Review

Diesel Spray: Development of Spray in Diesel Engine

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Abstract: Research and development in the internal combustion engine (ICE) has been growing progressively. Issues such as air pollution, fuel cost, and market competitiveness have driven the automotive industry to develop and manufacture automobiles that meet new regulation and customers’ needs. The diesel engine has some advantages over the gasoline or spark ignition engine, including higher engine efficiency, greater power output, as well as reliability. Since the early stage of the diesel engine’s development phase, the quest to obtain better atomization, proper fuel supply, and accurate timing control, have triggered numerous innovations. In the last two decades, owing to the development of optical technology, the visualization of spray atomization has been made possible using visual diagnostics techniques. This advancement has greatly improved research in spray evolution. Yet, a more comprehensive understanding related to these aspects has not yet been agreed upon. Diesel spray, in particular, is considered a complicated phenomenon to observe because of its high-speed, high pressure, as well as its high temperature working condition. Nevertheless, several mechanisms have been successfully explained using fundamental studies, providing several suggestions in the area, such as liquid atomization and two-phase spray flow. There are still many aspects that have not yet been agreed upon. This paper comprehensively reviews the current status of theoretical diesel spray and modelling, including some important numerical and experimental aspects.

Keywords: diesel spray; compression ignition engine; combustion; emission; spray process; atomization

1. Introduction

Energy transition and environmental issues on the restrictions of emissions have been paid much more attention in most countries across the world [1–4]. CO₂ emissions have been addressed as the dominant pollutant that contribute to climate change [5]. Hence, engine manufacturers should improve the performance of internal combustion engines by developing efficient engines with lower emissions [6,7]. Regardless of the stringent...
emissions regulation imposed by several countries, diesel fuel remains the major source of energy for heavy duty engines. The basic explanation for this is because diesel engines have a relatively higher thermal efficiency spark ignition (SI) than gasoline engines, which is especially important for heavy duty purposes.

In the diesel engine, mixture formation between air and fuel plays a vital role in the process of combustion, thus affecting emission qualities [8]. To enhance the combustion and lower the emission, it is essential to have comprehensive knowledge of the mixture formation. Prior to acquiring this knowledge, a thorough understanding of spray atomization must be first understood. Studies on diesel spray remains a crucial part of research in the internal combustion engine. The quality of the ignition is substantially influenced by local and temporal processes, as well as the completeness of combustion. The pollutants in the cylinder interact and break down, generating the components in the exhaust gas. This is specifically true for carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions. The process of fuel injection controls how well the engine performs in terms of combustion and emissions. Note that the injection system from the high-pressure common-rail diesel engine is currently viewed as one of the most viable ways to satisfy the increasingly strict emission standards for diesel engines. This illustrates the importance of diesel spray in the development of the diesel engine.

Spray is a process in which liquid is forced out of a particular container so that it becomes a mass of small-liquid drops. In the direct-injection internal combustion engine, fuel, which is still in its liquid phase, is injected by the injector into a gaseous condition in the cylinder. In a compression ignition engine, such a phenomenon is commonly known as diesel spray. The injected liquid fuel that is now inside the combustion chamber then begins to interact with the in-cylinder air instantaneously, leading to the dispersion of the liquid phase. As this liquid phase vaporizes, a flammable mixture is then generated to produce great power inside the chamber. The whole process is known as the spray evolution process, consisting of liquid-fuel breakup, atomization, and evaporation. A detailed knowledge in spray evolution is important as the mixture preparation, which later determines the quality of the combustion and emission formation, depends greatly on this process.

2. Diesel Combustion Process

Unlike gasoline engines, that use a spark plug to initiate the combustion, diesel engines work based on the principle of autoignition, as shown in Figure 1. Following fuel in the liquid form being injected into the cylinder, this fuel then mixes with the in-cylinder air at a high temperature and pressure, achieved by the high volumetric compression of the air. The typical compression ratios in diesel engines ranges from 15 to 22. Figure 1 shows one complete working cycle of a typical diesel engine via four strokes. The crankshaft must complete two revolutions (720°) per cycle of operation.

![Figure 1. Diesel engine four strokes process.](image_url)
Diesel engines can operate in high compression ratios, while their counterparts, gasoline engines, operate only in low to medium ratios to avoid engine knock. Due to these relatively higher compression ratios, diesel engines are more fuel efficient, making them a natural choice for heavy-duty purposes. In modern diesel engines that use common-rail technology, a high-pressure injector is used to insert high-velocity liquid fuel into the hot compressed air. The fuel pressure is raised to the desired level using a pump, which moves the liquid fuel from a tank to multiple injectors. As the engine load is subject to variation in the engine speed while the vehicles are operated, the load thus needs to be adjusted by regulating the fuel amount to be injected. Each injector then spreads the liquid fuel in small droplets. As the liquid fuel penetrates through the combustion chamber, this fuel then breaks down to smaller droplets, evaporates, as well as mixes with the in-cylinder gas. This is when the autoignition starts to happen, before the main combustion finally takes place in the chamber.

As mentioned above, the increase in injection pressure is considered as a promising approach to enhance combustion behaviors [9–13]. High-pressure injected diesel fuel could improve the engine performance and reduce particulate matter [14–18]. In addition to that, the increased injection pressure tends to accelerate the vaporization of droplets and the preparation of the combustible mixture [19–23]. As expected, this would reduce the ignition delay. Note that the process of combustion begins with the autoignition of the fuel and air mixture. The characteristics of autoignition are affected by the chemical as well as the physical properties of the fuel. As it is more difficult to observe those two properties macroscopically, the ignition delay is hence used as a key measure of the autoignition. However, in typical combustion, autoignition occurs in two stages that are categorized by these properties: physical and chemical.

The first stage of autoignition is determined by the physical properties of the liquid spray. The delay between the injection start, and the combustible mixture formation, is known as the physical delay. Such a delay is controlled by its physical properties (density, surface tension, and specific heat). Furthermore, the structures of the spray flow in the combustion chamber also have substantial effects on the physical delay. Take small- and large-scale hydrodynamic structures, for example, these types of structures tend to drive the entrainment of the air into the fuel jet in a turbulent environment. The liquid jet starts to break down and the spray begins to evaporate, caused by aerodynamic interactions and ambient air interactions, respectively.

The second stage of the autoignition is determined by the fuel chemical properties. The delay between the mixture formation and its ignition is known as the chemical delay. Such a delay is controlled by its chemical properties i.e., the molecular structure, adiabatic flame temperature, C/H/O ratio, and the sooting tendency. Therefore, the total ignition delay is the combination between physical and chemical delays. As far as the chemical kinetics are concerned, the process of chemical kinetics in the diesel engine is a complicated mechanism as it involves many simultaneous reactions. Although the rate of heat release that causes a rapid rise in pressure and temperature leading to autoignition is easy to observe, the chemical mechanisms involved microscopically are complex. These mechanisms include initiation, propagation, and the termination processes of the chain.

Firstly, the chain begins its initiation reaction by building a group of radical species from the reactants. The radicals then react with each other, as well as with other stable species, to form more radicals, resulting in the propagation of the chain reactions. Of these chain propagation reactions, chain branching reactions are of great importance as they determine the self-propagating flame that leads to combustion. These chain branching reactions can have an explosive effect on a combustion system by producing radicals that control the overall reaction rate. Lastly, the stable products are formed afterwards, which indicate the termination process of the reactions. The overall chain reactions thus consist of a complicated process of simultaneous chemical reactions, which are also subject to the mixture physical state.
In diesel or compression ignition engines, the combustion occurs in two phases following the autoignition of the mixture inside the cylinder [24,25]. They are premixed-controlled and mixing-controlled combustion. The premixed-controlled combustion occurs in a fuel-rich region and produces partially oxidized fuel fragments that diffuse outwardly, leading to the mixing-controlled diffusion flame that surround the premixed core region. The first stage (heat release along with temperature rise) takes place in a fuel-rich premixed region. The overall HRR is primarily controlled by the fuel mixing rate and oxidizer. Typical direct injection in the diesel engine is schematically illustrated in Figure 2.

![Combustion model of direct injection diesel](image)

**Figure 2.** Combustion model of direct injection diesel, reproduced from [26].

As the liquid fuel jet penetrates the cylinder, it entrains the surrounding gas. The liquid spray is then heated up and evaporation occurs at the spray edge. The more air enters the spray, the higher the evaporation rate of the spray. The combustion then starts, while the mixture reaches a particular equivalence ratio. In the region of the diffusion flame, the orange color represents the highest temperature, which is believed to be the primary location of NO production [27]. This region also oxidizes a great amount of soot that is generated in the fuel-rich region. This diffusion layer flame can be identified using the OH* chemiluminescence technique for laser-based optical combustion diagnostics [28–30].

There are a number of strategies to improve the diesel combustion process. The introduction of pilot fuel is believed to be able to reduce the combustion noise as it shortens the premixing process [31]. The pilot fuel could reduce the pressure-rise rate by allowing only a small amount of liquid fuel to be introduced for the premixed-combustion mixture, leading to lower NOx emission [32,33]. Just after this pilot fuel has been introduced, the appropriate amount of fuel should be injected immediately to avoid the formation of soot. A post injection is then needed, avoiding the formation of soot [34–36]. In addition to that strategy, the multiple injections approach was also proposed to obtain the desired MFR shape. The multiple injections strategy allows the injector to have a shorter injection duration for each split injection, allowing fuel to blend sufficiently with the air so that an improved mixture can be achieved. Such a strategy also increases the IMEP, which was found to reduce the emissions. The multiple injections strategy can also prevent the impingement of the spray onto the wall chamber, resulting in low hydrocarbon (HC) pollutant. The multiple injections concept in the diesel engine has nowadays been used widely, due to its several advantages. Its superiority compared to the single injection mode is achieved through three different stages: (i) pre-injection allows a small quantity of fuel to be injected, leading to a reduction in combustion noise and NOx emissions; (ii) the main injection provides optimized torque release without producing excessive particles from the combustion in the chamber; and (iii) post-injection gives a better soot oxidation rate by letting other small fuel mass to be injected after the main injection period.
3. Spray Atomization

Diesel spray is a crucial element of compression ignition engine operation, particularly during the injection of fuel. Many studies have been conducted focusing on spray atomization [37–41]. Several factors are known to be responsible for spray atomization. They were: (i) the aerodynamic forces; (ii) internal turbulent; (iii) boundary mutation at the exit of the nozzle; and (iv) internal flow cavitation. With the help of the optically-accessible-measurement technique, none of the factors mentioned above were found to influence the spray atomization independently. In fact, it is believed that a combination of some dominant factors is actually responsible collectively.

An aerodynamic force is defined as the force that a body experiences from the air (or other gas), where it is submerged. This force results from the relative velocity of the body and the gas. Aerodynamic force is produced by two factors: the normal force, which results from pressure acting on the body’s surface; and the shear force, which is a result of the viscosity of the gas, and is also referred to as skin friction. Shear force moves parallel to the surface, while pressure moves perpendicular to the surface. Both factors are regional. The pressure, as well as shear forces summed over the entire exposed region of the body, constitute the body’s net aerodynamic force.

When diesel spray leaves the orifice of the nozzle, aerodynamic-triggered break-up gradually contributes to the production of the mixture. It is important to remember that coherent liquid does not instantly break up into small droplets, and that a zone with ligaments and concentrated big droplets is present close to the nozzle exit. The internal turbulence, along with cavitation, have a more significant impact on the disintegration of the fuel during this process than compared to aerodynamic forces, hence it should be incorporated in the primary break-up process. Aerodynamic force causes the secondary break-up, which is the creation of smaller droplets, when the spray increases the break-up length. The balance between surface tension and aerodynamics is crucial to this process. As previously stated, the aerodynamic force, that primarily serves as ambient gas entrainment, dominates the break-up process, particularly for secondary break up. As a result, researchers pay close attention to the air entrainment.

Cavitation occurs as a result of sudden alterations in the shape of the internal nozzle and pockets from low-static pressure. Vapor phase disruptions, internal flow circumstances, wall roughness, as well as any surface-level microscale manufacturing flaws, all contribute to turbulence. Cavitation would raise the liquid velocity at the exit of the nozzle, which will affect how the spray forms and how it is made. Enhanced spray development is generally believed to result in a more complete combustion, less fuel consumption, and fewer emissions. However, because of its impact on the outgoing jet, cavitation can reduce flow effectiveness (discharge coefficient). Additionally, expanding cavitation bubbles on the inside of the orifice can lead to material degradation, reducing the injector’s lifespan and effectiveness.

Numerous studies have investigated internal flow cavitation [42–44]. It is believed that the disintegrations of the needle lift in the cavitation bubbles speed up the spray breakup. The cavitation of the nozzle hole could increase the spray angle and decrease the penetration of the spray tip. Interestingly, the nozzle hole inlet geometry could also influence the intensity of cavitation. It is important to remember that liquid fuel disintegrates into ligaments and large droplets at the stage of internal flow, before the spray comes out of the nozzle. This process, known as primary break-up, is caused by the internal flow cavitation and turbulence instability [45–47]. Figure 3 is break-up regimes of droplet.

The break-up mechanisms of these two factors usually occur simultaneously. Turbulent eddies formed the droplets in small aerodynamic condition, such as in nozzle-hole internal flow. It took place while the surface energy was smaller, compared to the radial fluctuation kinetic energy of the eddy flow velocity, which greatly affects the turbulent effect. It is also known that when the flow velocity is high, the cavitation starts to form. The cavitation takes place since the liquid phase vaporizes instantly when the pressure of local static is lower than vapor pressure (the static pressure decreases when the flow velocity increases). Thus,
a two-phase flow emerges in the interior of the nozzle hole once the cavitation is formed. This cavitation phenomenon is characterized by the vaporization of low temperature volatile elements.

**Figure 3.** Mechanism of droplet break-up, reproduced from [48].

The spray penetration was time-dependence, being proportional to the evolution timing. Droplets were formed in the spray during the second phase. In this phase, despite the drop in its penetrating velocity, the spray still continued to penetrate further inside the chamber because of energy from the late injection of high momentum fuel. As discussed previously, the break-up (secondary) was primarily initiated by the forces of aerodynamic. It was widely known that aerodynamic forces were greatly dependent on air entrainment. It was also known that aerodynamic forces were greatly dependent on the combustion, as well as the emission process in the cylinder. In fact, it is important to investigate the air entrainment in diesel spray. The surrounding air mostly entrained into the spray via the upstream.

The spray and wall interaction in the diesel engine has gained a great deal of attention recently. The impingement of spray on the wall primarily happens in a small-bore engine (high speed) and is believed to have a major effect on mixture formation, combustion, as well as emission. At this impinging condition, the spray atomization undergoes different processes compared to those of free spray. Two main primary differences are the improvement of the secondary break-up process due to smaller droplets formation at a large Weber number, and the reduction of unburned hydrocarbon and soot emission, due to liquid film formation at a low Weber number [49–53]. The interaction of wall and spray, mainly taking place in the small-bore high-speed diesel engine, not only has significant effects on mixture formation, but also on the combustion, as well as the emission process in the cylinder. In order to clarify the effect of spray impingement, an analysis of the two-dimensional piston cavity, along with flat wall impinging spray flame, is usually performed in a high pressure and temperature constant-volume engine-like combustion chamber [54–58]. As a basis for evaluation, free spray flame is normally also conducted.

To recognize the impact of diesel spray on the engine, the most influential factors within the spray structure must be first understood. Those determinant factors are illustrated macroscopically in Figure 4. Near the nozzle tip is the region in which the fuel in the liquid form is dense and uniform [59–61]. Below this dense area, fuel then begins to disperse, and waves begin to emerge at the edge of the spray. Lines of liquid also start
to exist and the pitches in the middle of these stripes increase additionally downstream. Afterwards, spray and air inside the chamber interact immediately. As a result of the penetrating spray, the air surrounding it then compresses the spray clusters to be compact. Simultaneously, the spray is transferring its momentum to the air leading to further dispersion of the spray. This is called the air entrainment effect [62–66].

![Illustration of diesel spray macroscopically](image)

**Figure 4.** Illustration of diesel spray macroscopically, reproduced from [67].

- Spray core: high dense spray region, the closer to the injector is, the denser it is.
- Spray angle: a bigger spray angle gives wider spatial distribution.
- Break-up length: a part of the liquid in the spray that does not disintegrate.
- Spray tip penetration: the macroscopic development of diesel spray.

Large angle spray is favored and is formed by short spray core and break-up length. Long break-up length, on the other hand, is avoided as it causes a narrow unsteady spray [68–71]. Moreover, due to its longer spray characteristics, the fuel might stick to the inner side of the chamber when it is impinged to the in-cylinder wall, leading to high hydrocarbon and particulate matter emissions. As the formation of the mixture continues, the spray volume is increasing parallel to the increase of an entrained air. As a consequence, the spray penetrates further due to the influences from such air entrainment effect and spray velocity. This phenomenon can be observed and analyzed by optical diagnostic techniques, which will be explained later.

### 4. Factors Affecting Spray Evolution

Injector technology plays a crucial role in determining the quality of atomization, particularly the injector type and its geometry [40,72–75]. For diesel engines, two types of injectors are normally used, namely, the piezo and the solenoid injector. The piezo injector has a relatively quicker response and opening, which results in shorter injection delay, thus allowing the injected fuel to blend with the air quicker. As a result, mixture formation can be improved leading to better engine performance and reduced emission pollutants. Furthermore, the quicker response of the piezo injector tends to ease the fuel mass delivery control and to enhance the profile of MFR.

In terms of injector geometry, nozzle configuration is classified into three main categories: the mini and micro sac, as well as the valve covered orifice (VCO) [40,76–79]. The difference in the injector nozzle geometry greatly affects the cavitation and evolution of the spray. The illustration of those configurations is displayed in the following Figure 5.
VCO is also subject to working conditions and can consequently lead to the oscillation of position just below the needle seat, thus minimizing the loss from throttling. Additionally, to example, VCO takes [40,76,77,83,84].

Furthermore, the injection pressure also causes back pressures of the spray that interact with the air [105–109].

The sac refers to the part of an injector that looks like a small bag and contains liquid fuel [51,80–82]. As a result, nozzles with this geometry can lead to unburned hydrocarbon left in the sac. Despite its drawback, the nozzles with sac configuration tend to have superior spray quality compared to VCO nozzle geometry, which have no sac configuration [40,76,77,83,84]. This is because the holes in the sac configuration are positioned just below the needle seat, thus minimizing the loss from throttling. Additionally, VCO is also subject to working conditions and can consequently lead to the oscillation of the needle. In more than one injector, for example, the pressure tends not to be uniformly distributed around the needle in the course of the opening. As a result, the holes-cycles mass flow varies. The VCO injector, however, is able to provide a specific fuel amount and govern the time of injection more accurately, since no sac volume has to be filled. Clearly, the sac and VCO configuration has different effects in the spray evolution. In terms of the cavitation, for example, vortex cavitation occurs in the sac configuration, while conventional cavitation takes place in VOC nozzle geometry.

In order to examine the impact of both the injector hole size and the pressure of the injection, Lacoste [85] evaluated the droplet velocity and SMD with the hole diameters set to be 0.1 and 0.2 mm, whereas the injection pressures were varied at two opposite conditions: low pressure (60 MPa), and high pressure (160 MPa). The results revealed that the smaller hole managed to reduce the droplet size and at the same time increase its velocity. The cavitation was also improved, thus leading to the enhanced turbulence effect. Therefore, the better atomization quality of the spray can be achieved by simultaneously using higher injection pressure and reduced hole size. The nozzle hole convergence can significantly affect the spray behavior. Note that the hole geometry could affect the spray behavior. Different nozzle structure could lead to different spray behavior [86–90].

The injection pressure is critical in determining the spray evolution [91–95]. A high-inertia effect from high-injection pressure results in high-velocity spray, thus creating better dispersion by forming relatively smaller droplets [53,96–99]. Higher-injection pressure could deliver the same amount of fuel relatively faster [100–104]. Moreover, the rise in injection pressure also causes back pressures of the spray that interact with the air [105–109]. This will lead to reduced breakup time and length. As a result, faster propagation and better atomization can be achieved, despite higher fuel concentration at the beginning of the injection. Note that the increased injection pressure can allow the entrainment of the air from the surrounding gas to completely develop, enabling droplets to interact with ambient gas [54,107,110–112].

Ambient pressure, along with density, have a great influence on macroscopic attributes of the spray [113–117]. Additionally, the rise in ambient density could reduce the length of spray penetration as well as widen the angle of the spray cone [39,65,114,118,119]. The ambient temperature primarily affects the spray behavior in terms of its evaporation rate, both microscopically and macroscopically. Hot ambient air inside the cylinder could improve the evaporation of the spray outer periphery and consequently decreasing the

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**Figure 5.** Three types of injector nozzle in diesel engines: (a) mini-sac volume; (b) micro-sac volume; and (c) valve covered orifice (VCO).
spray cone angle [39,107,120–122]. Increasing ambient temperature could lead to enhanced evaporation rate and thus considerably shorten the spray penetration length [123–127].

During the injection start, where the fuel in the liquid form is relatively dense, the spray penetration rate is not enhanced by higher ambient temperature; instead, it is influenced by the gas density [114,128–131]. As the spray penetrates downstream, the liquid fuel becomes less dense, thus increasing both heat as well as momentum transfers by the side of the front periphery. Although lower gas density could raise the penetration rate, the droplet clusters at the front periphery are separated more quickly, resulting in relatively far shorter spray length penetration. The raise in evaporation rate under hot ambient temperature could reduce the SMD. Note that higher ambient air temperature could reduce droplets size at the periphery. The center of the droplet, however, is not influenced by raised temperature owing to the high density.

Higher fuel temperature tends to produce vapor bubble and this phenomenon is known as cavitation [125,132,133]. In the liquid fuel injection behavior, cavitation combined with turbulence can improve spray performance in terms of the liquid atomization, droplets breakup and air entrainment. Under a particular case, such as an extreme condition, cavitation could result in a hydraulic flip that can worsen atomization.

One fuel property that significantly affects the combustion inside the cylinder is viscosity [134–138]. It influences the mixture formation, MFR, and particle size distribution. High viscosity fuel tends to stabilize the spray and delays the fuel dispersion as extra energy is needed to offset the effect of viscous force [139–143]. In contrast, low viscosity fuel has better dispersion resulting in shorter penetration length but wider cone angle [114,130,144–146]. Biodiesel, for instance, could hinder the fuel atomization owing to its high viscosity as well as surface tension content [147–151].

Surface tension is another determinant factor that influences the atomization as it signifies the energy amount needed to increase bubbles [152–155]. While surface tension affects the fuel surface area, volatility influences the spray evolution and mixture formation [114,156–159]. High volatile fuel tends to increase the evaporation rate and lowers SMD thus reducing the spray penetration length [160–165]. Low volatile fuel, on the other hand, has relatively lower evaporation rate, larger droplets size, thus increasing spray penetration length, which in some cases could lead to the wall impingement [166–170].

5. Modeling of Turbulent Diesel Spray and Combustion

The turbulence behavior of diesel spray and the combustion process play a considerable part in influencing the engine performance, combustion, as well as emission formation [171–174]. The physical understanding of these two concepts (diesel spray and combustion) brings a substantial contribution to the modeling in diesel engine combustion. The success of computational models is greatly dependent on how accurate the models can represent the actual combustion process inside the cylinder. Computational fluid dynamic (CFD) models have been proposed, improved, and implemented to capture the physical processes that determine turbulent combustion in diesel engines.

For the atmospheric pressure turbulent flames modeling, until today, most of the turbulent flame models have been approached using simple geometric configurations towards laboratory-scale, in which the flames pressure is assumed to be near atmospheric. This is because in such a condition the thermochemical conditions are well known, and sufficient measurement data are available. To investigate piloted flames, Sandia has generously provided turbulent flame data to facilitate several modeling studies in engine combustion. These data include Sandia C, D, E, and F flames, that are non-luminous, turbulent, and non-premixed. The fuel jet, along with pilot velocities, rise from flame C to F, and so do their local extinction effects. Therefore, while flame D shows mild extinction effects, flame F shows near global extinction effects. The flames provided by Sandia are suitable for modeling studies of turbulence chemistry interactions (TCI). The Damköhler number is often used to characterize the importance of TCI. The number represents the ratio of hydrodynamic to chemical time scales. Low-to-intermediate Damköhler numbers are of
particular concern here as they indicate the important phenomena occurs in turbulent and chemistry reactions. Dispersion, collisions of dispersed phase inter-particle, the modification of continuous phase turbulence, evaporation, mixing, as well as combustion, all take place concurrently in a true turbulent spray flame. It is a huge modeling challenge to deal with all of these intricacies and their relationships. Therefore, it is sensible to aim for advancement in individual sub-areas like breakdown, dispersion, mixing, and combustion, which cannot be completely viewed in isolation. Additionally, the benefits and drawbacks of the general modeling approach must be taken into consideration, including probability density function (PDF), direct numerical simulation (DNS), and large eddy simulation based on Reynolds averaged equations [175].

Several modeling studies have been proposed to improve the PDF-based models by exploring variants of transported modeling, such as composition and velocity-composition-joint PDF, advanced mixing models, improved and faster numerical algorithms, parallelization strategies, radiation modeling, and detailed chemistry. The turbulence modeling and flow structures configurations have been approached with both Reynolds average simulation (RAS) and large eddy simulation (LES). While RAS uses the PDF model, LES uses FDF, which stands for filtered density function. The multi-environment Eulerian-field PDF method, or often shortened MEPDF, has been developed as an alternative to particle-based Monte Carlo methods. The MEPDF method has relatively lower computational cost, while at the same maintain the benefits of simple transported PDF methods.

For high-pressure turbulent spray flames, modeling high-pressure turbulent spray, which can mimic the real flame in internal combustion engines, is a challenging task. Unlike the modeling for stationary turbulent flame, high-pressure turbulent spray flames require accurate high-temporal and spatial resolution. The task is even more difficult due to the transient ignition characteristics involving multiple combustion modes: premixed, mixing-controlled, and kinetically-controlled combustion. In direct-injection engines, the two-phase process of the spray increases the modeling complexity. Furthermore, limited reliable detailed data from experiments for real engine configurations limits the understanding of turbulent spray inside the cylinder.

It is important to remember that most of the diesel combustions are modeled based on measurements at atmospheric pressure [176–179]. In reality, the combustion process occurs at high-pressure involving spray breakup, droplet evaporation, two-phase heat and mass transfer, chemical kinetics, flame propagation, and other transport properties. This obviously requires a different approach as opposed to the near-atmospheric modeling method, considering the turbulent-chemistry interaction to realistically model the turbulent spray. Therefore, in order to produce realistic predictions for combustion and emission characteristics under such conditions, the model should be supported by a number of experimental results. The experimentation should be conducted to represent detailed thermochemical process to fulfill the prerequisite of advanced combustion of diesel technology. The Engine Combustion Network (ECN) from Sandia National Laboratories, provides the reliable experimental database performed in practical diesel engines. This is carried out to bridge the gap in modeling between the laboratory-scale flame and real modern diesel engines.

Note that the engine performance is considerably responsive to slight variations in the physical state of combustible mixture. Therefore, accurate modeling of the injector and spray behavior are needed to achieve realistic CFD predictions. The spray near the injector, in particular, is of great concern when the injected liquid fuel undergoes a series of instable processes resulted from complex liquid-gas phase interactions. This region often referred to as primary atomization region, is the dense-spray area and has been studied extensively. Still, comprehensive physical descriptions that affect the formation and growth of the spray have not yet been fully known. Furthermore, the lack of reliable experimental techniques that can sufficiently describe its physical characteristics has restricted the theoretical understanding of the spray formation. Several modeling findings, however, were
performed to describe the spray behavior statistically. Yet, no experimental results exist to validate these models. To solve this problem, most modeling strategies have to tune the model coefficients to match measurements further downstream of the injector. In this region, often referred to dilute-spray region, the physical behavior of the spray is relatively easy to understand due to its regularity.

A number of Eulerian- as well as Lagrangian-based methods were successfully employed to model the spray behavior in dilute sprays [180–184]. Such methods are also able to model the two-phase interaction involving droplets (liquid) and surrounding in-cylinder gas. Of the two methods, Lagrangian-based dispersed-phase is more popular for diesel spray modeling. Most of the Lagrangian models analyze the droplet evaporation by assuming the droplet properties to be uniform and the droplet internal circulation to be considerably fast. The interactions between the dispersed-phase droplets and strong turbulent flow within the combustion chamber are important factors to control the evaporation as well as heat transfer rates to and from the droplets. Therefore, assuming the droplets to have uniform properties that change with time is a reasonable approach in the dilute-spray region.

Multi-component droplet evaporation has also been paid attention due to growing interest in the engine development that operate on multi fuels. Initially, multi-component vaporization studies estimated the droplet evaporation as a single spray component of vaporization sequence controlled by volatility differences. Later, it was found that for multi-fuels consisting of different mass diffusivities, the evaporation rates were influenced by each spray component and limited by the low-diffusivity component. In general, the droplet evaporates due to combined effects of both volatility and mass diffusion of each spray components. However, when the mass diffusivity drops to zero, the vaporization rates are no longer subject to volatility of the components.

Most diesel spray modeling neglects the diffusive transport effect inside the droplets. While this assumption is widely accepted in conventional diesel engine condition, in-depth consideration should be taken into account if this assumption to be applied in a low-pressure low-temperature diesel engine. In such condition, the evaporation rate is relatively low so that wall film formation could be formed. As a consequence, the transient heating of the wall film and differential mass diffusion of the liquid components can significantly change the evaporation rates, thus altering the combustion as well as emission behaviors.

All in all, although the advancement of the rapid computational method has significantly improved the numerical predictions of spray behavior, a thorough understanding of the fundamental physical mechanism remains the key factor to the research in engine combustion. The physical phenomena inside the cylinder should be able to be modeled with simple, yet realistic flame configurations without using complex geometries. After being compared with the experimental results, the CFD model could hopefully accurately represent real engine combustion.

6. Optical Measurement Systems

Diesel spray phenomena in the combustion process is difficult to measure. It is considerably challenging to capture spray behavior [185]. In order to gain a deeper comprehension of diesel spray and fuel-air mixing phenomena, several optical techniques have been introduced. The optical diagnostic aims to investigate the spray behavior using non-intrusive method [186]. This method is generally categorized into two types: photography and non-photography. The photography technique intends to observe the macroscopic characteristics such as fuel distribution, spray length, and angle, whereas the non-photographic technique seeks to study the microscopic characteristics.

Specifically, based on the working principle, optical diagnostic techniques are divided into two: traditional diagnostic techniques based on conventional optics and laser-based diagnostic techniques [187]. Figure 6 shows the laser absorption-scattering (LAS) technique basic principle. When the two laser beams go all the way through the spray, the attenuation effect decreases the intensities. In the ultraviolet image, the lower intensity is caused by
scattering and absorption of the liquid as well as absorption of the vapor where the impact of the liquid absorption is insignificant [60,188,189].

![Injector](Image)

**Figure 6.** LAS technique basic principle, reproduced from [190].

The diagnostic techniques provide substantial information about the nature of the fuel flow or combustion under high temperature and pressure conditions, thus providing insights into the chemical and physical mechanisms of spray both on macro- and micro-scales. Various optical diagnostic methods have been adopted in previous studies, such as Mie scattering [191,192], Rayleigh scattering [193,194], Raman scattering [195,196], shadow graphy (SG) [191,197], phase doppler interferometry (PDI) [198], Schlieren photography [191,199], laser-induced (exciplex) fluorescence (LIF/LIEF) [123,200], and the combined method [201,202]. Table 1 shows the optical diagnostic techniques used for several phenomena capturing.

| Technique | Application                          | Phenomena Capturing                          | References            |
|-----------|--------------------------------------|----------------------------------------------|-----------------------|
| Mie Scattering | Diesel, gasoline engine               | Liquid distribution of spray                  | Kim et al. [191]      |
| Mie Scattering | Gasoline engine                        | Droplet size                                  | Mounaim-Rousselle and Pajot [192] |
| Raman Scattering | Diesel engine                          | Spray-wall interaction                        | Egermann et al. [195] |
| Raman Scattering | Spray-wall interaction (near wall condition) | Vaporizing diesel spray                      | Egermann et al. [196] |
| Rayleigh Scattering | Diesel engine                         | Liquid penetration                            | Idicheria and Pickett [193] |
| Rayleigh Scattering | Diesel engine                         | Vapor distribution                            | Pickett et al. [194]  |
| Schlieren | Diesel, gasoline engine                | Vaporization of diesel spray                  | Kim et al. [191]      |
| Schlieren | Diesel engine                          | Vaporization diesel spray                     | Payri et al. [199]    |
| Shadowgraphy | Diesel, gasoline engine                | Vapor distribution (a more shadow)            | Kim et al. [191]      |
| Shadowgraphy | Diesel engine                          | Diesel—water emulsion fuel injection sprays   | Emberson et al. [197] |
| Phase doppler interferometry (PDI) | Diesel engine                         | Macroporous and microscopic spray            | Gupta and Agrawal [198] |
| Laser-induced (exciplex) fluorescence (LIF/LIEF) | Gasoline engine                        | Mixing process                                | Bruneaux [200]        |
| Combined (Mie-Rayleigh) | Diesel engine                         | Evaporation of diesel spray                   | Adam et al. [201]     |

The distribution of liquid and vapor phases in diesel spray has gained great attention [126,189,203–205]. In the last two decades, a new technique called particle image velocimetry (PIV) has successfully advanced the research in mixture formation [206–208]. PIV has revealed that the nearby airflow can be classified into three different regions according to the flow property. In the first region (head vortex zone), the gas is initially pushed apart by the head front of the spray. The gas is subsequently recirculated in the
finally, in the last region, region 3 (near quasi static zone), the gas is entrained into the following spray zone.

7. Conclusions

Diesel engines have relatively higher efficiency compared to the gasoline engine, achieved by a higher compression ratio by eliminating the throttling losses as commonly found in gasoline engines. This superior benefit of high efficiency in diesel engines comes at the expense of the high level of emissions. The two most significant pollutants of diesel engines are NOx and PM. The latter stands for particulate matter and is commonly known as soot. Subject to engine load conditions, diesel engines produce a substantial amount of NOx. Several factors that determine the NOx formation include thermal NO, fuel-bound nitrogen, prompt NO, and N2O-intermediate. It occurs in a lean-fuel region, while soot emission, on the other hand, occurs in a rich-fuel region.

Diesel engine performance and pollutant emissions are the outcome of the chemical and physical developments taking place in the cylinder when fuel jets are ignited. Important in-cylinder processes include: the spatial and temporal development of liquid-fuel sprays; fuel vaporization, the mixing of vaporized fuel with in-cylinder gases; the low-temperature autoignition chemistry of fuel components; the high-temperature chemical kinetics of combustion and pollutant formation; as well as late-cycle mixing and burnout processes.

Diesel spray is a crucial event affecting the diesel engine performance, combustion, and emission characteristics. It has received considerable attention not only from automobile manufacturers, but also from academicians across the world. There are several major aspects of diesel spray, which have been considered the dominant factors, including injector cavitation, break-up process, and spray development. Spray cavitation suggest the importance of turbulence phenomenon caused by vapor bubble disruption in an injector, whereas the break-up process indicates the existence of a problem caused by liquid surface instability during the spray development. To observe these events, a number of measurement methods have been proposed, encouraging a new scientific achievement known as diesel spray laser diagnostics.

Many studies have been conducted focusing on spray atomization. Several factors are known to be responsible for the spray atomization. They were: (i) the aerodynamic forces; (ii) internal turbulence; (iii) boundary mutation at the exit of the nozzle; and (iv) internal flow cavitation. With the help of the optically-accessible-measurement technique, none of the factors mentioned above are found to influence the spray atomization independently. In fact, it is believed that the combination of some dominant factors is actually responsible collectively.

It is difficult to determine whether the cavitation has a constructive or adverse effect in engine performance. Although, the cavitation enhances the spray atomization, it also reduces the effective flow area (cross sectional area) which, in fact, deteriorates the combustion under large amount condition. Most researchers are, therefore, trying to reach an agreement on the effects of cavitation on engine performance. Additionally, aerodynamic forces play an important role as the spray exits the nozzle hole [31,40,41]. After the spray passes break-up length, aerodynamic forces cause the smaller droplets formation. This phenomenon is known as the secondary break-up. It relies greatly upon the ratio of aerodynamic and surface tension (as gas phase Weber number). The process of break up with low Weber number occurs in the downstream region, while that with high number takes place in upstream region. It is also important to remember that in diesel engine, spray penetration and angle are of significance on the utility of ambient gas and mixture formation rate. Overlong spray penetration causes several negative consequences such as higher hydrocarbon and carbon monoxide emissions, lower fuel economy, as well as more lubricant consumption due to wall wetting. On the other hand, short spray penetration is known to deteriorate the utilization of chamber gas.

Observing spray behavior in the diesel engine is a challenging task, requiring techniques that involve measurement in high-speed high-pressure and high-temperature con-
dition. There are, however, three parameters to measure the structure of the spray in diesel engine: spray shape, microscopic, and macroscopic characteristics. Besides spray shape and macroscopic parameters, microscopic is of great importance in diesel spray/combustion. Even though numerous studies have investigated these microscopic factors, no definitive theoretical concept has been made regarding the droplet size of diesel spray. These microscopic factors include: (i) mean diameter, (ii) droplets size distribution, and (iii) spatial distribution. For mean diameter, the Sauter mean diameter (SMD) is the most extensively utilized definition. The Sauter mean diameter could indicate the spray average evaporation qualities. For droplets size distribution, smaller droplet size leads to faster evaporation. Yet, smaller size droplets cannot maintain its momentum. As a result, after losing momentum, it fails to accelerate the mixing between fuel and air. For spatial distribution, this important factor affects the quality of diesel spray combustion. Although a number of optical measurements as well as numerical simulations have been conducted in the last two decades, the established evaluation method for spatial distribution of diesel spray has not yet been settled. A combination between the spray’s angle, penetration, volume and droplets’ spatial number concentration remain to be used to characterize the spatial spray distribution.

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