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Review

Review on the Effect of the Phenomenon of Cavitation in Combustion Efficiency and the Role of Biofuels as a Solution against Cavitation

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Abstract: Concerning the problem of wanting the performance of heat engines used in the automotive, aeronautics, and aerospace industries, researchers and engineers are working on various possibilities for improving combustion efficiency, including the reduction of gases such as CO, NOx, and SOx. Such improvements would also help reduce greenhouse gases. For this, research and development has focused on one factor that has a significant impact on the performance of these engines: the phenomenon of cavitation. In fact, most high-performance heat engines are fitted with a high-speed fuel supply system. These high speeds lead to the formation of the phenomenon of cavitation generating instabilities in the flow and subsequently causing disturbances in the combustion process and in the efficiency of the engine. In this review article, it is a question of making a state-of-the-art review on the various studies which have dealt with the characterization of the phenomenon of cavitation and addressing the possible means that can be put in place to reduce its effects. The bibliographic study was carried out based on five editors who are very involved in this theme. From the census carried out, it has been shown that there are many works which deal with the means of optimization that must be implemented in order to fight against the phenomenon of cavitation. Among these solutions, there is the optimization of the geometry of the injector in which the fuel flows and there is the type of fuel used. Indeed, it is shown that the use of a biofuel, which, by its higher viscosity, decreases the effects of cavitation. Most of these jobs are performed under cold fluidic conditions; however, there is little or no work that directly addresses the effect of cavitation on the combustion process. Consequently, this review article highlights the importance of carrying out research work, with the objective of characterizing the effect of cavitation on the combustion process and the need to use a biofuel as an inhibitor solution on the cavitation phenomenon and as a means of energy transition.

Keywords: combustion; cavitation; biofuel; nozzle; spray combustion

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1. Introduction

According to statistics on global energy consumption in 2021, more than 30% comes from oil [1–3], of which, more than 50% is used in transport. The car fleet has almost doubled in 20 years to reach more than 77 million vehicles produced in 2020, and despite a significant drop caused by the global COVID-19 epidemic (more than 90 million in 2019) [4,5]. For its part, the aeronautical field is not spared. Indeed, because the clientele is becoming increasingly mobile, the number of travelers has been multiplied by 10 within 40 years since the price of a flight has been made more accessible. With this intense activity linked to energy consumption, pollution is at the heart of the discussion, and it is important to reduce our carbon impact in order to reduce global warming [6–10]. To fight against global warming, various countries have agreed on a reduction in polluting emissions and are encouraging manufacturers to make their vehicles more environmentally friendly. To do this, two tracks can be used to limit pollution in these engines, the first is to improve the efficiency of the engine and the second is to modify the fuel used.

The efficiency of vehicle engines depends on several factors, such as the geometry of the combustion chamber, as well as the reactions that take place there (lubricating oils, etc.). These parameters have been widely studied in recent decades [11–22]: production lines are now optimized and these engines are increasingly reliable. However, an important aspect of engine efficiency—combustion—is not yet optimized, since our engines emit unburned gases such as carbon monoxide (CO) and greenhouse gases such as carbon dioxide (CO_2) [23–25]. In order to reduce the amount of carbon monoxide, it would be necessary to have a combustion with a decrease in unburnt gases; for this, the air-fuel mixture must be optimized [26–28]. By remaining on heat engines, in most cases, the fuel is sprayed into fine droplets through an injector, with the latter representing an element that plays a major role in ensuring an optimization of the air-fuel mixture; therefore, influencing the performance of the engine. To vaporize into fine droplets, the fuel must pass through a hole of a few hundred micrometers; thus, creating a strong acceleration of the fuel, due to this throttling, resulting in a sudden local drop in pressure (see Figure 1). This pressure drop can fall below the saturated vapor pressure; thus, causing the phenomenon of cavitation (see Figure 2).

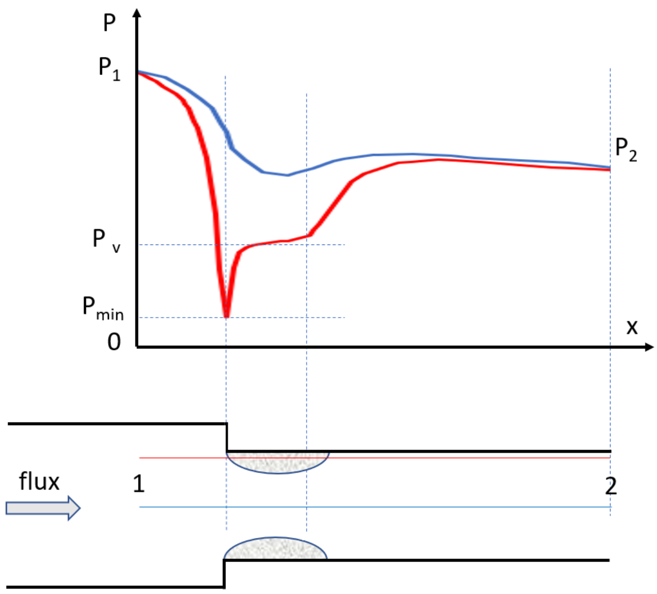

Figure 1. Schematic representation of the pressure level inside nozzle in the middle (blue line) and near the wall region (red line).

Cavitation is a known phenomenon, highlighted by Osborne Reynolds in 1894 [29] during the presentation of his work at Oxford, where he described his device. It consisted of a glass tube, 0.5 inches in diameter and 6 inches in length, with, in its center, a choke of a tenth of an inch which was fed to a water pipe on one end, while the other end was plunged with an inclination into a container filled with water. Although he does not pronounce the word “cavitation”, he describes the process: "Then as the bubbles of air and vapor would be carried with great velocity from the low pressure at the neck, where they formed, into the higher pressure in the wider portion of the expanding tube; so that the pressure being greater than the vapor tension, condensation would ensue, and the bubbles would collapse . . . ”. In 1917, Lord Rayleigh [30] put into an equation the value of the pressure developed by the collapse of a spherical bubble. This collapse leads to a sudden rise in temperature and pressure inside the bubble, which generates a shock wave, responsible for mechanical and sound vibrations, as well as the formation of a microjet, which causes an impact on the surface; thus, corrosion that can go as far as the deterioration of the injector, or the surface concerned, is created.

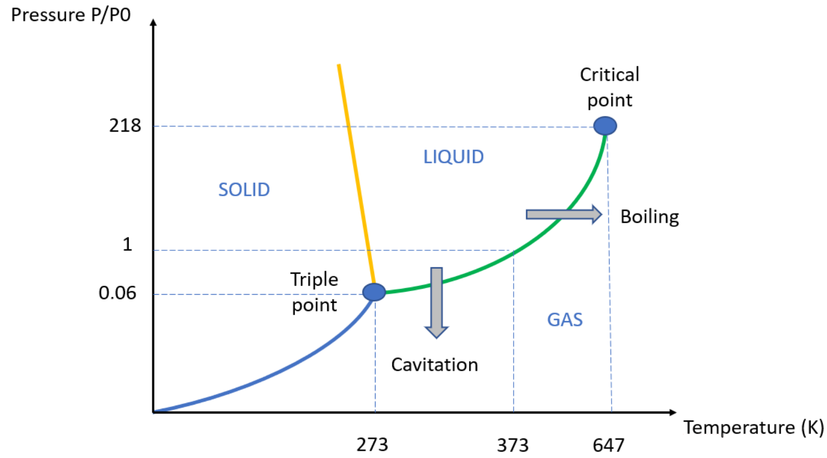

Figure 2. Water phase diagram, P0 = 10,1325 Pa.

This phenomenon of corrosion in injectors, caused by the phenomenon of cavitation, has been studied, demonstrating the harmful effects on injectors and their malfunctions [31–34]. Others have been interested in the formation of cavitation during the rupture of the oil film between the piston and the jacket of a combustion engine such as those of Yin et al. [35]. However, the most important effect is the variation in pressure and fuel flow caused by turbulence in the flow described above. As a result, the fuel supply to the engine is not optimized, the spray formed may have anomalies that result in an influence on the air-fuel mixture and, resultantly, on the efficiency of the engine. With that being the reason, it is essential to limit the effects of cavitation inside the injector in order to improve combustion.

In addition to wanting to reduce the effects of cavitation, the oil industries are making efforts to make their fuel cleaner by using fuels with zero or reduced carbon footprint. Biofuels, whose main advantage is being derived from plant matter, can meet this need. Thus, the amount of CO_2 released during combustion represents the amount of CO_2 absorbed during the development of the plant. In addition, due to local production, the carbon footprint of biofuel production, although not zero, is significantly lower than that of conventional fuels. The first generation of biofuel currently produced industrially is mainly of two types:

- Bioethanol: produced from sugar cane, cereals, and sugar beet. It is used in petrol engines.
- Biodiesel: derived from different sources of fatty acids, including soybean, rapeseed, palm oil, and other vegetable oils. It is used in diesel engines.

However, their production requires agricultural land that could have been used for other purposes. To limit this competition with the food chain, there is a second generation of biofuel (generated from agricultural waste, forest residues, and lignocellulosic biomass, etc.) that is set up [36–39]. Currently, researchers are studying a third generation of biofuel based on microorganisms or microalgae that are capable of producing biofuels [40–46]. Coming back to the problem of the phenomenon of cavitation in injectors, biofuels present an additional advantage compared to standard fuels: they are more viscous [47–50]. This higher viscosity allows them to have a lower speed in the injector; therefore, there is less turbulence, which would be favorable for a decrease in the level of cavitation in an injector. That is why it is interesting to look at the use of these biofuels.

1.1. Definition of the Studied Field

In order to better understand the influence of cavitation on combustion, it is necessary to understand the different stages. First, in order to better characterize the influence of the cavitation phenomenon, it is necessary to focus on the fluidic aspect of the flow; that is to say, on the one hand it is necessary to evaluate the effect of cavitation on the flow of fuel through the injector, and on the other hand, it is necessary to define the characteristics of the spray to finally determine the effects of cavitation on spray characteristics. In a second step, to highlight the role of cavitation on the performance of heat engines, a comparison between biofuels and standard fuels, as well as their mixture, is necessary. It is also necessary to highlight the contribution of using a biofuel as a solution, in relation to the harmful effects of cavitation.

1.1.1. Fluidic Studies

Flow Inside Nozzle

The aim of carrying out a study on the flow of fuel in injectors makes it possible to define what the physical parameters causing cavitation are, and how it would be possible to limit their effects. The role of a nozzle is to atomize the fuel into fine droplets so that it vaporizes more easily, and the air-fuel mixture is optimal. When addressing cavitation—being the change of liquid gas phase under the influence of a pressure variation that is smaller than that of the saturated vapor pressure—it seems logical to think that this phenomenon is beneficial in the combustion of fuel; however, the phenomenon of cavitation inside the injector hole is the source of disturbance in the flow of the fluid, causing a reduced efficiency at the injector and, therefore, a bad atomization.

A schematic diagram (see Figure 3) makes it possible to understand the flow of fuel through the injector and to show the different geometric parameters of the injector (radius of inlet curvature R, conicity, effective diameter D_{eff}, L/D ratio, and the angle of inclination of the injector hole θ). In order to limit cavitation in injectors, these geometric parameters are researched to determine the best choice, because the changes in these parameters must correspond to the different flow rates and injection pressures. The injection pressure has an influence on the speed of the fuel and is also an important parameter on the presence of cavitation. The movement of the needle also creates sudden variations in fuel flow that can lead to cavitation. The physico-chemical properties of the fuel play a preponderant role in the phenomenon of cavitation (such properties include viscosity, the saturating vapor pressure that characterizes the pressure below which the liquid is in gas form).

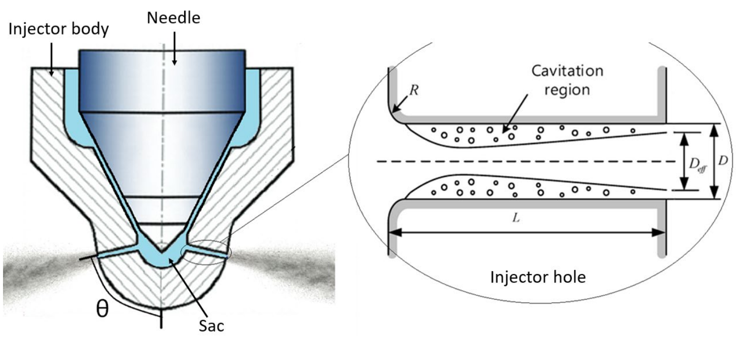

Figure 3. Schematic diagram of the injector nozzle and flow inside the hole of nozzle with cavitation.

Based on the elements presented above, the phenomenon of cavitation depends on many parameters, which is the reason that this phenomenon is still the subject of research today.

Spray Characteristics

In order to better understand the phenomenon of spraying, it is essential to know the conditions that are necessary to obtain a good atomization of the fuel. For example, in the case of a water jet, at the outlet of the pipes, the liquid has an oscillating structure with the presence of thin areas. It is in the thin area that the fluid ruptures into ligaments. In the case of injectors, the atomization of the fuel is carried out in two stages (see Figure 4).

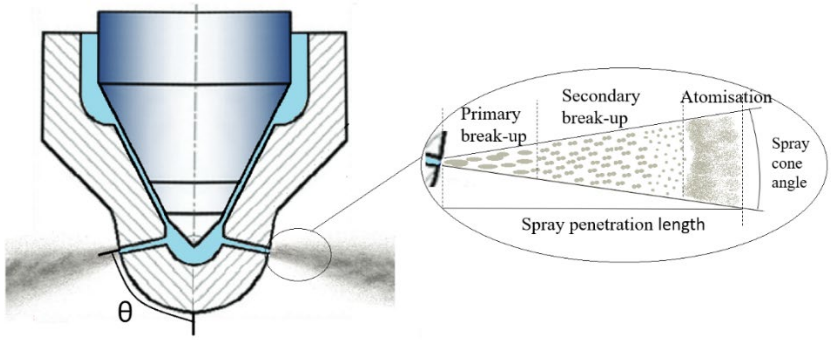

Figure 4. Spray characteristics at the nozzle exit.

The first stage, called "primary breakup", transforms the fuel into ligaments or clusters caused by a fuel velocity raised in stagnant air, so that the phenomenon of oscillation at the injector outlet does not exist. Then, these ligaments break into droplets, due to a surface tension lower than the frictional forces of the air—this step is called secondary breakup. Eventually, these droplets evaporate. The spraying phenomenon depends on several parameters, such as injection pressure, ambient pressure, fluid temperature, flow rate, and injector geometry, etc. Thus, the parameters that are essential to be able to characterize the spray are the spray angle, the length of penetration, the Sauter mean diameter (SMD) (giving the diameter of the droplets), the spatial distribution of the droplets, and the discharge coefficient. The greater the spray angle, the better the mixture of the fuel with the ambient air and the shorter the penetration length. The smaller the Sauter mean diameter (SMD), the better the vaporization of the fuel.

Nozzle Cavitation Effect on Spray

In order to burn, fuel must be sprayed into fine droplets. The efficiency of combustion depends, to a large degree, on the atomization quality of the fuel; therefore, studying the influence of cavitation on spray quality is essential. As previously mentioned, cavitation has a direct effect on the spray quality because it is the source of perturbation of the flow in the injector hole; therefore, it is the cause of the decrease in the mass flow and of modification in the geometry of the spray (the angle of the cone, the symmetry of the spray, and the spray length, etc.) and the quality of atomization (the diameter of the droplets).

1.1.2. Combustion Studies

Comparison between Fuel and Biofuel Combustion

To be able to substitute a standard fuel with a biofuel in engines, it is crucial, beforehand, to compare these different fuels in the production of harmful gases—on one hand, gases such as CO, NOx, and soot production, and on the other hand, the delay in ignition, the mixture fuel/oxidizer, equivalent ratio, flame temperature, and flame heat flux density, etc.

Effect of Cavitation on Combustion of Fuel or Biofuel Spray and Mixture

Disturbances in the flow of fuel inside the injector have an effect on the vaporization of the fuel. The combustion of this spray can have consequences on the performance of engines and the gaseous releases of greenhouse gases such as CO_2 or pollutants such as CO and NOx.

1.2. Methodology

This review paper will focus on the effect of the cavitation phenomenon in a biofuel-powered injector on the efficiency of a turbulent flame. A state-of-the-art review has been made among a selection of the five most important publishers dealing with the field of research including Elsevier, Sage, Taylor and Francis, Springer, and Wiley [51]. To follow the research carried out as part of the characterization of the cavitation phenomenon in industrial and aeronautical applications, a period from 1970 to 2020 has been defined. The terms "cavitation" and "combustion", representing the basis of the study, were entered into the database of each publisher in the field area "anywhere". To consider the main biofuels most cited, the keywords "Biofuel", "Biodiesel", "DME", "Oil", and "Bioethanol" were entered in the "keyword" area. Thus, 2062 articles could be selected from the 5 publishers. To refine the number of articles, a second step was conducted by adding "Injector" or "Nozzle" as the second keyword. This new step led to a selection of 102 articles, of which, following a first reading, 36 had to be rejected because they were too far from the scope of the study. Thus, 66 remaining articles are the subject of this bibliographic study. A distribution of the articles was made according to the theme addressed. Thus, two main groups could be retained, one group according to a fluidic study and another according to a thermal study. Then, each group was developed into several subgroups, as shown in Figure 5. A cumulative distribution of the pertinent articles in the different subgroups, according to the years the papers were published, was made and plotted in a histogram, shown in Figure 6. The first group of fluidic studies, called "Fluidic Studies", consists of two main subgroups, the first of which is "Cavitation and Nozzle", in which studies were conducted on the influence of cavitation in an injector on the flow of a fuel. The second subgroup is "Cavitation and Spray", in which the characteristics of spraying and atomization were studied. A third subgroup was added because some authors conducted a study in the two subgroups. This was named "Cavitation, Nozzle, and Spray". In the "Combustion Studies" group, the study of the first subgroup, "Combustion, Fuels, and Biofuels", focused on the comparison of the combustion of fuels and biofuels and their mixtures in terms of engine performance and gaseous releases. The second subgroup deals with the influence of cavitation on the combustion of standard fuels, this is called "Combustion, Cavitation, and Fuels". Finally, the last subgroup, "Combustion, Cavitation and Biofuels", deals with the effect of cavitation inside an injector on the combustion efficiency of a flame powered by biofuel.

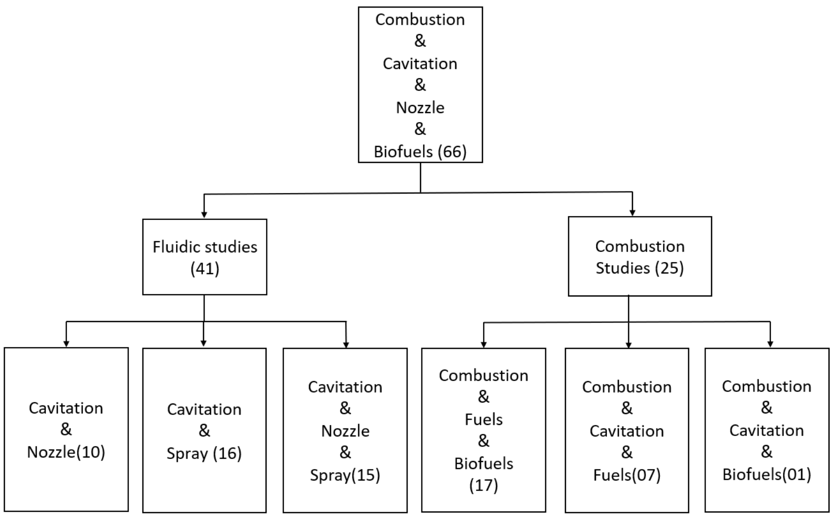

Figure 5. Bibliographic research diagram.

On the basis of the methodology presented previously, this paper will focus on the description of various works that aimed to characterizing the effects of cavitation in heat engines. The aim is to highlight the lack of research on the effect of cavitation on combustion efficiency in a heat engine. For this, there will be a part dealing with fluidic works in Section 2.1 and another part dealing with combustion works in Section 2.2.

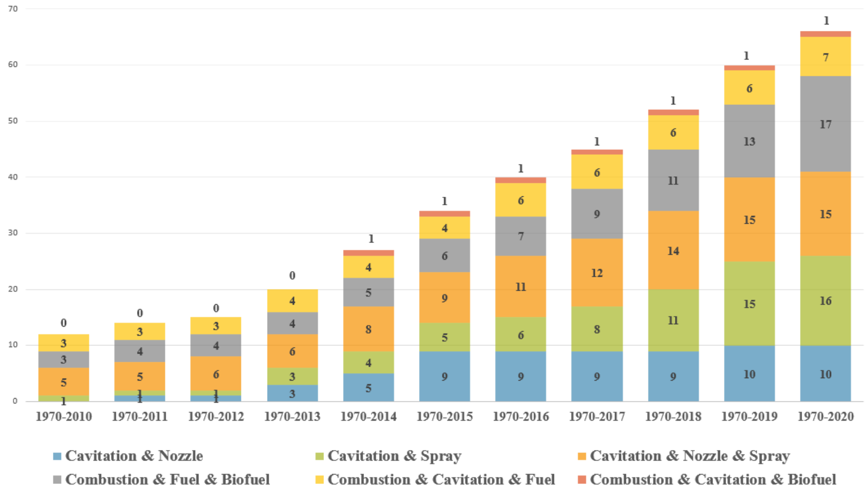

Figure 6. Relevant articles in the different subgroups in the last decade.

2. Presentation of the Work Resulting from the Bibliographic Research

In this presentation, we will discuss the papers resulting from bibliographic research according to the methodology described above.

2.1. Fluidic Studies

2.1.1. Cavitation and Nozzle

In this first subgroup are the papers describing the effects of cavitation inside an injector on the flow of fuel according to several study parameters, such as the geometry of the injector, the type of fuel, and the temperature, etc.

Effect of Injector Geometry

The geometry of the nozzle hole is crucial in the flow of fuel. In the chapter written by Wo et al. [52], entitled "Cavitation of Biofuel Applied in the Injection Nozzles of Diesel Engines", the authors present a synthesis of the conditions of the appearance of cavitation inside an injector that is powered by biofuels, such as the geometric shape of the nozzles (radius of entry, and the L/D ratio). Increasing the inlet radius has the effect of increasing the discharge coefficient and, thus, reducing the volume fraction of the steam, i.e., cavitation. By increasing the L/D ratio, the steam phase tends to move to the central part: this condition is the most unfavorable for the flow of fuel.

To study the effect of injector geometry on cavitation creation, a device using the shadowgraph method was used by Mauger et al. [53] to highlight cavitation inside a simplified and transparent 2D micro channel, fed with test oil at a pressure below 6 MPa. This optical measurement method makes it possible to visualize the formation of steam as well as the gradients of visible refractive index in gray level, which are caused by the turbulence of the fluid. These grayscales provide information on the flow rate. Images are recorded over a very short time of 300 ns, the spatio-temporal correlation functions are calculated according to the evolution of the gray level. To determine velocity fluctuations, a method similar to PIV particle velocimetry, without particle seeding, is carried out. It was noted that there was an increase in speed fluctuations at the outlet of the channel, but also for flow rates, with an amount of steam in the channel between 40% and 50%.

The influence of the L/D ratio of an injector hole on the cavitation flow, using diesel and biodiesel, was conducted by He et al. [54]. Their experiments showed that diesel cavitated more easily than biodiesel and that increasing the L/D ratio tends to decrease cavitation inside the nozzle hole. They also observed a reversal of the cavitation phenomenon, involving a drop in volume flow when increasing the injection pressure.

Effect of Flow Rate

A comparison between the flows of diesel and biodiesel inside an injector, obtained by a numerical study with an RNG k-ε model under OpenFOAM was carried out by Salvador et al. to consider the simulation of turbulence [55]. Their results on the calculation of the average of the steam field showed that biodiesel cavitates less than diesel. Regarding the effective speed, it is a little higher for diesel than for biodiesel. Another numerical study using FLUENT CFD was carried out by Mohan et al. [56] in order to highlight the effects of different parameters such as injection pressure, injector geometry, and fuel type (diesel or biodiesel SME (Soy Methyl Esther)) on the phenomenon of cavitation inside nozzle hole. To perform this study, the two-phase mixing model of Scherr and Sauer (2001) was used with the k-ε turbulence model. These numerical results showed that SME biodiesel, due to its lower viscosity, had a higher dynamic pressure and, therefore, tended to cavitate less compared to diesel. For the same cavitation factor, k, increasing the diameter of the nozzle hole increases the mass flow. Using the numerical results on the cavitation phenomenon that were obtained by the FLUENT CFD software in a new hybrid spray model in KIVA4 CFD code—which considers the cavitation inside the nozzle holes of the injector—Mohan et al. [57] were able to highlight that the cavitation of ethereal fuels was much greater than diesel fuel, since the number of ethereal fuels required to obtain the same engine power is greater compared with diesel. Spray simulation under KIVA4 CFD showed that the atomization of ethereal fuels was much better than diesel fuel.

Transient flow development, caused by the displacement of the needle of the nozzle of an injector of a diesel engine, was conducted by Sun et al. [58] by means of a numerical study through the CFD software ANSYS FLUENT. The flow and cavitation characteristics, as well as the evolution of cavitation in the nozzle, were analyzed. According to these numerical results, it has been shown that cavitation formation can only take place from a certain position of the needle, allowing the fluid to have the minimum required speed. Cavitation bubbles arise at the entrance of the nozzle, in the lower position of the nozzle, and then, when the speed increases, the bubbles move to the upper part.

Injection conditions on the development of cavitation in a transparent nozzle with double orifices were conducted by Ma et al. [59]. Their experimental work showed the presence of cavitation at the beginning of the opening of the needle, demonstrating that this cavitation is more important with the injection pressure. An average of the snapshots was made to highlight the clear variation in cavitation between each orifice, showing that cavitation depends on the geometry of the nozzle.

Effect of Fuel Temperature

A study of the effects of fuel temperature on the occurrence of cavitation in the flow was conducted numerically by He et al. [60] with the FLUENT software. The RANS k-ξ model made it possible to highlight the fact that the increase in fuel temperature can have an influence on the cavitation of the flow inside the injector. This study was corroborated by an experiment using a transparent injector, allowing the visualization of the phenomenon with a motion Pro-TM10000 fast camera and a Questar QM-1 long-range microscope. This study highlights a strong transient character of cavitation flow in the nozzles during the movement of the needle, which can be very chaotic during the period of quasi-closure of the needle.

The experimental results carried out by Tinprabath et al. [61] focused on the behaviors of a Bosch CRI 3.1 3-hole piezoelectric injector for different parameters, such as viscosity and fuel density in cold conditions, especially on low injection pressures using pure biodiesel or mixed with diesel. Tests were conducted at positive temperatures with fuels without additives showing that the increase in viscosity decreases the discharge coefficient. For tests at negative temperatures, additives were added. It has been noted that the addition of additives annihilates the effects of viscosity, thus, allowing biodiesel and diesel mixtures to have the same discharge coefficient as at higher temperatures.

2.1.2. Cavitation and Spray

In this second subgroup are the articles characterizing the spray according to different parameters, such as nozzle geometry, fuel temperature, injection pressure, and viscosity.

Effect of Injector Geometry

The geometry of the nozzles strongly influences the spray characteristics that have been the subject of numerous studies. For example, the effect of the input geometry of nozzles (pointed or rounded) was studied experimentally and numerically under the code KIVA3V R2 by Taskiran [62]. These experiments show that nozzles with a rounded inlet have a higher discharge coefficient than pointed inlet nozzles. This difference in discharge coefficient decreases with an increase in the ambient pressure. It was found that, with the pointed inlet nozzle, the diameter of the droplets is smaller than those with the rounded inlet nozzle. As a result, the evaporation of the droplets is faster, and the temperature increases rapidly with the pointed inlet nozzle. Similarly, the geometry of the nozzle holes, fed by biodiesel under different injection and back pressures, has a significant impact on the characteristics of the spraying, as shown by the study carried out by Yu et al. [63] on the holes of different injectors of the elliptical or circular type. They showed that the spray angle of the elliptical nozzles increased more than that of the circular nozzles when the back pressure increases. In addition, the spray of the elliptical nozzles increases the exchanges with the air and, thus, promotes the quality of the air-fuel mixture. Increasing the injection pressure increases the penetration length for both types of nozzles. However, for the same injection pressure, the elliptical nozzle has a smaller penetration length. It has been noted that the axes of the elliptical orifice change during the spraying process. This phenomenon decreases with an increase in back pressure. To highlight the effect of nozzle hole geometry and fuel viscosity, Ishak et al. [64] used two types of nozzles, one cylindrical, the other conical, powered by four different biofuels with different physical characteristics in terms of viscosity, surface tension, and density. The results of the numerical study on spray characteristics under ANSYS FLUENT, using the discrete phase model (DPM), showed that viscosity, density, and surface tension influence the diameter of Sauter droplets (SMD). Fuel properties play a predominant role in spray characteristics. Surface tension has a smaller impact on biofuel SMD. The geometry of the holes has a small effect on the penetration of the spray nozzle, although the conical shape gives a slightly higher penetration of the nozzle. The cylindrical hole nozzle generated significantly lower exit speeds, resulting in lower spray penetration than with the conical nozzle hole.

Studies on the effects of the nozzle hole L/D ratio and fuel temperature on different injection pressures, and the effects of ambient pressure on biodiesel spray characteristics were conducted by Geng et al. [65]. Their numerical work using FLUENT showed that injection pressure and fuel temperature have a greater impact on spray performance than the L/D ratio. Injection pressure has a significant effect on spray speed, penetration length, and mean jump diameter (SMD). When the fuel temperature is increased from 300 K to 350 K, the maximum concentration of the axial spray center decreases by 25.41% and the SMD decreases by 17.19%. As the L/D ratio increases, the concentration of the spray center also increases.

Effect of Fuel Temperature

The effect of fuel temperature on spray characteristics is also considered as a study parameter. Through their experimental and numerical studies under KIVA-3V CFD, on the effect of fuel temperature and ambient temperature on soybean oil methyl ester atomization (SME), Park et al. [66] showed that the variation in fuel temperature (300–360 K) did not have a great effect on the length of fuel penetration. The mass of evaporated fuel is greater in the center in the spray axis, it is more important as the ambient temperature increases. Increasing the temperature of the fuel decreases the density of the fluid, its dynamic viscosity, and its surface tension, which has the consequence of decreasing the axial velocity and increasing collisions between neighboring droplets.

In view of the new Euro VI standards for cold start problems, Tinprabath et al. [67] conducted an experimental study on the injection process of diesel and biodiesel blend. The authors showed that, under cold conditions, all the fuels used—such as diesel-biodiesel (B50), a winter diesel-biodiesel blend (B50 (W)), and pure biodiesel (B100)—had a discharge coefficient lower than under ambient temperature conditions. Cold temperature has a negative influence on the spray by increasing the length of penetration and decreasing the angle of spraying. Winter diesel, with an additive, showed a more efficient discharge coefficient compared with diesel, regardless of temperature. By adding biodiesel to winter diesel, the additive loses its effectiveness. Increasing the viscosity of the mixture by adding biodiesel has a detrimental effect on the spray by increasing the penetration length and decreasing the spray angle.

Koegl et al. [68] experimentally studied the spray structure of two biofuels (ethanol and butanol) in a constant volume chamber. The analysis of the shape and structure was carried out by laser-illuminated planar imaging. Two pieces of information could be analyzed: the laser-induced fluorescence and the Mie scattering. These were recorded simultaneously. The results highlighted that an increase in fuel temperature leads to faster atomization and a faster evaporation rate, leading to lower spray penetration and a smaller Sauter mean diameter (SMD). The surface tension and higher viscosity of butanol tends to achieve larger droplet diameters. In addition, the injection of butanol has differences in the different injections, due to a change in flow.

Effect of Injection or Ambient Pressure

The injection pressure is also a parameter to be considered. For example, experiments conducted on spraying characteristics near the nozzle of soybean biodiesel, di-n-butyl/biodiesel ether blends (DBE30), and pure diesel were studied by Tang et al. [69] using a high-pressure common rail injection system. The physical properties of spraying structures in the vicinity of nozzles were explored. Analysis of microscopic near-field spray images of the nozzle by high-resolution microscopy showed that the high surface tension and the viscosity of biodiesel result in low primary spray fragmentation and a smaller micro spray area compared with DBE30 and diesel. The high injection pressure leads to an increase in the micro spray area that is projected, due to the improved primary breakage. Similarly, the high ambient pressure promotes radial propagation of spray development and leads to a larger micro spray area.

The movement of the needle can affect the flow of fuel inside the injector and disrupt the spray. Moon et al. [70] have shown, by an experimental study, the effects of biodiesel on the transient movement of the needle and flow characteristics close to the single-round nozzle outlet of a high-pressure diesel injector, such as needle lift, needle velocity, exit velocity, and flow structure close to the outlet. To do this, an ultra-fast X-ray phase contrast imaging technique was used. The high viscosity of biodiesel slows down the movement of the needle and decreases flow performance. During the transient opening, a sharp increase in exit speed and spray width was noted for different fuels, with a slower increase for biodiesel and a smaller spray width compared with diesel. For lower injection pressures below 100 MPa the difference between diesel and biodiesel became small.

In order to better predict the physical processes involved in the atomization of diesel, biodiesel, and kerosene fuel, Crua et al. [71] carried out investigations near the nozzle outlet, allowing detailed observation of the emergence of the fuel through a long-range microscope. The dynamics of the phenomenon were captured by a fast camera that can render up to 5 million frames per second. It was observed that, in the early moments of spraying, the fluid had a mushroom-like structure that could be preceded by a micro jet (see Figure 7). This form was identified by the author as residual fluid trapped inside the nozzle orifice at the end of each injection. It was noticed that this residual fluid had a movement in the form of an "inner vortex ring", propelling a microscopic ligament of fuel.

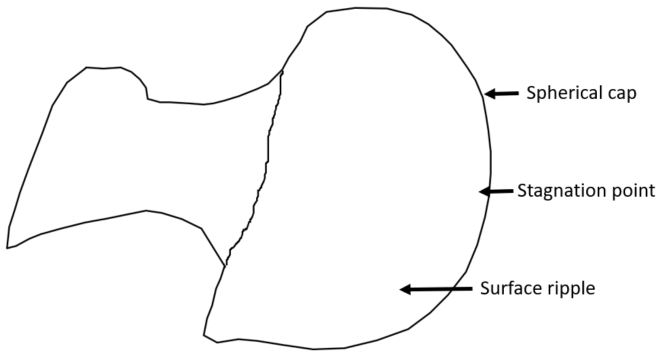

Figure 7. Description of emergence of the fuel near the nozzle outlet.

Studies on the spraying characteristics of biofuels in a pressurized gas flow have been studied by Jiao et al. [72], as a function of impulsion fluxes, Weber numbers, and liquid-to-gas density ratios. The aerodynamic action of the two fluids allows the fuel to atomize by shearing—first by forming ligaments that are then reduced to shorter ligaments, to fine droplets of fuel. The results obtained show that the increase in the density ratio favors the quality of the atomization and the number of ligaments and that the increase in the injection speed has an influence on the length of penetration of the fuel jet.

To understand the spraying behaviors that are essential for successfully using high-pressure injection systems (30–50 MPa) and biofuels (such as 2-methylfuran (MF), ethanol (ETH), and Isooctane (ISO)) in modern direct injection gasoline engines, experiments were conducted by Wang et al. [73], showing a unique spray nozzle structure with a bubble attached to a mushroom tip from 30 MPa for ethanol and 30–40 MPa for MF, given a higher surface tension. This phenomenon depended on the Weber number, which is a dimensionless number, to characterize the flow of fluids at the interface of a multiphase system. Of the three fuels tested, MF had the lowest peak spray speed in both near field (up to 1.6 mm) and far field (up to 48 mm) due to its high density. Due to a lower viscosity of MF and ISO, these have a larger macro cone angle than ETH.

Effect of Viscosity

Compared with diesel, biofuels generally have a higher viscosity, which is why this parameter is the subject of studies including the experimental work carried out by Galle et al. [74] on the influence of different biofuels, such as rapeseed biodiesel (RME), rapeseed oil (RSO), palm oil (PO), and animal fats (AF) on atomization and spray development processes compared to diesel. The authors have highlighted that, at low temperatures, the atomization of pure vegetable oil is very poor due to its high viscosity. The more important viscosity of biofuels results in a longer injection time than for diesel. The length of penetration depends more on the injection pressure than on the temperature of the biofuel. A literature review on the atomization process of biofuels in internal combustion engine applications and on the effects of this type of fuel on the spray fragmentation process was carried out by Boggavarapu and Ravikrishna [75]. The authors, in summarizing the literature, were able to highlight that biofuels generally have a higher viscosity, surface tension, and latent heat of vaporization, resulting in a different atomization and spray structures compared with fossil fuel. In addition, it has been noted that some studies have shown that the diameter of biodiesel droplets is generally larger than common diesel. The length of penetration is greater and the spray angle lower for biofuels compared to diesel. Adding DME mixed with biofuel and diesel improves the vaporization characteristics of the resulting fuel.

To decrease the viscosity of biofuels, Hou et al. [76] investigated the influence of the addition of DME in biodiesel according to different BD100, BD70, and BD30 blend ratios on the dynamic injection behavior in a common rail injection system. The effects of the injection pressure, the pulse width, the injection rate, the amount of injection, and the pressure at the inlet of the injector are determined. The results show that the duration of the injection is greater with the decrease in the ratio of biodiesel. The average amount of volume injection increases with the increase in the percentage of DME, compared with pure biodiesel. Geng et al. [77] digitally investigated the effects of adding ethanol to biodiesel on macroscopic and microscopic spray characteristics under FLUENT CFD software and experimentally verified the results. The simulation results show that biodiesel has a higher viscosity and surface tension than diesel, and that it is possible to decrease these physical parameters of biodiesel by adding ethanol. In addition, by adding ethanol to biodiesel, the penetration lengths and the diameters of the Sauter droplets decreased by 22.05% and 20.88%, respectively. BD70E30 fuel (70% biodiesel, 30% ethanol) has similar characteristics to conventional diesel, which is why this fuel seems to be able to replace conventional diesel fuel.

2.1.3. Cavitation, Nozzle, and Spray

In this third subgroup, the influence of cavitation on spray formation is studied, using a method to visualize the characteristics of the spray, the characteristics of the fuel, the angle formed between two nozzle holes, injection and ambient pressures, and fuel mixtures.

Effect of Viscosity

The physical characteristics of the fuel play a preponderant role in the cavitation inside the injector and in the spraying. Som et al. [78] used two different software programs for their numerical study. The first, FLUENT v6.3, allowed them to obtain simulations showing that the cavitation of biodiesel was less important than diesel fuel and that the disturbances of the flow inside the injector are less important for biodiesel. The second is the CONVERGE software, using the KH-ACT model for primary breakup and the KH-RT model for secondary breakup. The results have highlighted that biodiesel is more difficult to atomize, given a higher viscosity, and that increasing the temperature by 60 K allows to obtain a better result. The numerical study developed in KIVA4 CFD code by Mohan et al. [79] proposes a new hybrid spraying model by coupling the cavitation induced spray model with the KH-RT model. Three methyl esters (Methyl Oleate, Methyl Stearate, and Methyl Linoleate) were studied as a representative fuel for different biodiesels. In-house experiments using a constant volume spray chamber made it possible to validate the model presented. The results showed that the higher viscosity of methyl stearate tends to inhibit cavitation, followed by methyl oleate and methyl linoleate, due to their higher viscosity compared to diesel. This higher viscosity is responsible for decreasing the injection rate and increasing the spray penetration of methyl esters. The atomization of methyl linoleate is comparable to diesel, unlike methyl oleate and methyl stearate, where atomization is poorer.

The spray characteristics of used cooking oil biodiesel (B100) and its blend with diesel (B20) were compared with standard diesel by Mohan et al. [80]. Thus, the characteristics, such as penetration length, angle, and spray rate were studied using a constant volume spray chamber. The results showed that B100, by its higher viscosity compared with diesel, has a higher penetration and pulverization speed, unlike the angle of the cone, which was narrower. With the increase in chamber pressure, the angle of the cone increases sharply in contrast to penetration length. The shape of the jet is affected by cavitation inside the injector nozzle. Given the oxygen content of B100, it has a poorer equivalence ratio than B20 and diesel. These results were confirmed by a numerical study using a new model under KIVA4.

The study of the cavitation phenomenon for fuel mixtures was carried out numerically by Agarwal et al. [81] by simulating the contours of the vapor fraction for different fuels, such as diesel, biodiesels (Karanja, Jatropha), and their mixtures (KB5, KB20, KB100, JB5, JB20, and JB100). This study highlighted the phenomenon of cavitation of fuels arriving at the nozzle inlet in liquid form. This study was carried out in two stages, first Karanja and its mixtures with diesel, and then Jatropha and its mixtures. Regarding the Karanja and its mixtures, it was found that cavitation at the outlet of the nozzle reduces the mass flow of fuel. As for Jatropha and its blends, as biodiesel is added to the blend, the viscosity increases and the speed in the nozzle decreases. The cavitation zone decreased sharply with pure Jatropha (JB100), leaving it in liquid form at the nozzle outlet, suggesting poor atomization. Indeed, the JB100 has a higher viscosity than diesel, which inhibits the phenomenon of cavitation. Regarding the comparison between the two biodiesels, the cavitation contours continued until the exit of the nozzle for blends with Karanja biodiesel (KB05, KB20), and only JB05 for blends with Jatropha biodiesel, which would explain that this phenomenon would be due to be the relatively higher viscosity of the JB100 compared to KB100, which tends to inhibit cavitation. Spray characterization was undertaken based on spray penetration length, spray surface, and spray cone angle, showing that fuel atomization degraded with biodiesel blend. The angle of the spray cone of Karanja biodiesel increased with the increase in the concentration of the biodiesel blend. This increase in the angle of the cone would be due to the resistance of the air to incoming fuel droplets, unlike diesel which has a relatively higher evaporation compared to biodiesel. The comparison between the two biodiesels shows that Karanja biodiesel has a relatively lower viscosity and density than Jatropha biodiesel. In addition, Karanja biodiesel can evaporate faster in the engine's combustion chamber than Jatropha biodiesel. As a result, Karanja biodiesel appears to be a more promising biofuel than Jatropha biodiesel, when it comes to the air-fuel blend.

In order to highlight the spray characteristics of fuels such as dimethyl ether (DME) and diethyl ether (DEE) compared to standard diesel, Mohan et al. [82] undertook a numerical study under KIVA-4 CFD. A new hybrid spray model, made by coupling the standard KHRT model with a cavitation submodel, was used. Ether fuels have been shown to cavity more than standard diesel and have a lower spray penetration length, due to their lower viscosity than standard diesel. Ether fuels, with a higher Reynolds number and a lower Ohnesorge number compared with diesel, have a better ease of atomization compared to diesel. These studies highlight that fuel viscosity is the most dominant property in determining the atomization process.

Effect of Injector Geometry

A comparison on the injection process between pure diesel and pure biodiesel (soybean oil methyl ester) was made by the digital work of Battistoni and Grimaldi [83] through the CFD software AVL-Fire. This numerical study was carried out in two stages, first by a two-fluid Eulerian-Eulerian approach that considers the dynamics of the bubbles and then by a Lagrangian method of primary rupture to see the spray evolutions, using the results obtained beforehand. Two types of nozzles were analyzed, the first with cylindrical holes, the second with conical holes. The results showed that cavitation was highly dependent on the shape of the nozzle. Biodiesel provides a slightly higher flow rate in nozzles with high cavitation. In the case of conical nozzles, since cavitation is less important, the difference in flow rate between diesel and biodiesel is less pronounced. The effects of different viscosities and densities play an essential role in the behavior of different fuels. In order to study the spraying evolutions of the two fuels, the authors made a mapping to the exit zone of the hole to analyze the initialization of the primary fracture in a Lagrangian model. His simulations made it possible to address the evolution of spraying, penetration length, cone angle, and fuel atomization. The shape of the nozzle hole affects diesel more than biodiesel, regarding the angle of the cone and the length of penetration. In the conical form, diesel gives a longer penetration length than for biodiesel.

The study on the spray characteristics of diesel (D) and sunflower biodiesel (SFB) near the injector nozzle as a function of angle (AU) between two nozzle holes for different injectors were studied by Zhang et al. [84], using rapid X-ray phase contrast imaging and quantitative image processing. The spray width (SW) was defined as the width at the distance of 1.5 mm from the nozzle outlet. The angle formed between the nozzle holes had an influence on the spray characteristics close to the nozzle by the presence of vortex flow and cavitation in the nozzle holes, modifying the flow conditions at the exit of the nozzle.

The symmetry of the fuel spray can be modified by cavitation; in fact, when the cavitation is at the exit of the nozzle hole, we observe, in part of the spray, a disintegration of the fuel causing an asymmetry of the shape of the jet. An experimental study combined with a numerical study using AVL FIRE, conducted by Lešnik et al. [85], made it possible to study the influence of nozzle flow, cavitation, and fuel property (diesel and rapeseed oil biodiesel) on spray development and the primary breakup process. The development of spraying and primary breakup was conducted experimentally by means of a fast camera. The spray length and cone angle were determined by LabVIEW software. The numerical results show that the geometry of the injector strongly influences the flow of fuel and the onset of cavitation. The experimental results show that the length of penetration is influenced by the type of fuel used. The appearance of cavitation at the exit of the nozzle hole allows the fuel to better disintegrate locally but makes the shape of the jet asymmetrical. Increasing the pressure inside the spray chamber reduces the effects of the difference in viscosity of the fuels studied. The author points out that this type of biodiesel could be used in a diesel engine without much modification to its injection system.

Effect of Injection or Ambient Pressure

The parameters of injection pressure and ambient pressure have been studied by Yu et al. [86] on the spray characteristics of dimethyl ether (DME) and conventional diesel. The injection pressure varied from 25 to 55 MPa in a constant volume container pressured by nitrogen gas, while the ambient pressure varied from atmospheric pressure to 3 MPa. Cone angles and penetration lengths were measured using a series of chronological images taken by a CCD camera. For the characterization of the spray, the shadowgraphic method was used, through an Ar laser and an intensified charge coupling camera (ICCD). The results obtained showed that a higher injection pressure increases the vapor phase zone while it decreases, when the chamber pressure conditions were higher. Intermittent spraying may occur in the event that the solenoid current is not stable. The vapor phase of DME spraying was predominant in the spray edge region and downstream, so it can be assumed that the DME would have better flammability. The spray area increased with the increase in injection pressure. Kegl and Lešnik [87] studied the development of spraying in a spray chamber for a pressure of 4 MPa and 6 MPa using mineral diesel and biodiesel from rapeseed oil, respectively. Initially, an experimental study was conducted to characterize the spray (length of spray penetration and angle of the cone). In a second step, a modification of the mathematical model was carried out in order to consider the variation of the angle of the cone during spraying. The results showed that diesel had a larger cone angle and a lower penetration length that would be, due to the fact that diesel tends to cavitate more than biodiesel. Increasing the pressure in the spray chamber decreases the length of penetration of the diesel.

Other studies have been conducted on injection characteristics, such as injection delay, injection rate, and effective velocity in the flow passage of the nozzle for different fuel mixture ratios, such as that of Bang and Lee. [88], who investigated different ratios of mixing dimethyl ether (DME) with methyl ester derived from soybean oil (biodiesel). The experimental results showed that the injection time increased with the amount of biodiesel in the blend compared with pure DME. The effective speed increases with the increase in the amount of biodiesel. Decreasing the injection pressure significantly increases the injection delay, especially for B75 and pure biodiesel. The injection rate decreases with the increase of biodiesel in the blend. Regarding atomization, it has been shown that at high ambient pressure, DME evaporates faster than blending with biodiesel. In addition, for DME fuels containing biodiesel, or for pure biodiesel, it was revealed that the spray angle was greater than that of pure DME. The experimental study of the injection characteristics of biodiesel fuel mixed with ethanol, conducted by Park et al. [89], was analyzed using the measurement of injection rate, effective injection rate, and effective spray diameter. The results showed that the effective diameter of the nozzle decreases when the pressure in the contracted vein is less than the vapor pressure. However, when the pressure in the nozzle is below the vapor pressure, the fuel is in a cavitation state; therefore, it can be deduced that cavitation has an impact on the effective diameter of the nozzle. The atomization characteristics of biodiesel fuel mixed with ethanol were studied, according to local and global distributions and the global axial velocity. The results obtained showed that, due to the decrease in dynamic viscosity and density, biodiesel fuel mixed with ethanol has a reduced injection rate and injection delay. In addition, the addition of ethanol has improved the atomization performance of biodiesel fuel, as fuel blended with ethanol has a kinematic viscosity and low surface tension, allowing for greater interaction with ambient gas. The drop size of the biodiesel ethanol blend (BDE20) was smaller than that of the undiluted biodiesel, due to the lower dynamic viscosity of the blend. The author concludes by saying that the addition of ethanol in biodiesel has a beneficial action on the performance of fuel atomization.

The technique of laser light sheet and shading in the nozzle hole, used in the experimental study of Badock et al. [90], made it suitable to study the phenomenon of cavitation inside the injection nozzle. The results showed that from 380 µs, there is a growth in cavitation for 20 µs to extend almost to the exit of the hole of the spray nozzle. The advantage of this laser light sheet technique is to be able to detect a liquid core surrounded by cavitation that the shadowgraphic method does not allow. This method was also able to characterize the spray by highlighting, at the beginning of injection, the presence of a gas bubble at the outlet near the nozzle, which, by expanding—since the ambient pressure is lower than the internal pressure of the bubble—takes the form of mushroom. Another optical technique used by Wei et al. [91] consists of averaging about twenty binary images in order to obtain a calculated gray level, defining a dimensionless number S to highlight cavitation bubbles formed in the volume of the nozzle bag—the fresh fuel pushed the bubbles into the orifice, thus, increasing the cavitation flow. During the injection time, cavitation continued to grow, obscuring the orifice area. The variation in the injection pressure did not make it possible to modify the morphology of the cavitation, but the appearance of the bubbles occurred earlier and developed more quickly. The increase in the injection pressure contributes to the increase in the Reynolds number, thus, disturbances in the flow, and consequently cavitation, disrupts the fuel flow. An experimental study on the morphology of the spray near the outlet of the injector at atmospheric pressure was conducted for an injection pressure of 30–60 MPa, where a fungus-shaped structure appeared unchanged, visible from 180 to 350 µs after injection. This phenomenon could be related to the presence of cavitation bubbles in the jet or bubbles trapped in the nozzle between injections. The speed of this mushroom-shaped structure was slow, given the friction in the air caused by the low aerodynamic shape. By this fact, the progression of the jet was done radially, by increasing the angle of the spray cone with the presence of small ligaments and rupture droplets at the periphery of the fungus-shaped structure. By increasing the injection pressure, stronger cavitation appeared with higher turbulence, causing a strong primary breakup with a highly dispersed spray. The results were obtained from binary images converted by image processing in MATLAB. The effects of turbulence inside an injector on the spray of a biodiesel was studied numerically by Zhao et al [92], with the PISO algorithm (pressure implicit split operator) under OpenFOAM. The results showed that, the greater the turbulence in the injector, the more the shape of the ligaments at the exit of the injector tends towards a looped shape, caused by tangential forces.

2.1.4. Summary

The different fluidic studies have been gathered in Table 1 below:

Table 1. List of equipment used and the results obtained in the fluidic studies among relevant papers.

Fluidic Studies			
Experimental Studies			
Subject of Study	**Principle Results**	**Equipment Used**	**Bibliographic Reference**
Influence of the L/D ratio on cavitation inside the nozzle hole.	Increasing the entry radius increases the discharge coefficient decreases the vapor volume fraction.		[52]
Visualisation of cavitation by shadowgraphy method.	Speed fluctuations have been observed. Increasing the flow velocity has the effect of increasing the amount of cavitation.	Nd:YAG pulsed laser (wavelength kYAG = 532 nm and pulse duration = 6 ns) Optical zoom system 10-bit CCD camera	[53]
The influence of the L/D ratio of an injector hole on the cavitation flow using diesel and biodiesel.	Increasing the L/D ratio decrease cavitation.	A long distance microscope (QM-1, QUESTAR) High-speed digital camera (Motion ProTM10000) A high power LED light Flow rate meter (LC-E10/EL2) Transparent nozzle	[54]
Development of cavitation in a transparent nozzle with double orifices.	Increasing the injection pressure has the effect of increasing the amount of cavitation.	Transparent nozzle in PPMA High speed camera Light source	[59]
Viscosity and fuel density in cold conditions.	The increase in viscosity decreases the discharge coefficient.	Bosch CRI 3.1 3-hole piezoelectric injector Piezoelectric sensor and temperature sensor IAV@ Injection Rate system	[61]
Different injection and back pressure pressures on the characteristics of the spraying.	The spray angle of the elliptical nozzles increased more than that of the circular nozzles when the back pressure increases.	Two CCD cameras Two light sources (LED lights) Nitrogen, MATLAB software	[63]
The injection process of diesel and biodiesel blend.	The cold temperature has a negative influence on the spray by increasing the length of penetration and decreasing the angle of spraying.	Bosch CRI 3.1 piezoelectric micro-sac injector A pump and a pressure fuel tank High speed camera 15,000 frames per second A continuous 150 W halogen lamp A climatic chamber.	[67]
The spray structure of two biofuels (ethanol and butanol) in a constant volume chamber.	An increase in fuel temperature leads to faster atomization and faster evaporation rate leading to lower spray penetration and a smaller average Sauter diameter.	Two CMOS cameras A cube beam splitter Two pulsed 532 nm Nd:YAG lasers A five-hole DISI injector (BOSCH)	[68]
Spraying characteristics near the nozzle of soybean biodiesel, di-n-butyl/biodiesel ether blends (DBE30).	The high surface tension and viscosity of biodiesel result in low primary spray fragmentation and a smaller micro spray area compared to DBE30 and diesel.	A Nd: YAG laser A fluorescence diffusor A CCD camera A long distance microscope	[69]

Table 1. *Cont.*

Fluidic Studies			
Experimental Studies			
Subject of Study	**Principle Results**	**Equipment Used**	**Bibliographic Reference**
The effects of biodiesel on the transient movement of the needle and flow characteristics.	The high viscosity of biodiesel slows down the movement of the needle and decreases flow performance.	A CCD camera A scintillator crystal (LYSO:Ce) X-ray beam.	[70]
Investigations near the nozzle outlet.	Observation in the early moments of spraying that the fluid had a mushroom-like structure that could be preceded by a micro jet.	12 bit CCD cameras A Nd:YAG laser A light source An ultra-fast framing camera	[71]
Spraying characteristics of biofuels in a pressurized gas flow.	The aerodynamic action of the two fluids allows the fuel to atomize by shearing by first forming ligaments that are then reduced to shorter ligaments up to fine droplets of fuel.		[72]
Spraying using high-pressure injection systems and biofuels such as 2-methylfuran (MF), ethanol (ETH), and Isooctane (ISO) in modern direct injection gasoline engines.	A unique spray nozzle structure with a bubble attached to a mushroom tip from 30 MPa for ethanol and 30–40 MPa for MF given a higher surface tension.	An ultra-high-speed camera A long-distance microscope QM100 A 500W Xenon lamp High-pressure liquid pump.	[73]
The influence of different biofuels such as rapeseed biodiesel (RME), rapeseed oil (RSO), palm oil (PO), and animal fats (AF) on atomisation and spray development processes compared to diesel.	At low temperatures the atomization of pure vegetable oil is very poor due to its high viscosity. The length of penetration depends more on the injection pressure than on the temperature of the biofuel.	Constant volume combustion chamber A high speed CCD camera A Kistler 4067A2000 pressure sensor K-type thermocouple The Pump-Line- Nozzle (PLN) system	[74]
The atomization process of biofuels in internal combustion engine applications and the effects of this type of fuel on the spray fragmentation process.	The diameter of biodiesel droplets is generally larger than common diesel. Biofuel generally have a higher viscosity, surface tension and latent heat of vaporization resulting in a different atomization and spray structure compared to fossil fuel.	A literature review.	[75]
Investigated the influence of the addition of DME in biodiesel according to different BD100, BD70, and BD30 blend ratios.	The duration of the injection is greater with the decrease in the ratio of biodiesel. The average amount of volume injection increases with the increase in the percentage of DME compared to pure biodiesel.	Two Kistler 4067A2000 pressure sensors Two Kistler 4068 charge amplifiers A Tektronix A622 current probe and the Yokogawa DL750 data acquisition equipment.	[76]
The spray characteristics of used cooking oil biodiesel (B100) and its blend with diesel.	The results showed that B100, by its higher viscosity compared with diesel, has a higher penetration and pulverization speed unlike the angle of the cone which was narrower.	A constant volume spray chamber, Nitrogen (N2), common rail system, high pressure fuel pump, Denso common rail injector, Photron Fastcam SA5 high speed camera, and a 400W Hydrargyrum medium-arc Iodide (HMI) lamp.	[80]

Table 1. *Cont.*

Fluidic Studies			
Experimental Studies			
Subject of Study	**Principle Results**	**Equipment Used**	**Bibliographic Reference**
The spray characteristics of diesel (D) and sunflower biodiesel (SFB) near the injector nozzle as a function of angle (AU) between 2 nozzle holes.	The angle formed between the nozzle holes had an influence on the spray characteristics.	The XPCI, experiments commercial common rail injection system. A fuel tank A motor with high pressure pump and common rail. Apressure control unit and high pressure line.	[84]
The parameters of injection pressure and ambient pressure on the spray characteristics of dimethyl ether (DME) and conventional diesel.	A higher injection pressure increases the vapor phase zone while it decreases when the chamber pressure conditions were higher.	ICCD camera with resolution of 1280(H)X1024(V), an Nd:YAG laser (SL2-10, Continuum, 532 nm and 150 mJ), and a signal synchronization system such as injector driver (TDA-3200H, TEMS), and digital delay generator (Model 555, Berkeley Nucleonics Corp.).	[86]
The development of spraying in a spray chamber for a pressure of 4 MPa and 6 MPa using mineral diesel and biodiesel from rapeseed oil.	The results showed that diesel had a larger cone angle and a lower penetration length that would be due to the fact that diesel tends to cavitate more than biodiesel.	High pressure pump, injector provided with single hole, A data acquisition system (DAQ system), LabVIEW software, a digital high speed camera, and LED lights.	[87]
Injection characteristics with different ratios of mixing dimethyl ether (DME) with methyl ester derived from soy-bean oil (biodiesel).	The injection time increased with the amount of biodiesel in the blend compared to pure DME.	A piezo-type pressure sensor (Type 4045A50, Kistler), ICCD camera with resolution of 1280(H) $\times$ 1024(V), Nd:YAG laser, an injector driver, and digital delay generator (Model 555, Berkeley Nucleonics Corp.).	[88]
The phenomenon of cavitation inside the injection nozzle.	The presence of a gas bubble at the outlet near the nozzle takes the form of mushroom at the beginning of injection.	A Bosch Common Rail A High rail pressures, Nd:YAG-laser A CCD camera.	[90]
Cavitation bubbles formed in the volume of the nozzle bag.	The increase in the injection pressure contributes to the increase in the Reynolds number; thus, disturbances in the flow and consequently cavition disrupting the fuel flow. The morphology of the spray near the outlet of the injector a fungus-shaped structure appears unchanged visible from 180 to 350 µs after injection.	An optical transparent nozzle A common-rail direct injection system A high-pressure diesel pumps driven by electric motors, Nano Pulse Light (NPL) and Lamphouse (light source). A canon 700D camera with Electro-Optical System (EOS), and a microscope (QUESTAR QM-100) lens with large focal length.	[91]

Table 1. *Cont.*

Fluidic Studies			
Numerical Studies			
Subject of Study	**Principle Results**	**Software/Model Used**	**Bibliographic Reference**
Flow of diesel and biodiesel inside an injector.	Biodiesel cavitates less than diesel.	OpenFOAM/RNG k-ε	[55]
Influence of fuel type on cavitation inside nozzle hole.	SME biodiesel cavitates less compared with diesel.	FLUENT CFD/k-ε	[56]
Cavitation inside the nozzle holes of the injector.	Cavitation of ethereal fuels was much greater than diesel fuel.	KIVA4 CFD	[57]
Evolution of cavitation in the nozzle.	Cavitation bubbles arise at the entrance of the nozzle in the lower position.	FLUENT CFD	[58]
Increase in fuel temperature can have an influence on the cavitation.	The increase in fuel temperature can have an influence on the cavitation of the flow inside the injector.	FLUENT CFD/k-ε	[60]
The effect of the input geometry of nozzles (pointed or rounded).	The nozzle with a rounded inlet has a higher discharge coefficient than the pointed inlet nozzles.	KIVA3V R2	[62]
Spray characteristics.	Fuel properties play a predominant role in spray characteristics. Viscosity, density, and surface tension influence the diameter of Sauter droplets.	FLUENT CFD/discrete phase model	[64]
The effects of the nozzle hole L/D ratio and fuel temperature for different injection pressures and ambient pressure on biodiesel spray characteristics.	Injection pressure and fuel temperature have a greater impact on spray performance than the L/D ratio.	FLUENT CFD	[65]
Effect of fuel temperature and ambient temperature on soybean oil methyl ester atomization (SME).	The variation in fuel temperature (300–360K) did not have a great effect on the length of fuel penetration.	KIVA-3V	[66]
The effects of adding ethanol to biodiesel on macroscopic and microscopic spray characteristics.	Biodiesel has a higher viscosity and surface tension than diesel, it is possible to decrease these physical parameters of biodiesel by adding ethanol BD70E30 fuel (70% biodiesel, 30% ethanol) has similar characteristics to conventional diesel.	FLUENT CFD	[77]
The physical characteristics of the caburant in the cavitation inside the injector and in the spraying.	The cavitation of biodiesel was less important than diesel fuel and that the disturbances of the flow inside the injector are less important for biodiesel.	FLUENT v6.3 and CONVERGE, KH-ACT (primary breakup) KH-RT (secondary breakup)	[78]
A new hybrid spraying model by coupling the cavitation-induced spray model.	The higher viscosity of methyl stearate tends to inhibit cavitation followed by methyl oleate and methyl linoleate due to their higher viscosity compared to diesel.	KIVA4 CFD/KHRT	[79]

Table 1. *Cont.*

Fluidic Studies			
Numerical Studies			
Subject of Study	**Principle Results**	**Software/Model Used**	**Bibliographic Reference**
Simulation of the contours of the vapor fraction for different fuels such as diesel, bio-diesels (Karanja, Jatropha), and their mixtures (KB5, KB20, KB100, JB5, JB20, JB100).	Cavitation at the outlet of the nozzle reduces the mass flow of fuel. Karanja biodiesel appears to be a more promising biofuel than Jatropha biodiesel, when it comes to the air-fuel blend.		[81]
A new hybrid spray model by coupling the standard KHRT model with a cavitation submodel.	Ether fuels have been shown to cavity more than standard diesel, also have a lower spray penetration length due to their lower viscosity than standard diesel.	KIVA4 CFD/KHRT	[82]
A comparison on the injection process between pure diesel and pure biodiesel (soybean oil methyl ester).	The shape of the nozzle hole affects diesel more than biodiesel regarding the angle of the cone and the length of penetration.	AVL-Fire	[83]
The influence of nozzle flow on spray development and the primary breakup process.	The geometry of the injector strongly influences the flow of fuel and the onset of cavitation.	AVL-Fire	[85]
The effects of turbulence inside an injector on the spray of a biodiesel.	The greater the turbulence in the injector, the more the shape of the ligaments at the exit of the injector tends towards a looped shape caused by tangential forces.	OpenFOAM/PISO algorithm	[92]

2.2. Combustion Studies

2.2.1. Combustion, Fuel, and Biofuel: Effect of Fuel Type

Nowadays, the technological challenge of combustion engines is to be able to have the most perfect combustion, with an extremely low amount of harmful gas, in order to be able to obtain ecological labels. For example, active research on the replacement of fossil fuels by biofuels has been carried out with the aim of reducing these gaseous emissions.

To evaluate the performance of a biofuel-powered combustion engine, Ulusoy et al. [93] conducted an experimental study on the use of used cooking oil in a 48 kW direct injection 3-cylinder tractor engine, to determine whether this fuel could be substituted for diesel. The engine ran for 100 hours from 1100 to 2400 rpm with used cooking oil. The tests were carried out in two stages to assess the effects of waste oils on the life cycle of the engine. The results showed that the engine performance values of used cooking oils have similar properties to those of diesel fuel, but in long-term use, a significant reduction in engine torque of up to 14.48% with used oil, depending on engine speed and a consequent increase in smoke. In addition, dark deposits at the end of the injectors were found to disrupt the spraying of the fuel. The elements detected indicate ash from the combustion of waste oils and cooking products. Other studies have focused on the effect of biodiesels derived from used cooking oil, Karanja oil, and Jatropha oil on the spraying process experiments were carried out by Hwang et al. [94]. In order to be as close as possible to the real conditions of a diesel engine, the injection pressure of 80 MPa was achieved by a solenoid injector connected to a common rail. The high-speed shadowgraphic method was used to define macroscopic evaporation characteristics. Atomization characteristics, such as droplet distribution, as well as Sauter mean diameter (SMD) were measured by Phase Dopper Interferometry (DPI). The air-fuel equivalence ratio was defined using mathematical correlations. According to shadowgraphy images, biodiesels have shown greater difficulty in obtaining an air-fuel mixture because the volubility of biodiesel is lower than standard diesel. In addition, the average diameters of the droplets were larger and the injection rate slower for biodiesel, given their higher viscosity and surface tension. The characterization of the spray flame for the different fuels was carried out using the brightness of the flame, in fact, the authors showed that the brightness of the flame is essentially composed of two sources: a yellow-red diffusion flame from incandescent soot particles and the green-blue premixed flame of excited gaseous species, such as CH and C2 radicals. The colors of the resulting images are broken down into RGB value. These values are used to calculate the hue value (the Hue H index), which corresponds only to each RGB combination. An H value between 0 and 80 indicates the presence of scattering flames, and the coloration of the flame is due to the emission of radiation spectra from the heated soot particles. On the other hand, an H value between 180 and 300 indicates the presence of premixed flames, and the staining is due to chemiluminescence emissions of excited radicals. By this method, it was shown that biodiesel would produce less soot but more NOx. In order to compare two biodiesel fuels—one from cooking oil (BDFc) and the other from palm oil (BDFp)—to common diesel, Kuti et al. [95] conducted experiments. The results showed that BDFp has a longer penetration length with a lower spray angle. On the other hand, for the ignition delay, the BDFp was shorter. Flame take-off lengths were shorter, indicating a small percentage of air drained upstream. BDFc flame temperatures were lower than diesel. Broumand et al. [96] presents the spray combustion of FPBO (fast pyrolysis bio-oil), showing that significant research has been conducted to facilitate the use of this liquid biofuel. In order to reduce its viscosity, it is recommended to heat it beforehand to 353 K or to mix it with alcohol to improve vaporization and ignition. Mixed double fluid nozzles are recommended for use with FPBO. The reason for the use of this type of nozzle is that the atomization mechanism is based on the surface tension and not on the viscosity, which is advantageous for biofuel. However, the use of lower quality or aging FPBOs has a detrimental effect on combustion. For burner systems, small-model combustion chambers have shown excellent results for considering its use on an industrial scale.

On the other hand, by focusing on mixtures between different existing fuels, some researchers have carried out experiments on fuel blends in order to reduce gaseous emissions. A study on the effects of a fuel mixed with two fuels with boiling points one high, the other low was carried out by Senda et al. [97]. In an experiment using a fast-compression machine (RCM) and an optical engine, mixed fuels consisting of liquefied CO_2 as an additive and n-tridecane (representing diesel) were used with the aim of simultaneously reducing soot and NOx emissions. In other experiments, different types of mixed fuels composed of gasoline or gasoline and diesel were tested to see the effects on evaporation and ignition processes. The result of an engine experiment showed marked reductions in soot and HC emissions and fuel consumption. The study on the performance and emissions of diesel engines, powered by a mixture of mineral diesel fuel with biodiesel, such as rapeseed and soybeans, conducted by Valentino et al. [98], highlighted a similarity regarding instantaneous fuel flow and liquid penetration for all mixtures studied under different working conditions. On the contrary, the angle of the spray cone shows a dependence on the viscosity of the fuel. A combustion comparison between diesel, RME50 (diesel and rapeseed methyl ester), and SME50 (diesel and soybean methyl ester) was carried out. This comparison shows a higher specific fuel consumption for fuel mixtures, mainly due to their low energy content associated with the difference in physical and chemical properties. However, similar levels of NOx and CO between diesel and blends have been identified. Barroso et al. [99] studied the impact of mixing diesel with bioethanol on the thermal efficiency of an industrial boiler. To do this, a series of experiments were conducted on combustion tests, demonstrating a significant difference between the flames of the two fuels. The quantities of soot, NOx, and SO2 emitted for bioethanol were lower than for diesel, conversely, the quantities of CO are greater for bioethanol without modification of the burner. To achieve the proper functioning of the burner with bioethanol, some improvements must be made, such as changing the nozzles for nozzles of larger capacities, modified the airflow, replacement of the flame detector, and increased revision of the fuel supply system that is more prone to cavitation. The gas recirculation fraction (the percentage of oxygen in the exhaust gas) must be changed in order to avoid a decrease in boiler capacity. However, in order to keep a suitable yield, it is advised by the author not to exceed 50% of bioethanol mixture, so mixing diesel with bioethanol can have a real advantage in terms of reducing pollutants. An experimental study was conducted by Ravi et al. [100] on the effects of adding propanol in a WPO (waste plastic oil) and diesel mixture on the performance and emissions of a single-cylinder DI diesel engine. To do this, three ternary mixtures, D75-WPO20-P05, D70-WPO20-P10, and D65-WCO20-P15 were used. The addition of propanol has reduced fume emissions compared to pure diesel and diesel mixed with WPO. Regarding the release of NOx, D75-WPO20-P05 fuel was the best fuel compared to the others. Fuel consumption for ternary blends was better than for pure diesel fuel and that blended with WPO. The BTE of the D65-WCO20-P15 proved to be even better than the basic diesel operation. The addition of propanol seems favorable regarding emissions and performance, compared with diesel mixed with WPO. Its use would be an advantageous strategy for the use of a recycled component (WPO) and a bio-renewable component (Propanol). Experimental work on the emission and combustion performance characteristics of a 4-cylinder indica diesel engine, powered by biodiesel (yellow oleander oil—YOO) and produced by hydrodynamic cavitation, was conducted by Ashok et al. [101]. The fuels studied were a blend of diesel with YOO biodiesel at 10%, 20%, and 30%. The results showed that the S-values of engine performance (BSFC and EGT) were better for blends compared with diesel and that BTE increased by up to 20%. Regarding gaseous emissions, NOx increased while CO, HC, and fumes decreased. Paturu and Vinoth Kanna's experimental study [102] looked at performance and emissions on a single-cylinder direct-injection diesel engine powered by radish biodiesel. Various proportions of biodiesel in diesel were analyzed (pure diesel, B25, B50, B75, and B100). The results obtained on the performances showed that the gaseous emissions for biodiesels B100 and B75 were more favorable than diesel for CO, NOx, and HC. In order to reduce reliance on diesel in the Indian agricultural sector, a study on the use of used plastic oil (WPO) in a direct injection (DI) diesel engine was developed by Dillikannan et al. [103]. WPO was extracted in the laboratory by catalytic pyrolysis in an extraction unit. The WPO was then mixed with diesel and oxygenated n-hexanol. Three ternary mixtures were analyzed: D50–W40–H10, D50–W30–H20, and D50–W20–H30. The lowest NOx emissions were shown to be for the D50–W20–H30 mixture. On the other hand, increasing the amount of n-hexanol in the mixture decreases the value of BTE. The realization of the ternary mixture allows the use of a recycled and renewable fuel in diesel engines. The experimental tests of Kumar et al. [104] were conducted to study in comparison with diesel, performance, combustion, and emissions on a computerized CI single-cylinder diesel engine, powered with B20 (diesel mixture with 20% Mahua methyl ester, obtained by transesterification with methanol, using an acidic and alkaline catalytic process). Engine performance, combustion, and emissions are examined by measuring BSFC, BTE, cylinder pressure, MGT, HRR, CO, HC, NOx, and smoke opacity with each of the nozzles having hole diameters of 0.2, 0.28, and 0.31 mm. A smaller orifice has been shown to improve air-fuel mixing, atomization, and vaporization, which leads to a shorter burning time. B20 fuel showed better results, such as performance at lower partial loads, combustion, and emissions compared to the benchmark diesel. The combination of the B20 with the smallest orifice showed appreciable results in terms of performance, combustion, and emissions; however, the downside was that NOx was increased.

Soot emitted is also an important topic on reducing pollution. Studies have been conducted to compare the amounts of soot emitted by biofuels and fossil fuels. A comparison between diesel and WCO (waste cooking oil) biodiesel on combustion characteristics in an optically accessible compression-ignition engine was experimentally performed by Hwang et al. [105]. To do this, the engine was modified to set up the optical device, allowing a preliminary study on the spray characterization. The experimental results showed that

WCO biodiesel had a longer injection time than diesel, due to a higher dynamic viscosity. The penetration length was greater for WCO biodiesel compared with diesel. The spray angle being narrower with a higher density, WCO biodiesel has a bad air-fuel mixture, which makes it possible to envisage a less efficient combustion of WCO. Indeed, the results obtained showed that WCO biodiesel had a delayed combustion phase, a lower pressure peak, and a lower heat release rate than diesel, due to the less favorable air-fuel mixture. As for gaseous emissions, there was a decrease in CO, HC, and PM and an increase in NOx for WCO. The diameter of soot particles is smaller for WCO compared with diesel. On the other hand, soot from WCO biodiesel seems more a oxidizing than that of diesel. Following the analysis of the combustion flame, WCO biodiesel showed lower soot incandescence and shorter flame duration. Experiments conducted by Xuan et al. [106] on the impact of cooling an injector jacket on the spraying and combustion developments of a mixture containing 60% gasoline and 40% hydrogenated catalytic biodiesel, were studied using a constant volume combustion chamber (CCVC), operating in GCI mode. Experimental results showed that cooling the injector contributes to a significant increase in the length of penetration of the spray and the amount of soot produced. The review article by Lee et al. [107] shows the spraying, atomization, combustion, and emission characteristics of gasoline direct injection (GDI) engines. The fuel is injected directly into the combustion chamber to form a fuel-laminated air mixture for ultra-poor combustion. To do this, various injection and airflow strategies are implemented, such as multiple injection and spray-guided techniques. Studies have been conducted on soot production. It has been shown that a lot of soot is produced when the engine is cold. Indeed, when the fuel film is on a piston whose surface is cold, the fuel has trouble vaporizing. As a result, this slick of fuel while burning creates soot. A laminated combustion strategy will lead to a reduction in NOx production and better combustion efficiency. The numerical approach made it possible to model the combustion pressure and the flame development process (speed and direction). However, no studies on gaseous emissions have been carried out, according to the author. The addition of alternative alcoholic fuels (bioethanol, biobutanol, and DMF) reduced NOx and CO emissions but increased the size of the droplets due to the higher viscosity and surface tension compared with gasoline.

As we have seen previously, the injector plays a prepondering role in the efficiency of the engine, given the temperatures inside the engines, it is possible that the injector becomes clogged by cooking effect and consequently reduces the efficiency of the engine. That's the reason that the experimental study by Hoang et al. [108] compares the cooking effects of an injector of a Yanmar TF120M engine after 300 hours of operation with diesel and biodiesel (Jatropha oil), preheated to 363 K, or not, on the spray, in terms of penetration length and angle of the spray. He observes that the accumulation of deposits in the injector has a significant influence on the length of penetration and decrease in the angle of the spray. The spray study was carried out using a Sony A9 camera with a speed of 20 frames/second. Similarly, a reduction in thermal efficiency of 0.31% for diesel, 1.70% for PSJO90 (Jatropha oil preheated to 363 K), and 3.82% for SJO30 (Jatropha oil not preheated) was found. The temperature of the preheating system is maintained by means of a temperature probe. The author also notes a sharp increase in carbon monoxide (CO) emissions of 28.18% and hydrocarbons (HC) 40.52% with SJO30 at nearly 300 hours of operation. Despite a significant decrease in NOx, his conclusion does not argue in favor of SJO30. In addition, it warns of unstudied effects regarding corrosion.

Other researchers have managed to obtain a new category of fuel through ultrasonic treatment on biofuels. For example, Mariasiu et al. [109] have studied the effects of the ultrasonic irradiation process of diesel and biodiesel on NOx emissions. Irradiating fuel with ultrasound causes significant variations in physical parameters. Thus, a B25 mixture and diesel fuel were subjected to ultrasonic radiation for a period of 420 s and 350 s, respectively. With this type of treatment, NOx emissions for biodiesel fuel have decreased by 8%–18.2% depending on the engine load compared to untreated biodiesel. However, NOx emission values are higher than diesel fuel. It has been found that the prolonged storage of treated biodiesel leads to fuel degradation, in particular with an increase in oxidizing products in the fuel. These results can be improved by future research on methyl esters (soybeans, palm oil, and sunflowers, etc.).

In addition, these biofuels, given their viscosity compared with standard fuel, have shown lower levels of cavitation for identical configurations [76].

2.2.2. Combustion, Cavitation, and Fuels

In this subgroup, we will see the effects of cavitation on the combustion of standard fuel oil.

Effect of Cavitation on Combustion Efficiency for Different Nozzle Geometry

In order to conduct a study on the effects of internal nozzle flow by modifying the geometry of the nozzle hole inlet on spray combustion, Ganippa et al. [110] used two nozzles whose inlets were modified by hydro-erosive grinding. The first nozzle, with 0% hydro-erosive grinding (i.e., without modification), the second with 20% hydro-erosive grinding, giving a rounded inlet. In order to compensate for the greater frictional losses and the lower discharge coefficient for the unmodified nozzle, the diameter of the hole was increased to obtain the same pulse speeds of the spray. The results show that the different discharge coefficients imply that the flows inside the nozzles have different levels of turbulence and cavitation. However, since the sprays had the same speeds, their behavior was identical in terms of spray dispersion, spray penetration length, ignition time, combustion temperature, flame volume, soot concentration, and take-off distance. The authors showed that for realistic injection and combustion conditions, the internal flow structure of the nozzle does not matter, as long as it does not change the momentum. The effects of nozzle orifice geometry (i.e., conicity and hydro-erosive grinding) on the spraying and combustion processes were examined by Sibendu Som et al [111], using a new model (KH-ACT) under the CONVERGE CFD software, considering turbulence and cavitation inside the injector nozzles. The results show that the conicity of the nozzle hole and rounding the nozzle inlet by hydro-erosive grinding tends to reduce cavitation and disturbances inside the injector. Thus, the primary rupture is less effective resulting in larger droplets, with an increase in the length of penetration and a worse atomization. Therefore, the air-fuel mixture is reduced and ignition occurs further downstream. Flame take-off lengths are higher for hydro-erosive ground nozzles than conical nozzles. The amount of soot produced is highest for the conical nozzle, while the amount of NOx produced is highest for the hydro-erosive ground nozzle, indicating the classic trade-off between them. Further studies were carried out by Som and Aggarwal [112] using the new model (KH-ACT) to see the effects of primary breakup modelling on the spray and combustion characteristics under diesel engine conditions. The results highlight that the inclusion of cavitation and turbulence improves primary breakup, resulting in smaller droplets, decreased liquid penetration, and increased radial dispersion of the spray. According to the authors, the KH-ACT model is in better agreement regarding the length of penetration of the spray and the location of flame take-off for spray combustions. The relationship between the internal flow, cavitation behavior, and spray combustion of a full-size diesel nozzle was analyzed by Hayashi et al. [113] by both experimental measurements and numerical simulation. In order to highlight the cavitation inside the injector, a full-size transparent nozzle was developed. The visualization of the phenomenon was carried out through a fast camera. In this study, the relationship between internal nozzle flow and spray combustion was conducted in a fast-compression machine. Two nozzle hole diameters (R = 0.016 and 0.033 mm) were analyzed, the results show that the inlet radius of the nozzle hole influences the formation of cavitation, the characteristics of spraying, and combustion. Indeed, for the radius of 0.033 mm, the shape of the cavitation changes from the form film type cavitation to string type cavitation caused by the swirling movement in the hole of the nozzle, the angle of the cone is larger, the ignition time shorter, and there is a wider flame. The others show that the type of cavitation is influenced by various factors such as the inlet radius of the nozzle hole, the state of the flow in the nozzle bag, the flow velocity in the nozzle hole, and the instability of the flow in the nozzle hole, due to the separation of the flow at the inlet of the nozzle hole. In order to highlight the influence of cavitation on combustion, two injectors, nominally identical, heavy diesel spray C (C for cavitation) and spray D injectors with a hole diameter of the order of 200 µm was used in different combustion plants of three independent research laboratories, using constant volume precombustion tanks (IFPEN, Sandia) and a tank heated to constant pressure (Caterpilla). Both injectors have minimal differences in terms of mass flow and orifice diameter, one of the injectors was manufactured with a straight hole and a sharp orifice inlet to induce cavitation, while the other injector was subjected to hydro-erosive grinding and features a convergent hole. The results of this work, shown by Maes et al. [114], highlight that the effect of cavitation has an influence on flame lift-off length and ignition delay.

Effect of the Cavitation on the Air/Fluel Mixture

The entire combustion process in an engine was considered by a three-step hybrid numerical simulation (THSA) approach led by W. Yu et al. [115]. Initially, a full cavitation model was used to study the internal nozzle flow, then a Kelvin-Helmholtz/Rayleigh-Taylor (KH-RT) model predicted fuel spraying. The third step was conducted by the KIVA4 code in order to simulate the combustion of the engine in three dimensions, using the results of the two previous studies. A comparison between different combustions was conducted between conventional direct injection combustion (CDIC) and partially premixed combustion (PPC) powered by diesel, petrol, and diesel/petrol mixture (GD). The results showed that gasoline has a higher cavitation, injection speed, and turbulent energy compared with diesel. Increasing the amount of diesel decreases the phenomenon of cavitation. Regarding spray characteristics, it has been shown that increasing the ratio of gasoline in fuels improves the air-fuel mixture. Compared with CDIC, PPC has much lower total NOx emissions due to a lower combustion temperature. Extremely low amounts of NOx and soot were obtained in gasoline-powered, partially premixed combustion (PPC). According to the authors, despite the relatively poor lubricating properties of gasoline, it could advantageously be used in a compression-ignition engine powered by high pressure by developing the fuel supply and injection system. The characteristics of internal nozzle flow, spraying, combustion, and emission of different traditional diesel fuels, gasoline, and two types of WDF (gasoline-diesel mixture and kerosene) for two different types of injectors (piezoelectric and solenoid) were realized by W. Yu et al. [116]. The piezoelectric injector has a faster needle opening and injection response than the conventional solenoid injector for faster and more accurate injection control. The effects of turbulent kinetic energy and injection rate were studied by a KH-RT model considering cavitation and turbulence. The resolution of the chemical reaction was achieved by coupling the KIVA4 and CHEMKIN code. Two combustion strategies, namely partially premixed combustion (PPC) and highly premixed combustion (HPC), powered by traditional diesel, gasoline, and two types of WDF were developed by the group of authors in a previous study. These results highlight that gasoline has the highest cavitation compared to the other three fuels, and has the highest turbulent kinetic energy and injection speed. In addition, the spray penetration of gasoline is the shortest and the spray rate the lowest, while the spray angle is the largest, which allows for better performance in the air-fuel mixture. However, the authors point out that, due to its poor lubricating properties, gasoline is almost impossible to use in high-pressure common rail systems and that intensive cavitation caused by the low viscosity of gasoline will also cause great damage to fuel injectors. From the analysis of combustion and emissions, diesel has higher NO emissions while gasoline produces more CO emissions.

2.2.3. Combustion, Cavitation, and Biofuels

In the Argonne National Laboratory (USA), a source of biofuel called phytol (C20H40O) has been developed, through photosynthetic bacteria, which is a heavy alcohol with properties (cetane index, heat of combustion, heat of vaporization, density, and surface tension, etc.) similar to those of diesel, suggesting that it could be suitable in a mixture with diesel. However, since the viscosity and vapor pressure of phytol are different, a numerical study under FLUENT on the effects of a mixture of P5, P10, and P20 phytol (5%, 10%, and 20% phytol by volume) with diesel inside an injector was conducted by Ramírez et al. [117] in order to compare the injection and cavitation characteristics in the different mixtures. To do this, CFD calculations on the surface, discharge coefficients, and mass flow rates of the diesel and phytol mixtures were compared under the corresponding engine operating conditions. The numerical results obtained show that the phytol, because of its higher viscosity, has a lower flow rate in the injector; therefore, has a tendency to cavitate less. An analysis of performance and emissions in a single-cylinder compression-ignition engine for different phytol-diesel mixtures showed that lower heat of combustion for phytol blend, compared with diesel, results in lower power for identical fuel flows. Therefore, higher consumption can be expected with a phytol-diesel mixture than with pure diesel. However, since phytol has a higher oxygen content, it helps reduce CO emissions. This experimental study makes it possible to say that phytol as a mixing agent makes it possible to mitigate the effects of cavitation inside an injector without degradation of the engine's performance in terms of gaseous release.

2.2.4. Summary

The different combustion studies have been gathered in Table 2 below:

Table 2. List of equipment used and the results obtained in the combustion studies among relevant papers.

Combustion Studies			
Experimental Studies			
Subject of Study	**Principle Results**	**Equipment Used**	**Bibliographic Reference**
Using cooking oil as a diesel substitute.	The engine performance values of used cooking oils have similar properties with diesel fuel.	Wager 6500 model smoke (opacity) Meter, Scanning Electron Microscopy (SEM) Energy Dispersive X-Ray analysis.	[93]
Definition of macroscopic evaporation characteristics.	the brightness of the flame is essentially composed of two sources: a yellowish-red diffusion flame from incandescent soot particles and the greenish-blue premixed flame of excited gaseous species such as ch and C2 radicals.	High-speed shadowgraphic method.	[94]
The effect of injection pressures on the ignition and combustion characteristics of two biodiesel fuels, one from palm oil (BDFp), and the other from cooking oil (BDFc) compared to common diesel.	BDFp has a longer penetration length with a lower spray angle, the ignition delay the BDFp was shorter.	A high-pressure gene- rator (High Pressure Equipment Co. model 37-5.75-60) Pressure transducer A xenon lamp two reflecting mirrors A high-speed video camera.	[95]
The spray combustion of FPBO fast pyrolysis bio-oil.	It is recommended to heat it beforehand to 353 K or to mix it with alcohol to improve vaporization and ignition Small-model combustion chambers have shown excellent results for considering its use on an industrial scale.		[96]

Table 2. *Cont.*

Combustion Studies			
Experimental Studies			
Subject of Study	**Principle Results**	**Equipment Used**	**Bibliographic Reference**
CO_2 liquefied as an additive and n-tridecane representing diesel were used with the aim of simultaneously reducing soot and NOx emissions.	Reductions in soot and HC emissions and fuel consumption.	An optical engine A high-speed direct camera Argon ion laser A shadow photography method.	[97]
Performance and emissions of diesel engines powered by a mixture of mineral diesel fuel with biodiesel.	A higher specific fuel consumption for fuel mixtures mainly due to their low energy content associated with the difference in physical and chemical properties.	Pulse/Delay Generator system A Stanford DG535 Delay Generator A digital image processing software (IMAGE PRO-PLUS) A CCD camera, 1376 × 1040 pixels, 12-bit resolution A macro lens A 25 mm lens	[98]
The impact of mixing diesel with bioethanol on the thermal efficiency of an industrial boiler.	Mixing diesel with bioethanol can have a real advantage in terms of reducing pollutants without exceeding 50% bioethanol.	A vertical 100 kW experimental boiler An oil burner with different Danfoss nozzles with a 60° solid cone spray A chimney	[99]
The effects of adding propanol in a WPO (waste plastic oil) and diesel mixture on the performance and emissions of a single-cylinder DI diesel engine.	The addition of propanol has reduced fume emissions compared to pure diesel and diesel mixed with WPO.		[100]
The emission and combustion performance characteristics of a 4-cylinder indica diesel engine powered by biodiesel (yellow oleander oil YOO) produced by hydrodynamic cavitation.	The s-values of engine performance: BSFC, EGT, were better for blends compared to diesel and that BTE increased by up to 20%.	Diesel engine AVL DIX emission diagnostic system.	[101]
Performance and emissions on a single-cylinder direct-injection diesel engine powered by radish biodiesel.	The gaseous emissions for biodiesels B100, B75 were more favorable than diesel for CO, NOx, and HC.	4 stroke, kirloskar, TV 1 direct injection diesel engine, AVL 444 digital di-gas analyzer.	[102]
The use of used plastic oil (WPO) in a direct injection (DI) diesel engine.	The realization of the ternary mixture (D50-W40-H10, D50-W30-H20 and D50-W20-H30), allows to use a recycled and renewable fuel in diesel engines.	DI diesel engine Common rail direct injection.	[103]
Performance, combustion and emissions on a computerized CI single-cylinder diesel engine powered with B20 (diesel mixture with 20% Mahua methyl ester).	The combination of the B20 with the smallest orifice showed appreciable results in terms of performance, combustion and emissions. But, the only downside was that NOx was increased.	A single cylinder diesel engine An AVL emission analyzer An AVL smoke meter.	[104]

Table 2. *Cont.*

Combustion Studies			
Experimental Studies			
Subject of Study	**Principle Results**	**Equipment Used**	**Bibliographic Reference**
A comparison between diesel and WCO (waste cooking oil) biodiesel on combustion characteristics.	WCO biodiesel had a longer injection time than diesel due to a higher dynamic viscosity. A decrease in CO, HC and PM and an increase in NOx for WCO The analysis of the combustion flame, WCO biodiesel showed lower soot incandescence and shorter flame duration.	A single-cylinder direct-injection diesel engine A high-pressure common-rail injection system A piezoelectric pressure transducer (6052C; Kistler) An exhaust gas analyzer (MEXA 1500D; Horiba) A smoke meter (415S; AVL)	[105]
The impact of cooling an injector jacket on the spraying and combustion developments of a mixture containing 60% gasoline and 40% hydrogenated catalytic biodiesel.	Cooling the injector contributes to a significant increase in the length of penetration of the spray and the amount of soot produced.	A pre-heated constant volume combustion chamber (CVCC) A common rail injector A single-hole cylindrical nozzle diameter of 120 µm A high-speed schlieren imaging	[106]
The spraying, atomization and combustion, emission characteristics of gasoline direct injection (GDI) engines.	A lot of soot is produced when the engine is cold.		[107]
The coking effects of an injector of a Yanmar TF120M engine with diesel and biodiesel (Jatropha oil).	The accumulation of deposits in the injector has a significant influence on the length of penetration and decrease in the angle of the spray.	A diesel engine Yanmar TF120M Scanning Electron Microscopy (SEM) A high- speed camera Sony A9.	[108]
The effects of the ultrasonic irradiation process of diesel and biodiesel on NOx emis-sions.	NOx emissions for biodiesel fuel have decreased by 8 to 18.2% depending on the engine load compared to untreated biodiesel.	Testo 330 XL exhaust gas analyzer A Weinlich M 8000 dynamometer in accordance with the methodology of the research in the field (Szybist et al. 2007; Kegl et al. 2008).	[109]
A study on the effects of internal nozzle flow by modifying the geometry of the nozzle hole inlet on spray combustion.	The different discharge coefficients imply that the flows inside the nozzles have different levels of turbulence and cavitation.	A common rail injection system A CCD camera.	[110]
The relationship between the internal flow, cavitation behaviour and spray combustion of a full-size diesel nozzle.	The inlet radius of the nozzle hole influences the formation of cavitation, the characteristics of spraying and combustion.	A high-speed camera (Photron FASTCAM SA1.1) A strobe light (Sugawara ESD-VF2M-U2) a high-speed camera (Shimadzu HPV-2A) for a micro-particle image velocimetry (PIV) method.	[113]
Two Spray C (cavitation) and Spray D injectors with a hole diameter of the order of 200 µm in different combustion plants of three independent research laboratories.	Cavitation has an influence on Flame lift-off length and ignition delay.		[114]

Table 2. *Cont.*

Combustion Studies			
Numerical Studies			
Subject of Study	**Principle Results**	**Software/Model Used**	**Bibliographic Reference**
The effects of nozzle orifice geometry (i.e. conicity and hydrogriding) on the spraying and combustion processes.	The conicity of the nozzle hole and rounding the nozzle inlet by hydrogriding tends to reduce cavitation and disturbances inside the injector.	CONVERGE/(KH-ACT)	[111]
the effects of primary breakup modelling on the spray and combustion characteristics under diesel engine conditions.	The inclusion of cavitation and turbulence improves primary breakup, resulting in smaller droplets, decreased liquid penetration, and increased radial dispersion of the spray.	KH-ACT	[112]
The entire combustion process in an engine.	Gasoline has a higher cavitation, injection speed and turbulent energy compared to diesel, increasing the amount of diesel decreases the phenomenon of cavitation.	KIVA4/(KH-RT)	[115]
The characteristics of internal nozzle flow, spraying, combustion and emission of different traditional diesel fuels, gasoline and two types of WDF.	The spray penetration of gasoline is the shortest and the spray rate the lowest, while the spray angle is the largest, which allows for better performance in the air-fuel mixture.	KIVA4 and CHEMKIN/(KH-RT)	[116]
Petrodiesel replacement numerical study by a biologically-derived heavy alcohol called phytol ($C_{20}H_{40}O$).	The phytol has a lower flow rate in the injector; therefore, it has a tendency to cavitate less.	FLUENT	[117]

3. Conclusions

In order to justify the need to carry out studies to improve the performance of internal combustion engines, this report highlights the different achievements found in the literature over the last fifty years, by highlighting their limitations.

The bibliographic research was based on sources from the five publishers—Elsevier, Sage, Taylor and Francis, Springer, and Wiley—who represent those who are the most in demand. The objective was to highlight the role of the cavitation phenomenon inside an injector on the performance of a combustion engine. In the methodology used, it was a question of finding the most relevant articles in the period from 1970 to 2021 according to specific keywords. This identified 66 articles.

In view of the studies obtained, it has been shown that most of the work deals with cavitation from the point of view of fluid mechanics (63%) without associating combustion (37%). Indeed, it is shown that the phenomenon of cavitation has harmful effects on the flow of fuel in the injector, on the formation of spray, and on the atomization of the fuel. It has also been shown that biofuels, as a substitute for standard fuels, have advantages concerning this cavitation phenomenon. Indeed, it has been shown that the latter tend to cavitate less due, to their higher viscosity; therefore, these can be a solution to the problem posed, especially since this type of fuel is promising in terms of carbon footprint.

Other studies have attempted to link the effects of cavitation on the combustion process by focusing on the effect of fuel type on combustion efficiency and propose solutions such as hybrid fuel blending, adding additives to neutralize the effects of temperature, and ultrasonic treatment of fuel to reduce NOx, CO, and unburned gases. These studies were carried out without direct interaction between the cavitation phenomenon and the combustion process and represent a minority number, compared with all studies dealing with the effects of cavitation in heat engines.

This observation makes it possible to justify the lack of studies in this theme and the importance of bringing new knowledge on the role of cavitation in an injector on the efficiency of combustion. For this, it could be possible to characterize the efficiency of combustion according to the level of cavitation.

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Nomenclature

BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CDIC	Direct injection combustion
CFD	Computational Fluid Dynamics
CO	Oxide carbon
CO_2	Dioxide carbon
COVID	COrona Virus Disease
D_{eff}	Effective diameter
DME	Dimethyl ether
DPM	Discrete phase model
HPC	Highly premixed combustion
HRR	Heat release rate
KH-RT	Kelvin-Helmholtz and Rayleigh-Taylor
KH-ACT	Kelvin-Helmholtz Aerodynamics Cavitation Turbulence
NOx	Nitrogen oxides
PPC	Partially premixed combustion
R	Radius of inlet curvature
RANS	Reynolds-averaged Navier–Stokes
RNG	Re-Normalization Group
RME	Rapeseed Oil Methyl Ester
RPM	Round per minute
SMD	Sauter mean diameter
SME	Soy Methyl Esther
SO2	Sulphur dioxide
θ	Angle of inclination of the injector hole
WPO	Waste plastic oil

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