that as the pressure increases the disintegration of the drops is better and the Sauter mean diameters show excellent values i.e. diameters below 100µm. This is favourable for good combustion of jatropha oil. Average drop diameters above 100 µm show poor jet disintegration. However, the increase in pressure must be achieved under reheating conditions (with the increase in temperature). It should therefore be noted that the reheating of the jatropha-gazole mixture has an advantage for energetic use in the Riello Gulliver R01 burner.

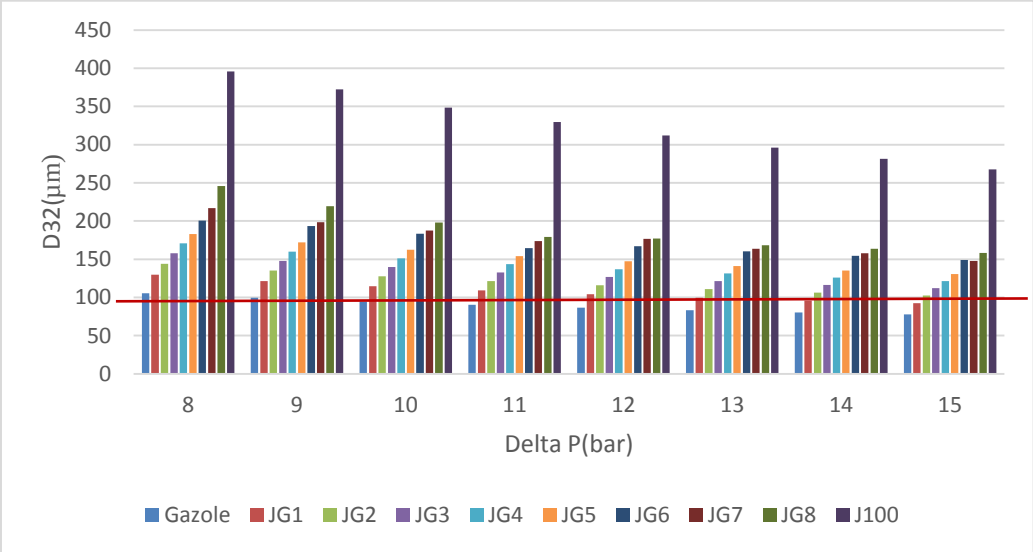

Fig. 12. Sauter's average diameter as a function of pressure difference (pure jatropha-gazole oil mixture) at 50°C

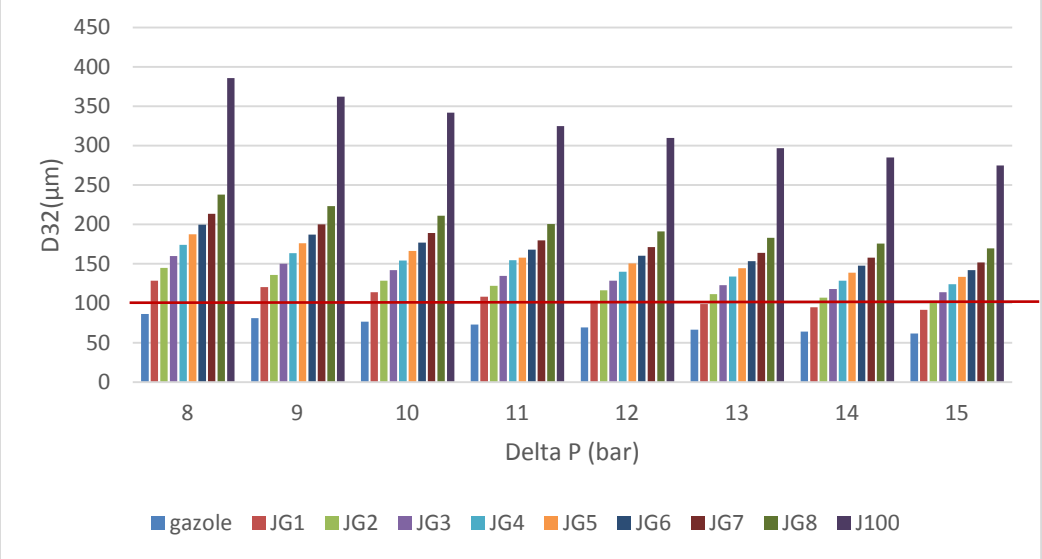

Fig. 13. Sauter's average diameter as a function of pressure difference (pure jatropha-gazole oil mixture) at 60°C

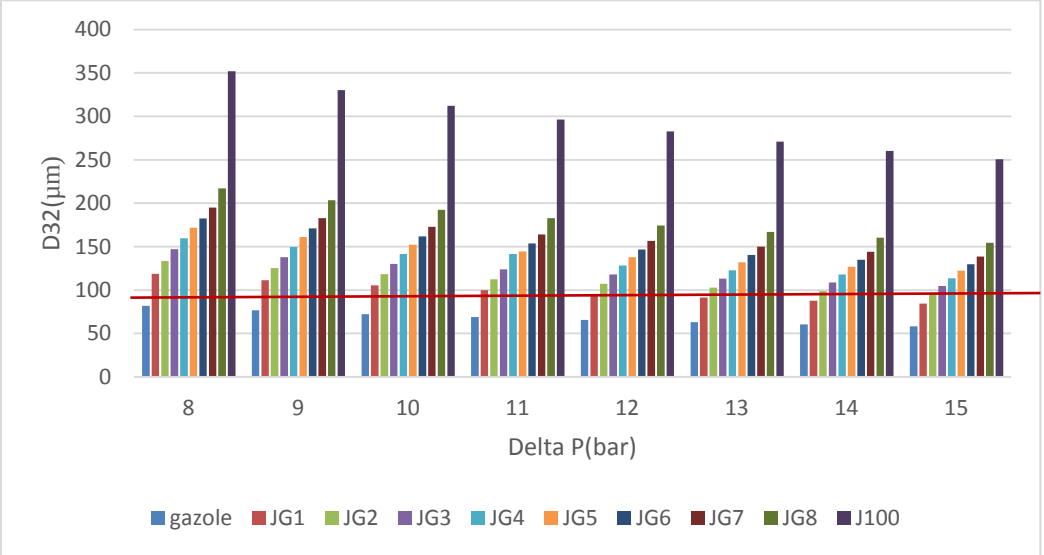

Fig. 14. Sauter's average diameter as a function of pressure difference (pure jatropha-gazole oil mixture) at 70°C

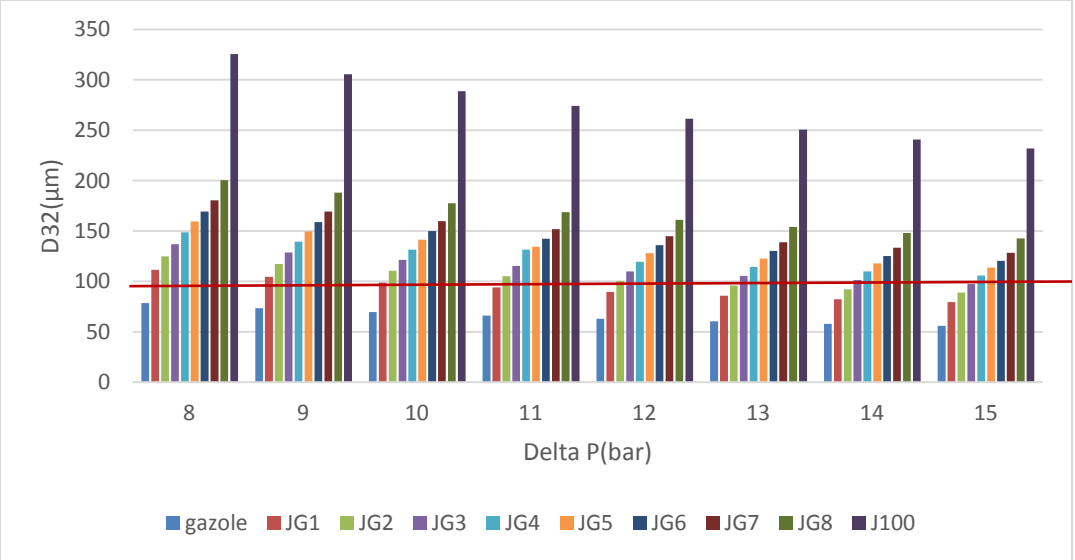

Fig. 15. Sauter's average diameter as a function of pressure difference (pure jatropha-gazole oil mixture) at 80°C

Table 5. Evolution of Sauter diameter (D32) below 100 µm as a function of temperature (Tmin) and pressure (Pmin)

Temperature (°C)	Sauter's average diameter (D_{32}) (µm)	Pression (bar)	Carburant
80	98,795	10	JG1
	95,971	13	JG2
70	95,414	12	JG1
	98,656	14	JG2
60	98,856	13	JG1
50	99,700	13	JG1

6. CONCLUSION

This study consisted of the simulation of the atomization and spray particle size of pure jatropha oil for use in burners. The objective was to study the conditions for a good atomization of jatropha oil in a Riello Gulliver RG01 burner. Simulation results of atomization and spray particle size are compared with experimental results obtained for other oils from the literature. The results show that there are temperature and pressure conditions for adequate atomization and Sauter mean diameters below 100 µm. For pure jatropha oil a temperature of 130°C under a pressure of 14 bar is required. For blends the pressure and temperature must be adjusted according to the proportion of oil in the blend. Parameters such as temperature, pressure and viscosity of the pure jatropha oil or its mixtures with diesel therefore play a big role in the atomization and particle size of the spray. For a good use of the pure vegetable oil or its mixtures with diesel fuel, it is necessary to heat it up to the right temperatures. If these conditions are well met, pure vegetable oil can be used in the food industry with less risk. In sum, this study has given us an overview of the complexity and diversity of the phenomena that arise when pure vegetable oils are used as fuel in a boiler burner in an oil mill.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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