Engineering 5 (2019) 519–534

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Engines and Fuels—Review

The Possibility of Active Attitude Control for Fuel Spray

Masataka Arai

Tokyo Denki University, Tokyo 120-8551, Japan

A R T I C L E I N F O

Article history:
Received 26 April 2018
Revised 1 February 2019
Accepted 16 April 2019
Available online 7 May 2019

Keywords:
Internal combustion engine
Fuel spray
Spray control
Spray behavior
Fuel injector

A B S T R A C T

The internal combustion engine (ICE) is an attractive power source for automobiles, with its superior storability, transportability, and suppliability of liquid fuel with high energy density. Compact ICEs with high performance and a low environmental load are greatly needed. In the future, smart active control of combustion by means of fuel spray injection must be considered as a breakthrough technology to address serious issues related to conventional ICEs, such as emissions. A designed fuel injection rate and spray pattern during the injection period have been technically developed, and combustion can be partially controlled in the conventional ICE. However, spatial fuel distribution is not progressing as desired in the field of combustion; thus, new and effective active control technologies for fuel spray are very necessary for the smart control of combustion. Cavitation, flash boiling, spray-to-spray interaction, spray-to-wall interaction, and air flow have potential as a basis for active attitude control of fuel spray. This article uses evidence from the literature to discuss the possibility of active spray attitude control for future fuel spray combustion technology in a smart compact ICE.

1. Introduction

The internal combustion engine (ICE) is an attractive power source for automobiles. Our daily lives heavily depend on transportation vehicles based on high-performance ICEs, which have the advantages of superior storability, transportability, and suppliability of liquid fuel with high energy density. However, ICE vehicles are also related to serious issues involving energy resources, the economic situation, and the environment—a "3E" (i.e., energy, economy, and environment) tri-lemma problem, as shown in Fig. 1. To solve this 3E tri-lemma problem, more compact ICEs with high performance and a low environmental load are required.

Electricity and other alternative power sources have recently become widely used in light-duty vehicles (LDVs). Fig. 2 [1] shows trends in the LDV market in the United States. Various perspective reports have been produced regarding the expansion market of electric vehicles (EVs). These reports show that the EV market size is slowly expanding, although society wants a rapid and more drastic expansion of the market. The power source of hybrid electric vehicles (HEVs) is liquid petroleum, as in ICEs, and the petroleum engine market will remain as the main market of LDVs in 2050. EVs are a suitable transport technology for maintaining a clean environment. When the electricity of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) comes from natural energy such as photovoltaics, use of these vehicles contributes to the reduction of greenhouse gas (GHG) emissions. However, electricity is a risky energy source for vehicles due to its lower storability, transportability, and suppliability in the case of unexpected disasters. These disadvantages may be some of the reasons behind the low penetration speed of BEVs into the transportation market.

High-efficiency and low-emission ICEs have been developed using various engine technologies including combustion improvement, after-treatment system development, and a hybrid system with a generator–battery–motor subsystem. For combustion improvement, new designs for the fuel injection rate and spray pattern during the injection period have been technically developed, and combustion can now be partially controlled in a conventional ICE. As a result, high-performance and low-emission engines have recently been commercialized.

This article proposes the new concept of attitude control of a fuel spray. *Fuel spray attitude* involves the configuration, movement orientation, and relative position of the fuel spray in the combustion chamber. The concept of *attitude control* includes: ① prediction of the current attitude, including spray penetration, spray width, and the plume angle of the spray; ② determination

E-mail addresses: marai@mail.dendai.ac.jp, arai@gunma-u.ac.jp

https://doi.org/10.1016/j.eng.2019.04.010

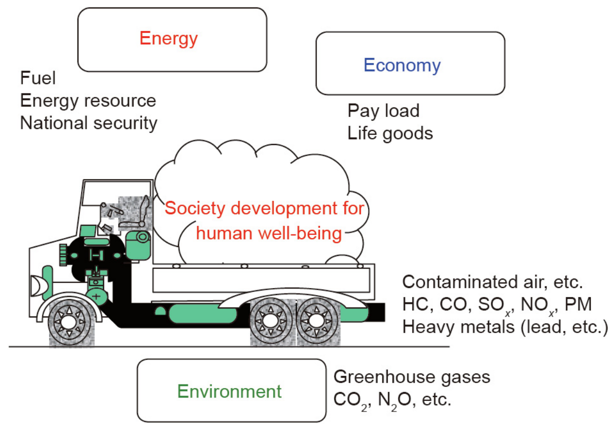


Fig. 1. The "3E" tri-lemma problem of ICE vehicles. HC: unburned hydrocarbons; PM: particulate matter.

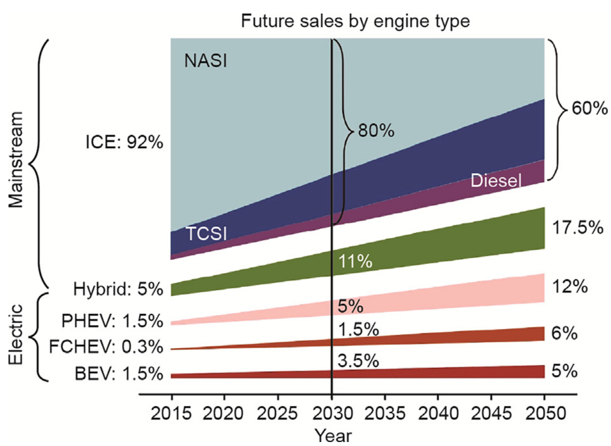


Fig. 2. The evolving LDV market in the United States: Percent sales by powertrain type from 2015 to 2050. Other major regions are likely to have a similar evolution; diesel in Europe is currently at about 50 % of ICEs sales, but that fraction is slowly decreasing [1]. FCHEV: fuel cell hybrid electric vehicle; NASI: natural aspirated spark ignition engine; TCSI: turbo-charged spark ignition engine.

of the desired spray attitude in the chamber space; and ③ use of active control hardware to obtain the desired attitude. In the combustion field, a great deal is known about spray behavior, but little information is available concerning desired spray behavior. Thus, active control technologies for fuel spray attitude have not yet been developed. However, the establishment of a desired spray concept and the development of effective active control technologies for fuel spray are very necessary for the smart control of combustion. Cavitation, flash boiling, spray-to-spray interaction, spray-to-wall interaction, and air flow have potential as a basis for the active attitude control of fuel spray. This article uses evidence from the literature to discuss the possibility of developing active spray attitude control in order to achieve a suitable spray for future fuel spray combustion technology in smart compact ICEs.

2. Passive and active fuel spray control

It is well known that formation of the fuel spray mixture is the most important governing phenomenon of diesel combustion [2]; it is also a key process of the formation of the combustible mixture in a direct-injection spark ignition (DISI) engine. Fig. 3 shows how diesel spray dispersion in the combustion chamber contributes to the improvement of diesel combustion [3]. A wide spray angle of well-penetrated spray, along with high swirl and an intense squish air flow contribute to the formation of a suitable combustion mixture that is spatially dispersed in the chamber. The heat-release rate is considered to be controlled in order to obtain high power and reduce the combustion noise, NO_x, and soot emissions, as illustrated in Fig. 4 [4]. It can be controlled using the fuel injection rate (time phase control). Injection rate control has become the main technology target of recent studies on advanced diesel combustion [5].

In order to discuss the active attitude control of spray, it is necessary to clarify the spray parameters to be controlled and the controlling methods used to do so. Table 1 summarizes the items and methods involved in fuel spray control. The spray tip penetration, spray angle, and microscopic structure of the fuel spray are the main items involved in fuel spray control. These are usually considered to be the characteristics of the spray.

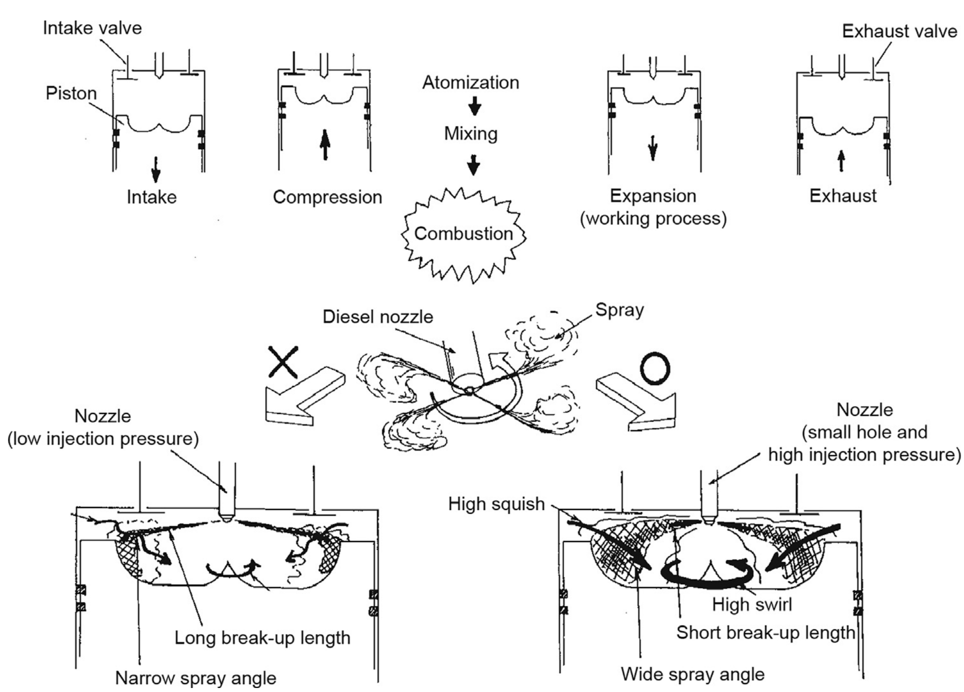


Fig. 3. Diesel spray combustion [3].

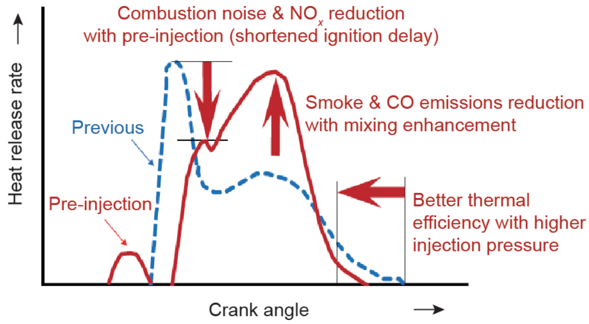


Fig. 4. Change of the heat-release rate profile for diesel combustion improvement [4].

However, relative characteristics involving the combustion chamber configuration and combustion condition are also important for spray attitude control because the desired attitude of the spray usually changes with changes in the chamber configuration, engine speed, load, and so on.

The methods used for fuel spray control can be classified into static and dynamic methods. Items that are controllable by static methods are the design parameters of the fuel spray injection, which usually remain unchanged under different engine operating conditions. However, some controllable items—classified as dynamic parameters—should be artificially changed for different engine speeds and loads. Such items are further classified into passive and active control items. *Passive control items* are controlled in a subsidiary manner to other parameters. For example, the injection rate of fuel changes in a subsidiary manner with changes in engine load. Similarly, while flash boiling of gasoline spray is usually observed in the early injection phase of a DISI engine, it cannot be controlled autonomously.

In contrast, *active control items* are autonomously controllable parameters. However, active control methods for these parameters have not been developed. The implementation of such active control methods will lead to great advancement in active fuel spray attitude control and in ICE technologies.

The following section discusses the possibilities of active control, with a particular focus on the active attitude control of fuel spray that is suitably dispersed in the chamber. Examples of attitude-controlled fuel sprays are provided in Fig. 5, which shows spray attitude control during the injection period. Once the active control of spray injection becomes possible, it will result in suitable fuel vapor distribution corresponding to the engine speed and load.

There are two kinds of spray control: time phase (temporal sequence series) control, such as injection rate control; and spatial phase control. With the full utilization of up-to-date spray technologies, artificial control of spray dispersion in a space can be partially attained by appropriately designing the spray angle and wall impingement. However, a new spray dispersion control principle is needed for future engine development—in other words, "spatiotemporal control" of the fuel spray is needed.

3. Passive fuel spray control

It is well known that gasoline direct-injection (GDI) spray is affected by the gas density in the cylinder. Fig. 6 shows examples of gasoline spray being injected and evaporated in low and high gas density surroundings [6]. In these examples, the injection pressure of the gasoline spray is 20 MPa and the surrounding temperature is 700 K—a temperature that is high enough for evaporation. The photos in Fig. 6(a) show spray behavior corresponding to naturally aspirated (NA) engine operation. Three fuel plumes and fuel vapor trace can be observed. The photos in Fig. 6(b) depict sprays corresponding to turbocharged engine operation. Due to the high surrounding gas density, the spray penetration is shortened and its penetration direction is changed from the original direction. Three spray plumes can be seen to be gathering together, due to the lack of air entrainment inside the plume cone. Fig. 7 [6] illustrates the analysis of the liquid and vapor plumes shown in Fig. 6.

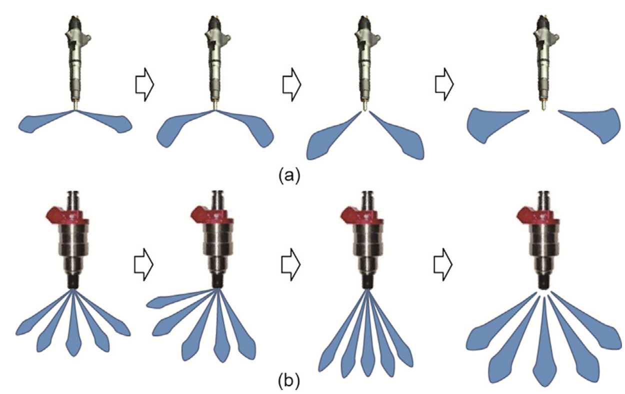


Fig. 5. Examples of attitude-controlled fuel spray. (a) Diesel injector; (b) gasoline injector.

Table 1
Control items and methods of fuel spray.

Control methods		Control items
Characteristics of the spray		• Spray tip penetration • Spray stagnation • Penetration direction • Spray angle • Symmetry of spray plume • Spray dispersion • Microscopic feature of spray (droplet size, turbulence, etc.)
Design parameters of the fuel spray injection	Static control	• Nozzle configuration/geometry • Injection pressure • Back pressure (surrounding pressure) • Fuel properties • Temperature • Others
	Dynamic control	• Passive: injection rate (timing, pattern, and injected mass); nozzle cavitation; flash boiling; air flow (swirl, tumble, and squish); wall impingement (cylinder wall and piston top); and others • Active: variable geometry nozzle; injection rate (cycle-to-cycle variation for lean-rich combustion); injection response (needle lift and injection pressure); nozzle cavitation; flash boiling; forced vibration (nozzle vibration); secondary atomization (obstacle impingement and guide wall); spray-to-spray interaction; air flow (swirl, tumble, and squish); wall guide; additional actuators (air jet and acoustic pulse); and others

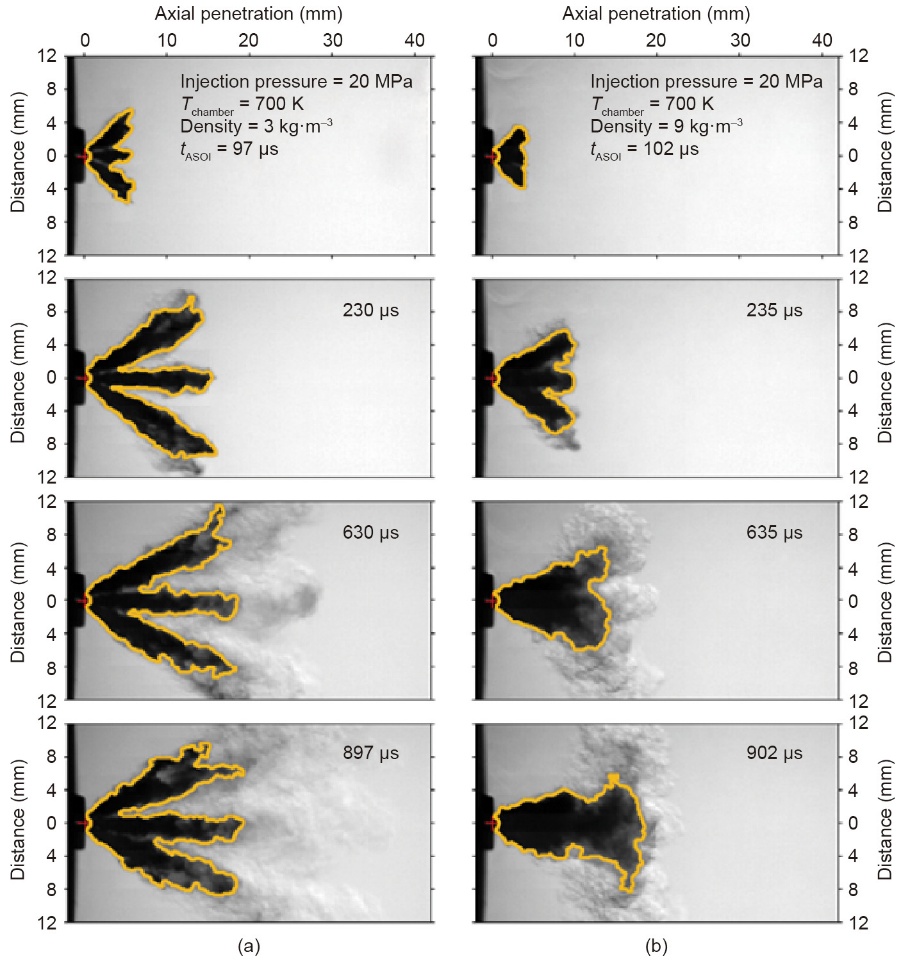


Fig. 6. Liquid spray comparison between (a) lower gas density conditions and (b) higher gas density conditions using raw images and detected contours. t_{ASOI}: time after start of injection [6].

The differences in the spray and vapor plumes under these two conditions come from the differences in spray attitude, which depends on the surrounding gas density. These differences result in different fuel vapor distributions in the cylinder and affect the combustion quality related to the operation condition of the engine. Detailed information—such as the surrounding gas density—is needed on the fuel distribution under each operating condition. Many reports are available on spray attitude behavior [7,8]. However, spray behavior is controlled in a subsidiary manner to the surrounding gas density, and cannot be controlled autonomously. If the injection direction of a multi-hole injector could be actively controlled, the desired vapor plumes could be obtained independently from the surrounding pressure.

Wall impingement is an inevitable phenomena of diesel spray; its impingement behavior is investigated with spray tip penetration. This kind of information is useful for matching the design of the combustion chamber configuration with that of the injection system, including the diesel nozzle and injection pressure. Fig. 8 shows a typical diesel spray impinging onto the wall [9]. The dispersion of the wall impingement spray is very different from that of the free spray. A great deal of research [3] has been conducted on wall impingement spray in order to obtain a suitable diesel spray, as shown in Fig. 3. However, spray dispersion is controlled in a subsidiary manner by the wall impingement angle, and thus cannot be changed during the injection period.

Fig. 9 shows the typical behavior of normal impingement diesel spray. Here, the spray behavior is evaluated using the radial penetration length after impingement. The effect of the injection mass on the penetration is small because the spray tip movement is governed by the initial injection part of the spray; however, the injection pressure has a strong influence on the penetration. Spray tip penetration after impingement is controlled by the wall inclined angle, wall distance, and injection pressure. Therefore, diesel spray dispersion in the combustion chamber cannot be designed independently from these static control parameters.

The attitude of the impingement spray is mainly controlled by the impingement distance and impingement angle. The effects of these controlling parameters are dominant, and they are usually matching parameters of the fuel spray and combustion chamber [2]. Active control of the impingement spray attitude might be possible if the piston configuration could be changed during engine operation.

4. Active fuel spray control

4.1. Variable geometry nozzle

Nozzle geometry is an interesting design parameter of the nozzle. For a diesel injector, an adequate nozzle length and length-to-nozzle-diameter ratio (L/D) are usually selected in order to obtain the widest spray angle. Divergent and convergent nozzles are sometimes used to change the spray. The spray tip penetrations and spray angles of designed sprays are investigated as representative spray characteristics for injection conditions. Regarding a special configuration nozzle, a trial of a V-type intersecting nozzle

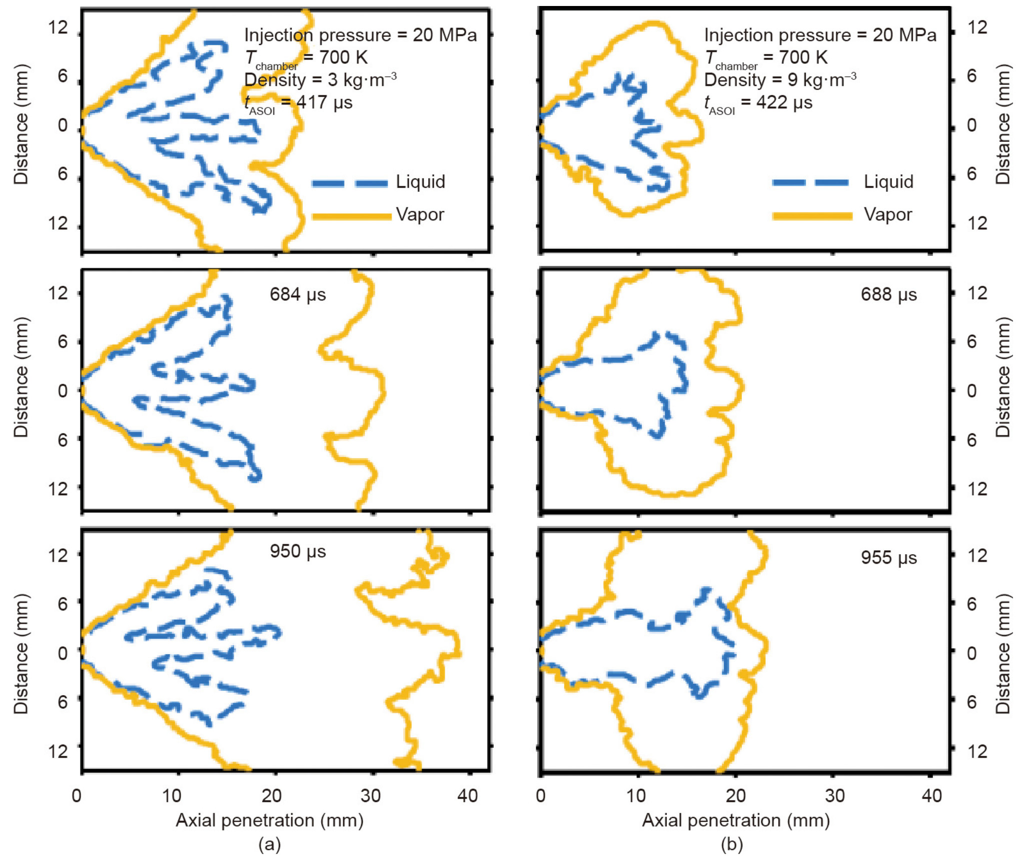


Fig. 7. Liquid and vapor spray contour comparison between (a) lower and (b) higher gas density levels at a chamber temperature of 700 K and an injection pressure of 20 MPa [6].

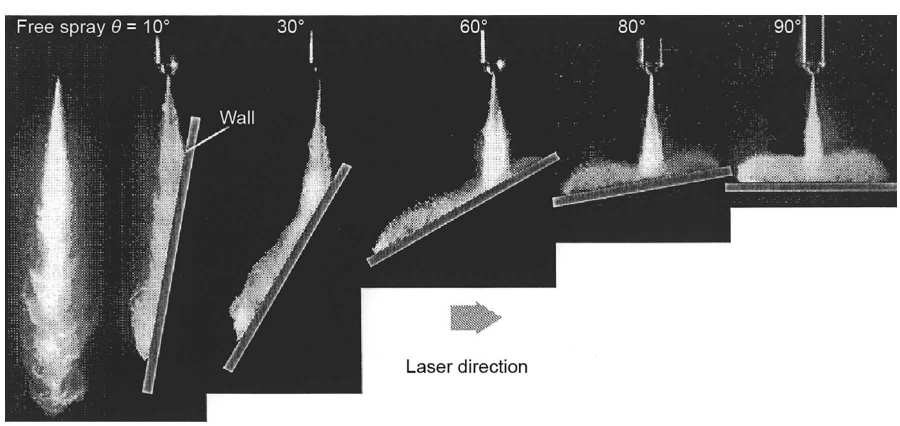


Fig. 8. Free and wall impingement diesel sprays [9]. θ: impingement angle.

can be found in the literature [10]. As shown in Fig. 10 [10], two nozzle holes meet together at the exit position. Fig. 11 [10] shows the angle of the spray injected through the V-type nozzle; it can form a flatness spray plume with an elliptical cross-sectional structure. This suggests the possibility of spray attitude control by means of nozzle geometry change, although it is not possible in terms of practical technology.

Investigation into the characteristics of a spray formed by V-type nozzle has recently become popular, and a great deal of useful information has been accumulated [11]. However, few attempts have been made to apply this knowledge to active attitude control. Individual flow rate control for the *A*–*O* and *B*–*O* nozzles shown in Fig. 10 forms the basis for active control, and nozzle cavitation control, which will be mentioned later in this work, will provide a solution.

Other evidence indicating the possibility of spray attitude control can be found in the off-axis needle valve motions shown in Figs. 12 and 13 [12]. Here, the spray penetration direction and length are obviously changed by the offset of the needle valve. According to the original result of this research, the offset of the needle lift should be suppressed in order to ensure good reproducibility of the diesel spray for precise control of diesel combustion. However, this result suggests the possibility of spray attitude control by means of needle movement. X-ray shadowgraph technology to observe the off-axis movement of the needle has recently been developed [13–15]. The next step in establishing the new attitude control is offset ratio control by means of a new actuator.

The two examples provided above are research works intended to determine the spray characteristics that are affected by nozzle geometry. However, a more important point of these works is that

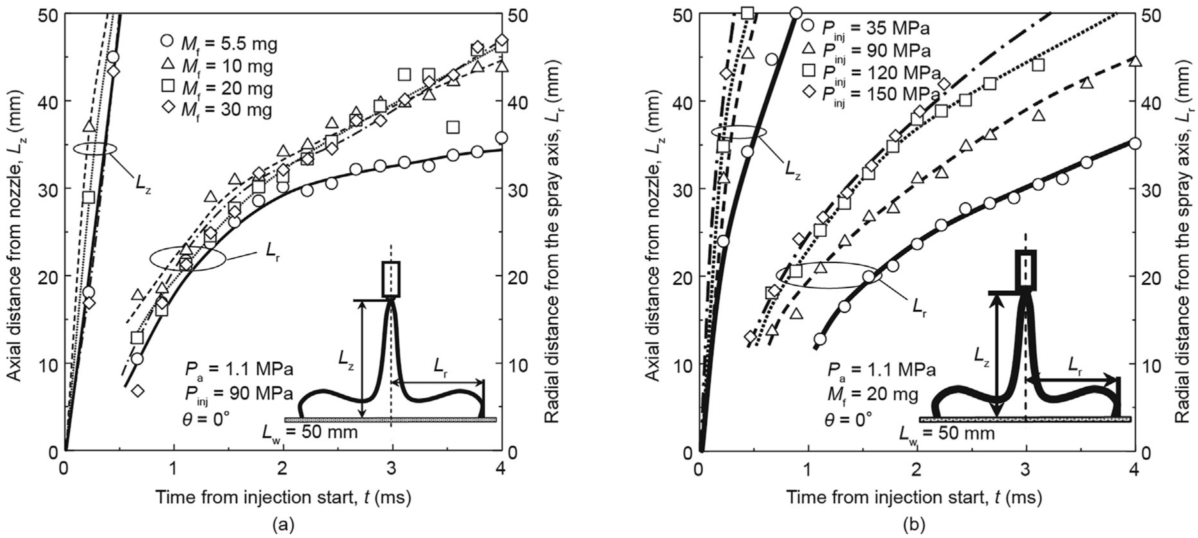


Fig. 9. Spray tip penetration of the wall impingement diesel spray. (a) Injection mass (M_f) effect; (b) injection pressure (P_{inj}) effect. L_r: radial spray penetration; L_z: spray penetration; P_a: ambient pressure.

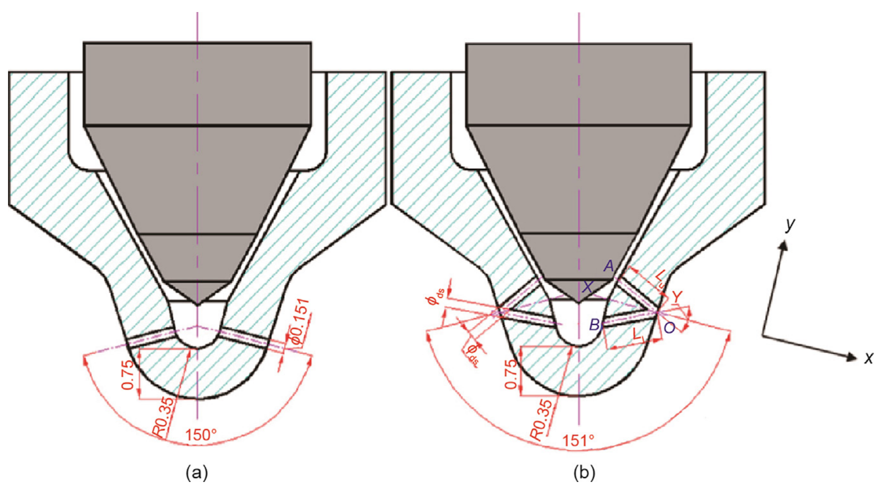


Fig. 10. Geometries of (a) a cylindrical hole nozzle; (b) a V-type intersecting hole nozzle [10]. ϕ_{ds}: diameter of sub-hole; L_u: length of the upper sub-hole; L_l: length of the lower sub-hole.

they indicate the possibility of artificial control of the spray attitude. Based on the above research works, the present author has developed the following two conceptual ideas for artificial spray attitude control during the injection period.

The first conceptual idea is a method of diesel spray control by means of needles with various geometries. The needle lift can be changed by the injection pressure of the fuel. This suggests the possibility of artificial control of the needle lift by injection pressure during the injection period. Fig. 14 illustrates the conceptual ideas of a throttling pintle needle and a sub-needle connected by a spring. These forms of needle control might result in changes in the spray attitude during the injection period, as shown in the figure. Fig. 15 illustrates the second idea for a DISI injector, in which a swinging orifice plate or nozzle-choking mechanism is adopted. In this idea, an additional actuator for plate swinging or nozzle choking is needed. It is the opinion of this author that future development of micro-electromechanical systems (MEMS) technology will make it possible.

4.2. Injection rate

A recent cutting-edge technology involves injection rate control by regulating the piezo stack voltage of a common rail diesel injector. As shown in Fig. 4, time-dependent control of the fuel spray supply is the substantial meaning on heat-release rate control; many trials have been performed, and some methods have been commercialized. Figs. 16–18 provide an example of injection rate control by means of the piezo stack voltage [8,15,16]. The stack voltage is controlled by a proportional-integral-derivative (PID) controller unit. Once the frequency responses of the piezo and the main moving parts, such as the needle, are improved, this system will allow more detailed and precise control of the injection rate. Various methods of injection control have recently been proposed [17,18].

In addition to the future improvement of precise injection rate control, control of spray penetration direction and spray attitude is desired, because suitable fuel dispersion in the combustion chamber space depends greatly on the engine speed and load. A double acting needle and other difficult methods such as that shown in Fig. 14 must be considered for more advanced smart injector technologies.

4.3. Nozzle cavitation

Cavitation at the inlet of the nozzle or orifice promotes liquid jet breakup because cavitation bubble disruption results in intense

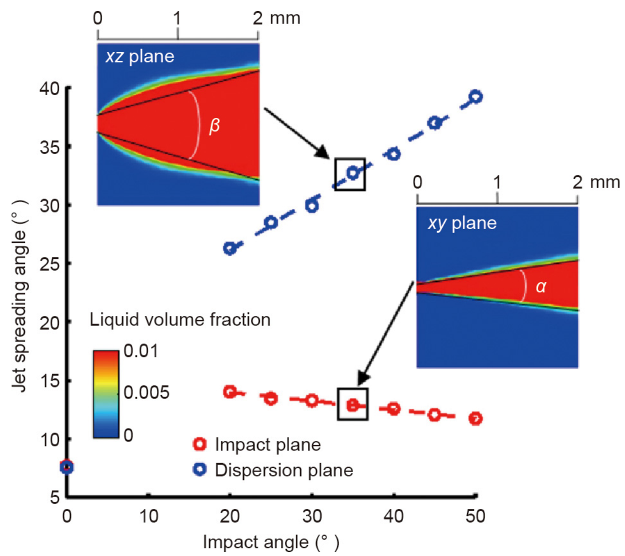


Fig. 11. Variations of the jet spreading angles with the impact angle. α: angle in xy plane; β: angle in xz plane [10].

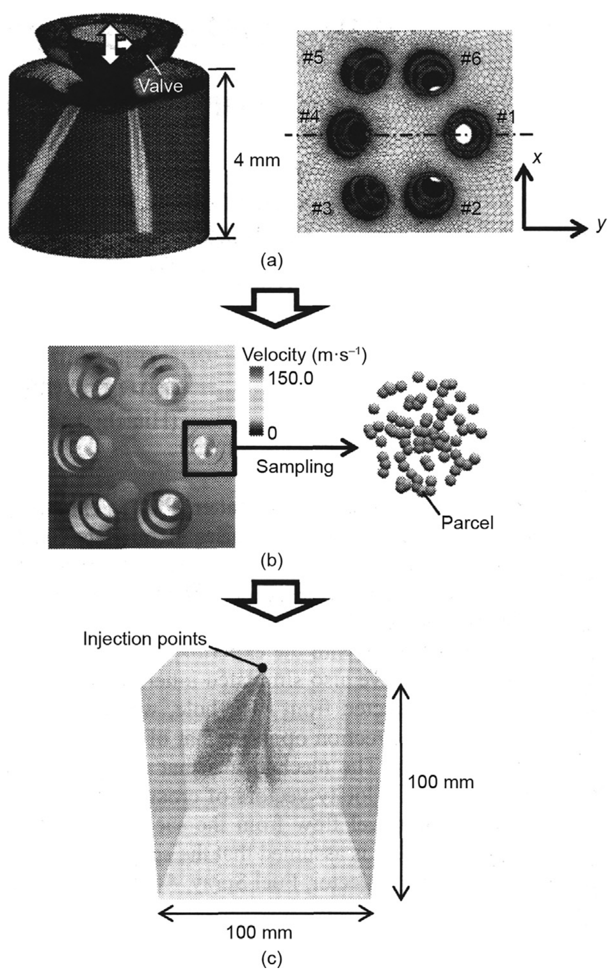


Fig. 12. Off-axis valve nozzle. Procedure of the inner nozzle flow and spray simulation [12]. (a) 1st step: inner nozzle flow simulation with valve motion; (b) 2nd step: data sampling of hole outlets; (c) 3rd step: spray simulation.

turbulence in the flow inside the nozzle. When an asymmetric configuration is adopted for the inlet port of a nozzle, the breakup and spray formation phenomena differ when examined side to side [19]. Fig. 19 [19] shows evidence of asymmetric spray formation. The left side of the inlet port has a smooth entrance of 45°, and no cavitation is induced. On the other hand, strong cavitation is induced at the right side of the inlet port, where the entrance has a sharp edge of 90°. The breakup process of the liquid jet is well promoted at the right side of the nozzle. The direction of the issuing spray jet is then distorted to the right side, and the spray dispersion is completely different from the spray that is injected from an axisymmetric nozzle. This finding suggests the possibility of jet direction and dispersion control by means of cavitation.

This phenomenon is usually known as less axisymmetric spray formation, which is not suitable for precise combustion control, and axisymmetric geometry of the inlet port is recommended. However, when the inlet configuration is artificially changed during the injection period, the injection direction and spray dispersion can be changed and suitable spatial dispersions can be respectively formed for various combustion conditions.

The asymmetric inlet effect has also been confirmed using a large-scale diesel injector model [20]. Fig. 20 [20] shows an enlarged injector model and a method to change the inlet condition. The asymmetric inlet is caused by an eccentric set of the needle. Two kinds of cavitation can be observed in Fig. 21: the sheet cavitation that is stuck at the entrance edge of the nozzle, which is known as general nozzle cavitation; and the vortex cavitation (vortex tube) that originates on the surface of the needle. The spray dispersion angles shown in the left column of the photos are drastically widened by this vortex cavitation.

Injection rate control is the fundamental parameter of engine operation, and is determined by the injection pressure and period of injection. Since the discharge coefficient of a nozzle has a strong relationship with the nozzle cavitation, cavitation control for reproducible spray or steady cavitation is considered to be suitable for precise control of combustion. Figs. 22 and 23 show the effect of nozzle geometry on the discharge coefficient [21]. In this research work [21], the discharge coefficients of the convergent and divergent nozzles are compared with that of a conventional cylindrical nozzle.

The intensity of nozzle cavitation is evaluated by the cavitation number. Intense cavitation sometimes results in a hydraulic flip flow, and the discharge coefficient decreases obviously. Conventional operation range of a diesel nozzle over a range of cavitation flows and constant discharge coefficients is desirable for injection rate control. The convergent nozzle shows no cavitation flow, as it comes from the low-pressure decrease at the inlet. This appears to be suitable for injection rate control, whereas a wide angle spray is not expected for a convergent nozzle. Regarding cavitation in a diesel nozzle, the nozzle shape effect and fuel temperature effect were recently demonstrated [22,23].

Both sheet cavitation and string cavitation (vortex cavitation in Fig. 21) result in a wide spray angle. Fig. 24 summarizes the effect of cavitation on diesel spray combustion [24] and shows that string cavitation can more effectively improve the formation process of diesel spray, resulting in easy ignition and a wide flame. String cavitation usually originates at the surface of the needle. However, in a multi-hole nozzle, concatenation of the cavitation strings occurs in the sac space. Although this situation might result in stronger string cavitation, its occurrence is hard to control.

A typical characteristic of string cavitation is its onset position. The present author's proposal for cavitation control involves an additional cavitation trap on the surface of the needle. Fig. 25 shows a conceptual idea for string cavitation control. If a groove is cut on the surface of the needle, steady string cavitation might start and develop from the groove (Fig. 25(a)). Following the needle lift movement, the position of the string cavitation moves from the lower side of the nozzle inlet to the upper side. This situation might cause a change in the spray dispersion direction, as shown in Fig. 25(b).

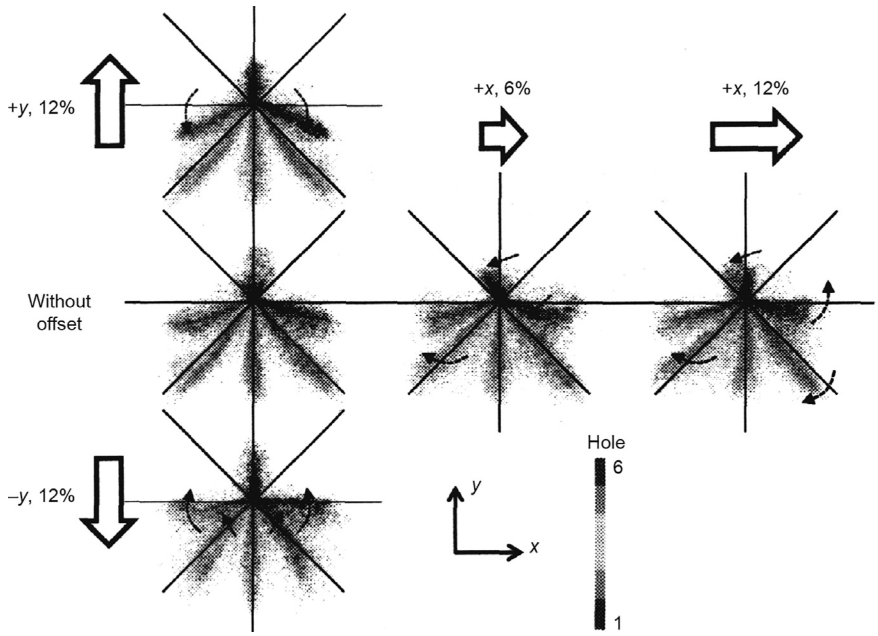


Fig. 13. Top view of the spray shapes calculated with various off-axis valve motions at 0.8 ms [12].

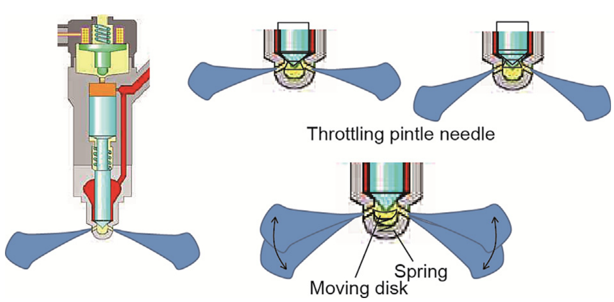


Fig. 14. The conceptual ideas of a throttling pintle needle and a sub-needle connected by a spring.

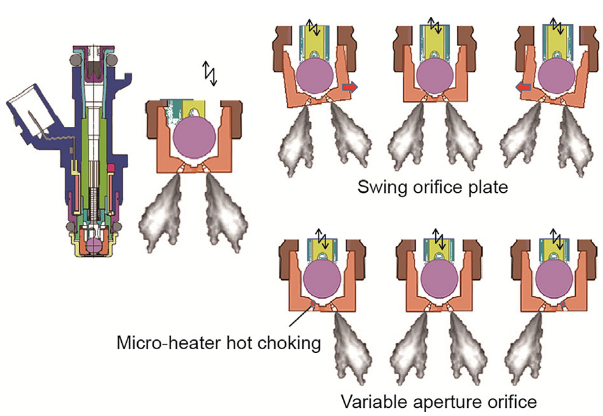


Fig. 15. The conceptual ideas of orifice plate swinging and nozzle hole choking.

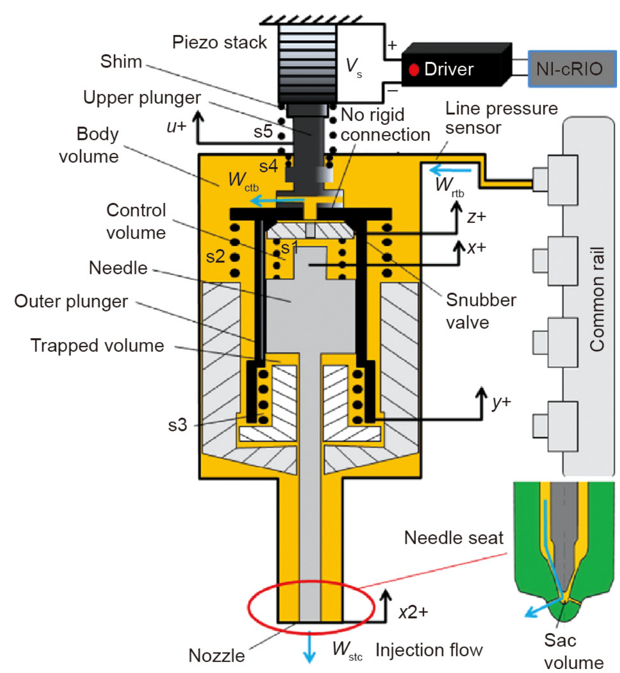


Fig. 16. Injector schematic of 0.8 ms injection rate control by means of the piezo stack voltage [15].

4.4. Flash boiling

Flash boiling of liquid fuel is observed when superheated fuel is injected [25–28]. Even though the fuel temperature is not particularly high, a superheated fuel condition also occurs when fuel is injected into a cylinder in which the in-cylinder pressure is lower than the saturated pressure of the fuel. Flash boiling involves a sudden phase change from liquid to vapor. When the superheated temperature is not particularly high, partial flash boiling is induced at the outlet of the injector, where the fuel static pressure falls from the injection pressure to below the saturated pressure of the fuel. Fig. 26 [25] shows a typical example of a partial flash boiling spray. Compared with normal spray, the spray angle increases and the tip penetration decreases. It is notable that part of the injected fuel suddenly changes to the vapor phase while the other part remains in the liquid phase as a spray. This results from the heat balance of the excess enthalpy of the injected fuel and the latent heat of the flash boiling part of the injected fuel. Quick

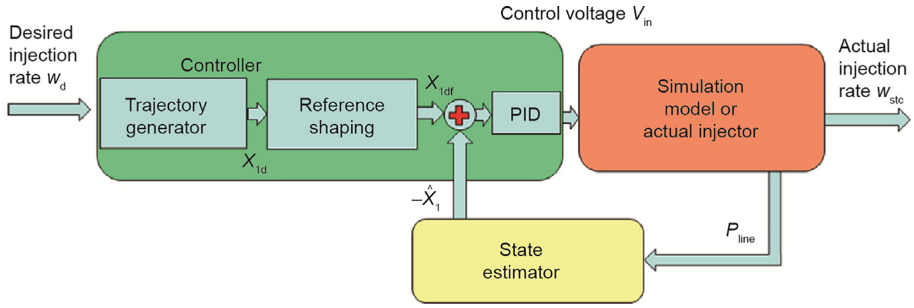


Fig. 17. PID control block diagram [8].

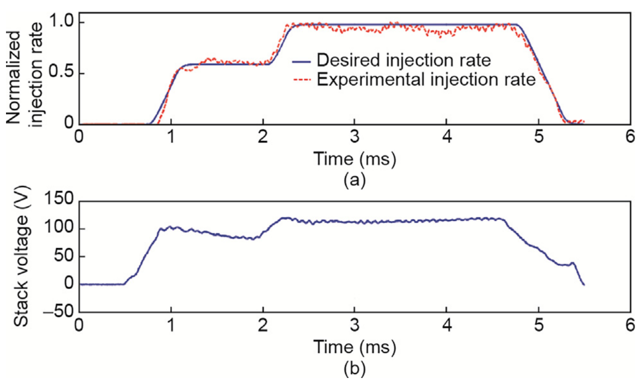


Fig. 18. Experimental (a) normalized injection rate and (b) stack voltage at 600 bar (1 bar = 0.1 MPa) line pressure, 60% toe height (dynamic surface control) [15].

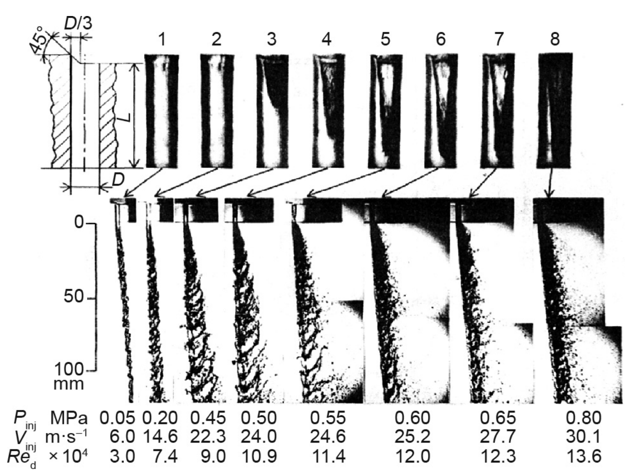


Fig. 19. Atomization process and jet angle of a high-speed water jet injected from a nozzle with an asymmetric inlet. V_{inj}: injection velocity; Re_d: Reynold number by nozzle diameter base [19].

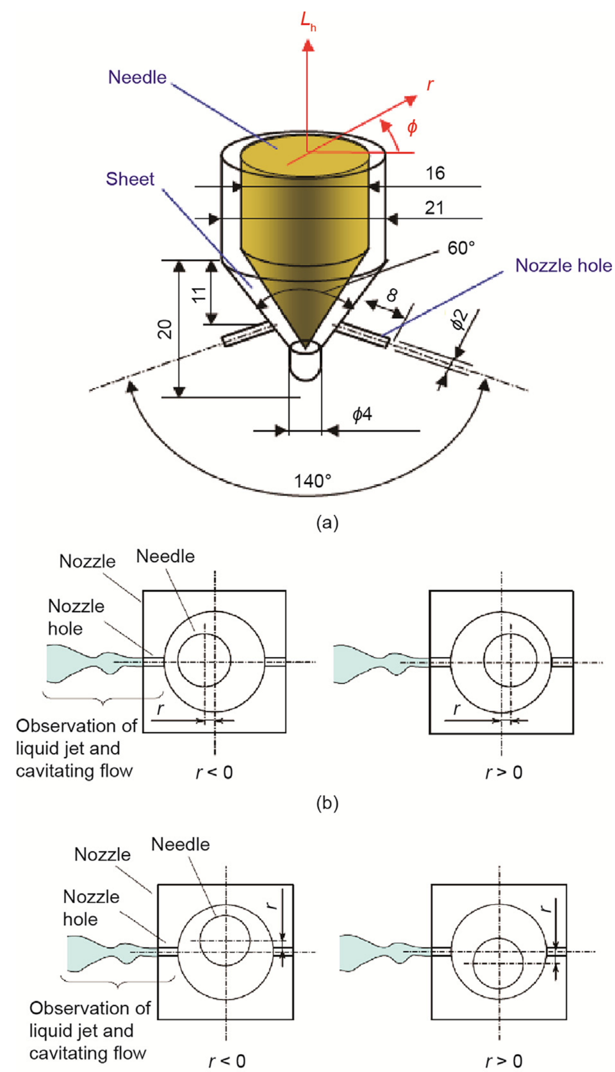


Fig. 20. Diesel injector with an eccentric needle (10-times-enlarged water-injection injector model) [20]. (a) Schematic illustration of the injector; (b) radial location of needle at azimuthal angle of 0°; (c) radial location of needle at azimuthal angle of 90°. Unit: mm.

evaporation of the whole spray and a wide angle of the spray/vapor plume are apparent features of a flash boiling spray.

When the fuel is injected through a multi-hole injector such as a DISI injector, the wide angle of the spray plume results in interaction among neighboring spray plumes. Fig. 27 [26] summarizes the results of a flash boiling spray. When the surrounding pressure decreases to the under-saturated pressure of the fuel, flash boiling partially starts, resulting in widening of the spray angle. As the surrounding pressure decreases, the spray angle increases and eventually induces interactions between the neighboring spray plumes. This leads to a decrease in the plume-to-plume distance; finally, collapsing of the multi-plume configuration occurs.

A wide spray angle and quick evaporation of the flash boiling spray is suitable for mixture formation. However, quick evaporation means a quick loss of the penetration momentum, and prevents homogeneous dispersion of the fuel vapor into the whole cylinder. In particular, when collapsing is induced by strong flash boiling, the fuel vapor concentration in a center zone of the

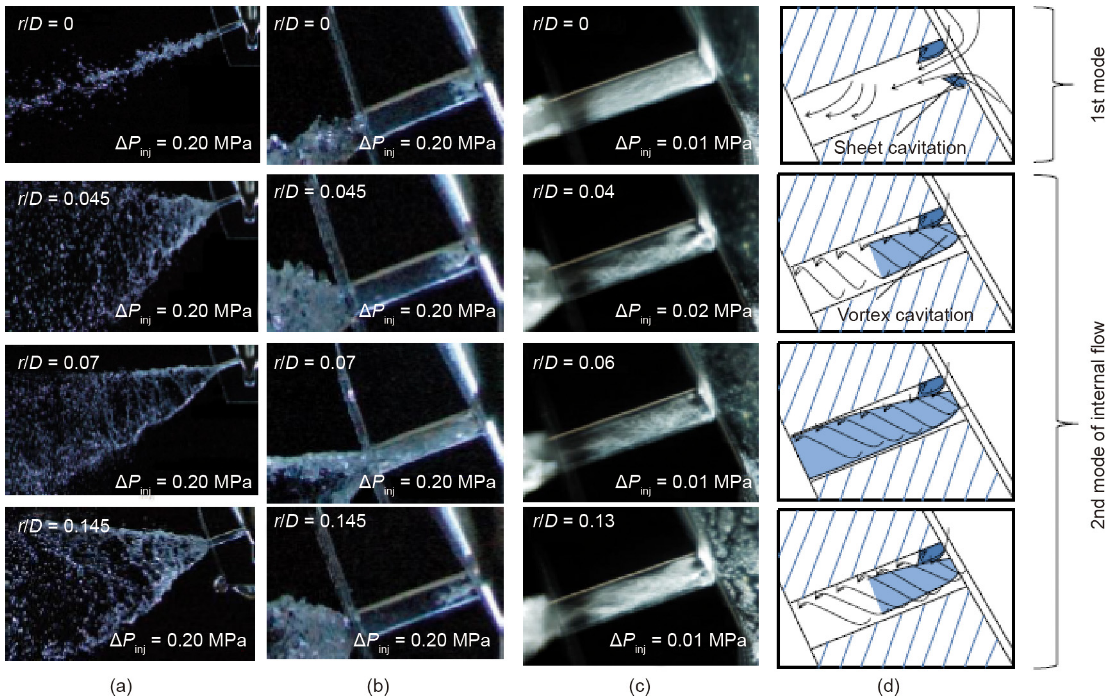
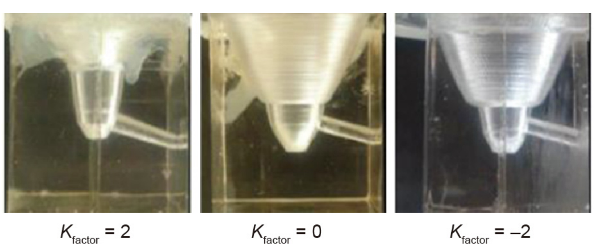


Fig. 21. Effect of the radial location of an eccentric needle on (a) spray, (b) cavitation, (c) stream lines, and (d) bubble flow pattern (ΔP_{inj} = 0.20 MPa, L_{h} = 0.5 mm, θ = 90°) [20].



Nozzle type	D_{in} (mm)	D_{o} (mm)	K_{factor}
Convergent nozzle	2.0	1.8	2
Cylindrical nozzle	1.8	1.8	0
Divergent nozzle	1.6	1.8	–2

$$K_{\text{factor}} = \frac{D_{\text{in}}\,(\mu\text{m}) - D_{\text{o}}\,(\mu\text{m})}{100\,(\mu\text{m})},\quad \text{CN} = \frac{P_{\text{inj}} - P_{\text{g}}}{P_{\text{g}} - P_{\text{v}}} = \frac{1}{Ca_3}$$

Fig. 22. Convergent and divergent diesel nozzles [21]. D_{in}: diameter of the needle inlet; D_{o}: diameter of the needle outlet.

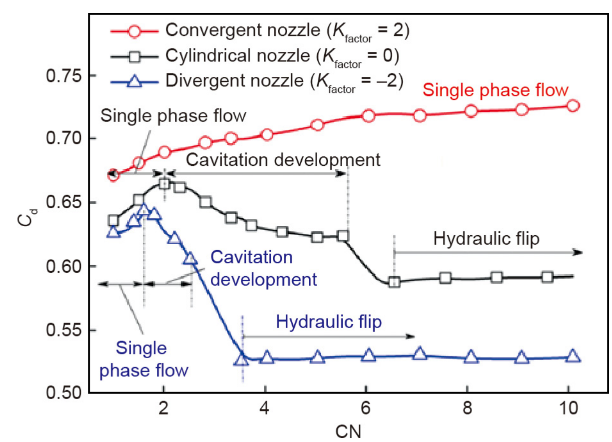
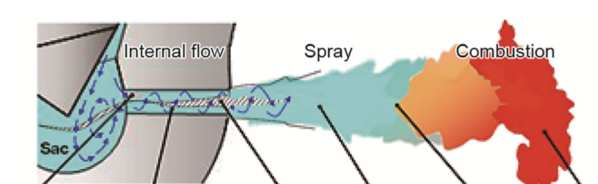


Fig. 23. Effect of nozzle geometry on discharge coefficient [21]. C_{d}: discharge coefficient.

multi-hole spray remains high. Fig. 28 shows a conceptual application of collapsing fuel spray to attain an axisymmetric stratified fuel charge system. In this case, ignition is forced at the stoichiometric fuel vapor zone in the center, and flame propagates to the lean mixture located near the cylinder wall. This setup might prevent end-gas knocking because no rich mixture exists near the wall. Here, a high-response micro heater is needed in order to control the fuel temperature.

4.5. Spray-to-spray interaction

There are three possible cases of spray-to-spray interaction [29]: liquid jet to liquid jet interaction and secondary atomization at the impingement point, which is well known; the interaction of fully developed sprays; and liquid jet to fully developed spray interaction.



Film cavitation	Nozzle flow	String cavitation	Spray angle	Ignition position	Luminous flame
Narrow area	Vortex flow over sac volume	Strong	Wide	Near nozzle	Wide
Wide area	Turbulence by cavitation with weak vortex	Weak	Narrow	Far nozzle	Narrow

Fig. 24. String cavitation effect on diesel combustion [24].

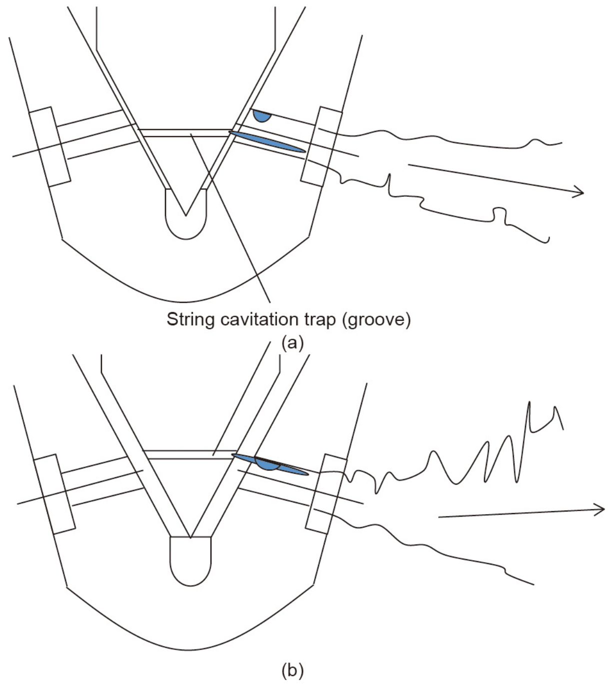


Fig. 25. A conceptual idea of string cavitation control by means of a needle groove. (a) A groove is cut on the surface of the needle; (b) the position of the string cavitation moves to the upper side.

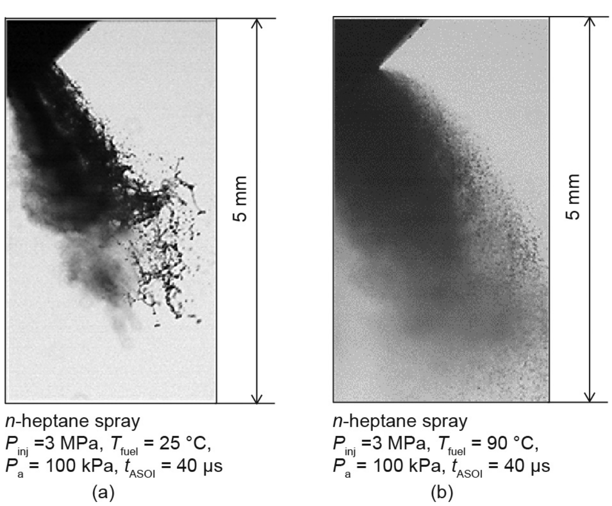


Fig. 26. Normal and flash boiling sprays [25]. (a) Liquid spray; (b) flash boiling spray. T_{fuel}: temperature of fuel.

The 90° and 60° impingements of fully developed sprays are shown in Fig. 29 [29]. The fundamental behavior of the fully developed spray plume is similar to that of a gaseous plume, and the impingement behavior of these sprays is easily imaged based on a fluid dynamics analysis of the gaseous jet. Two impingement sprays are gathered together. The spray penetration direction changes from the original direction to a newly developing direction, and a swelled spray is newly developed after impingement. The spray does not penetrate in the original direction, and the penetration length decreases due to the loss of momentum. The velocity and momentum component normal to the impingement interface is dispersed as turbulence. The newly developed spray then swells and the penetration momentum decreases. Fig. 30 shows an example of liquid jet to fully developed spray. In this situation, the penetration direction of the liquid jet is maintained after impingement. In other words, the liquid jet can control the penetration direction of the fully developed spray.

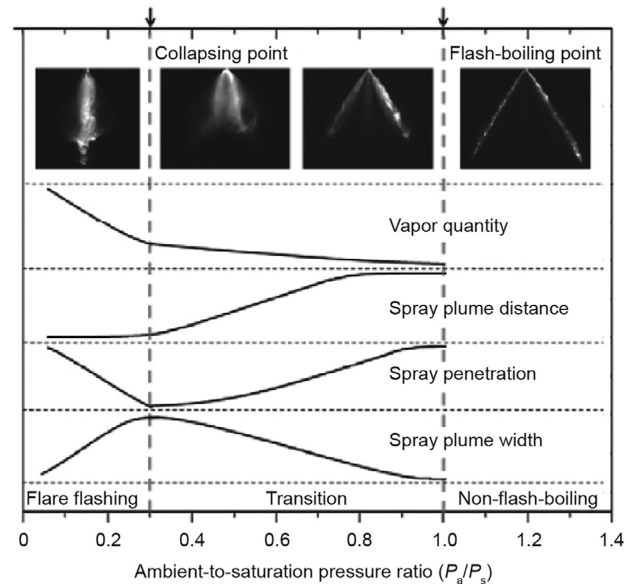


Fig. 27. Characteristics of a flash boiling alcohol spray [26].

The principal effect of spray mutual interaction is the momentum loss of the original sprays. Many applications of this effect can be considered. Fig. 31 shows two applications proposed here. Fig. 31(a) depicts short-penetration diesel spray formation. This application requires not only spray-to-spray interaction technology, but also additional turn-back spray technology, which will be mentioned later in this paper. Using this concept, wall impingement that forms undesirable fuel film on the wall could be avoided. Fig. 31(b) depicts a stratified fuel charge for a GDI engine. Spray-to-spray interaction technology is useful for the formation of spatially stagnated spray.

4.6. Spray-to-wall interaction

Fig. 32 shows the typical behavior of a diesel spray injected into a modeled transparency combustion cavity. The cavity diameter is 60 mm. The fuel spray is injected into a high-pressure cavity (1.5 MPa) by means of a common rail injection system with 90 MPa. Here, three spray plumes formed by the six-hole injector are illuminated, and another three spray plumes are cut by means of elimination pipes in order to maintain a clean image. Due to the high speed and high momentum of the diesel spray, the main part of the spray is impinging onto the cavity wall. This results in more important behavior of the mixture formation than of the non-impingement spray.

The impingement behavior of the spray depends greatly on the impingement angle, as shown in Fig. 8. However, much of this information is concentrated into the wall-spreading spray of normal impingement, because all of the typical behavior of the impingement spray is echoed in the behavior of a normal impingement spray. The photo depicts the laterally spreading spray, fuel film on the cavity surface, mutual interaction by neighboring spray, and turn-back spray along the bottom of the cavity.

When an impingement wall has a recess at the impingement point of the spray, the spray behavior after impingement is different from that in the case of flat wall impingement [30]. Fig. 33 [30] shows examples of spray reflection from the recessed wall. In this case, the diameter of the recessed hole becomes the

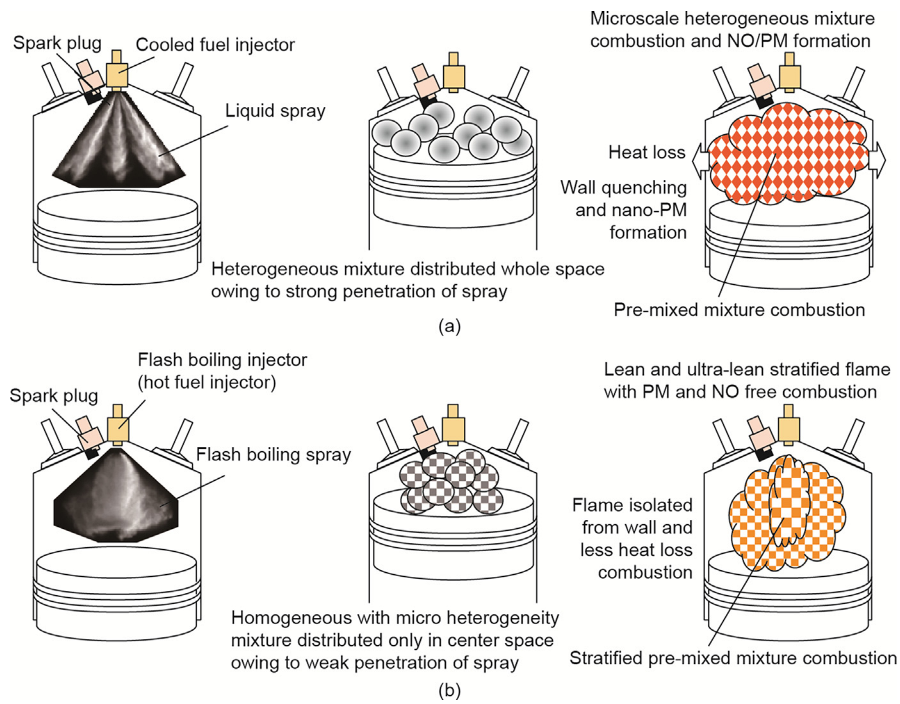


Fig. 28. A conceptual application of flash boiling gasoline injection [26]. (a) Conventional gasoline spray combustion; (b) flash boiling gasoline spray combustion.

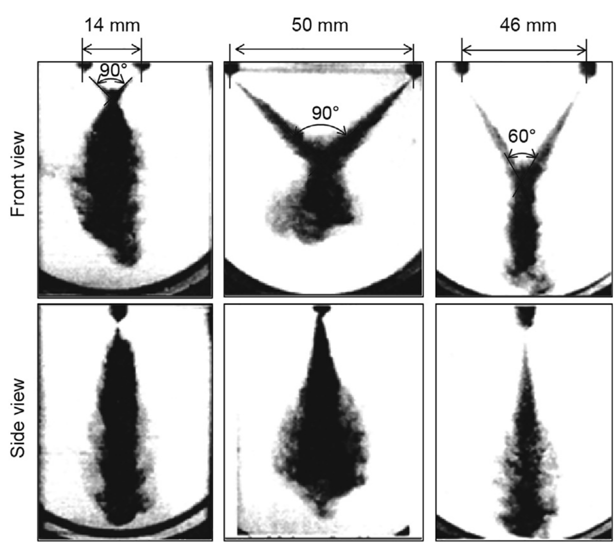


Fig. 29. Spray-to-spray impingement [29].

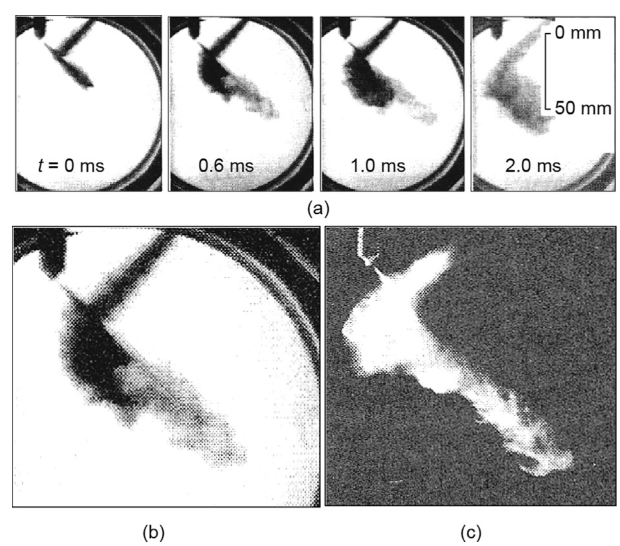


Fig. 30. Jet-to-spray impingement [29]. (a) Shadowgraph from $t = 0$ ms to $t = 2.0$ ms (impingement angle: $\theta = 90°$, impingement point: $S_{z1} = 15$ mm, $S_{z2} = 45$ mm); (b) enlarged shadowgraph and (c) tomographic view with laser sheet at $t = 0.6$ ms.

main parameter determining the spray reflection. When the recess diameter is larger than the spray width before impingement, the spray is reflected from the wall, and lateral expansion is suppressed. In other words, turn-back spray is formed. When the recess diameter is smaller than the spray width, no obvious effect of the recess is observed. This finding suggests that the small-scale surface roughness of the impingement wall has no effect on the apparent behavior of the impingement spray. On the other hand, there is a possibility that spray reflection can be promoted by a curved surface.

Fuel film may form on a wall. To determine the wall film movement, a bottom view observation setup has been used, as shown in Fig. 34 [31]. The impingement wall of this setup is a glass plate with a width of 40 mm, where a part of the impingement diesel spray spreads beyond the side periphery of the glass plate. In the

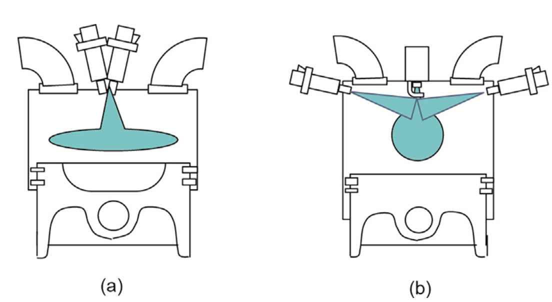


Fig. 31. A conceptual application of spray-to-spray interaction for homogeneous and stratified fuel charges. Wall free stagnated spray for (a) homogeneous charge compression ignition (HCCI) combustion and (b) GDI combustion.

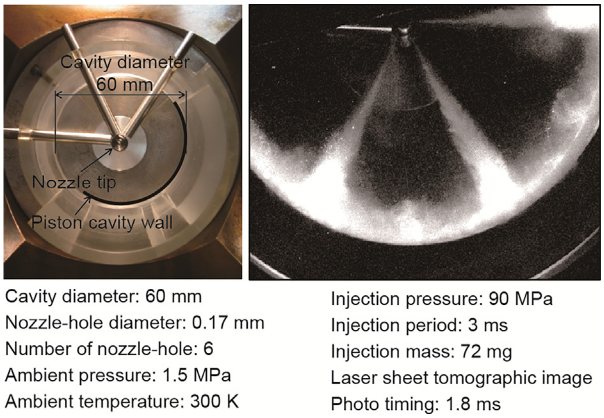


Fig. 32. Behavior of diesel spray impinging onto a cavity wall.

photos labeled t = 1.10 and 1.66 ms, a trace of impingement spray or thick fuel film can be clearly observed around the impingement center; its diameter corresponds with the diameter of the diesel spray before impingement. Around this thick trace, a thin flared trace appears. At t = 2.35 ms, this flared trace can be observed not only on the glass plate, but also outside of it. There is no difference between the flared traces on the glass plate and those outside. Since the movement of the adhered fuel film is restricted by the high viscosity of the liquid fuel, it is doubtful that the flared trace is an adhered fuel film on the glass plate. There is a possibility that the fuel film or dense spray is slipping on the glass. This spray behavior suggests many implications regarding the control of flame development, as explained in Fig. 35.

Another important motion of the impingement spray in a practical combustion cavity is backward or returning spread from the impingement wall in the nozzle direction [32]. Fig. 36 [32] depicts the typical flow in a two-dimensional (2D) model cavity. After impingement, the spray flows down to the bottom of the cavity; then, it returns in the nozzle direction. This type of movement is called a vertical vortex. The photos show a kind of turn-back spray; however, the turn-back pattern is different from that induced by the recessed wall shown in Fig. 33. Instead, the pattern looks like a wall-guided turn-back. It can promote internal burned gas mixing (i.e., internal exhaust gas recirculation (EGR)) to the spray when combustion occurs in the vertical vortex spray. The spray tip penetration after impingement and the intensity of the vertical vortex along the bottom wall can be changed by the configuration of the cavity.

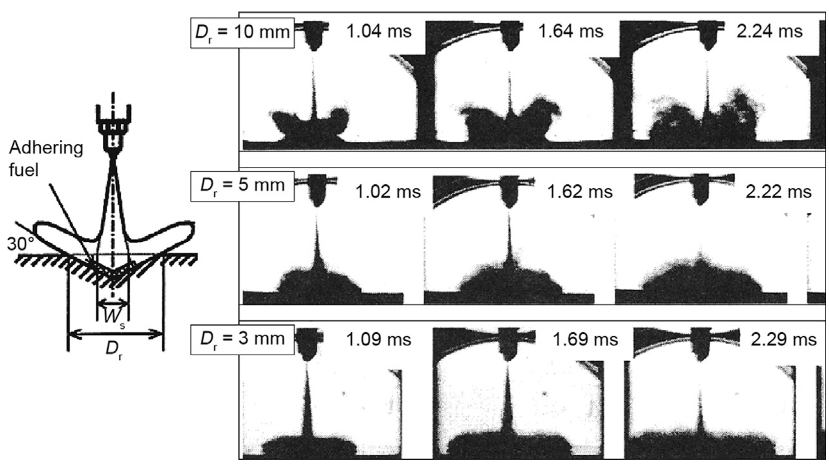


Fig. 33. Behavior of diesel spray impinging onto a recessed wall. Upper photo shows the large recess effect (D_r = 10 mm). Middle and lower photos are 5 mm and 3 mm recess cases [30].

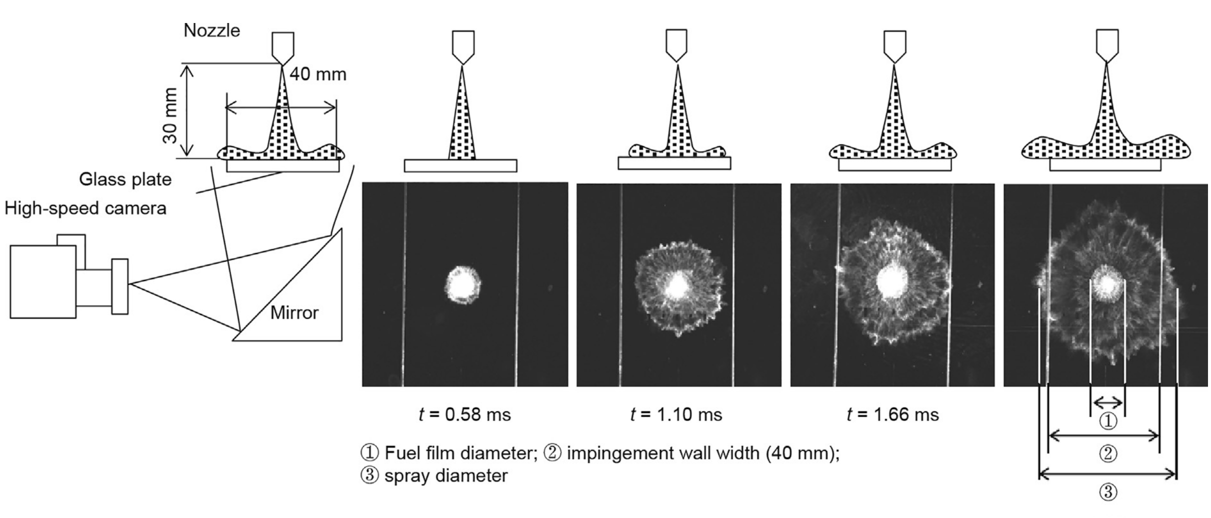


Fig. 34. Bottom views of wall-impinging spray, radially spread spray slipping on the wall, and fuel film stuck on the wall [31].

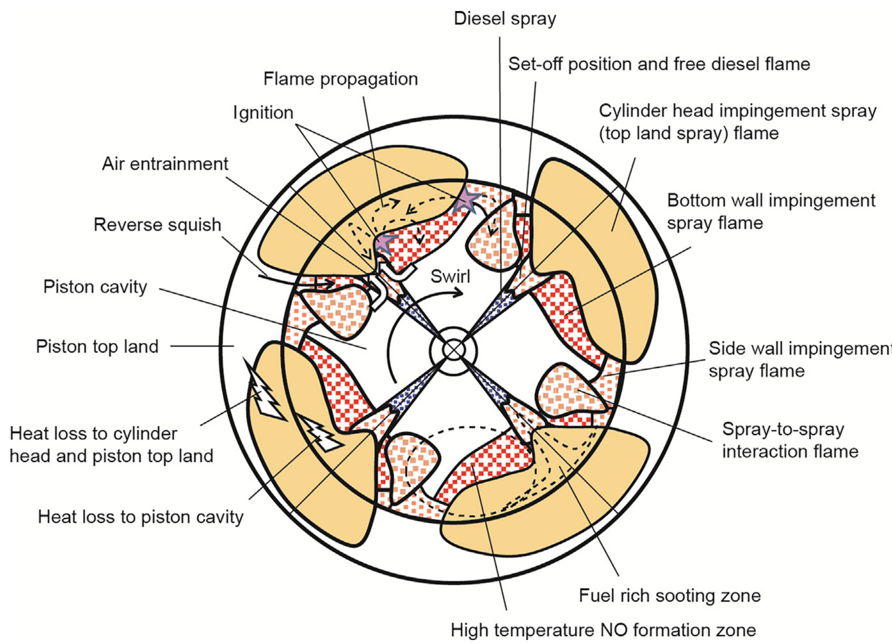


Fig. 35. Diesel spray combustion behavior in the cavity and on the top land of the piston.

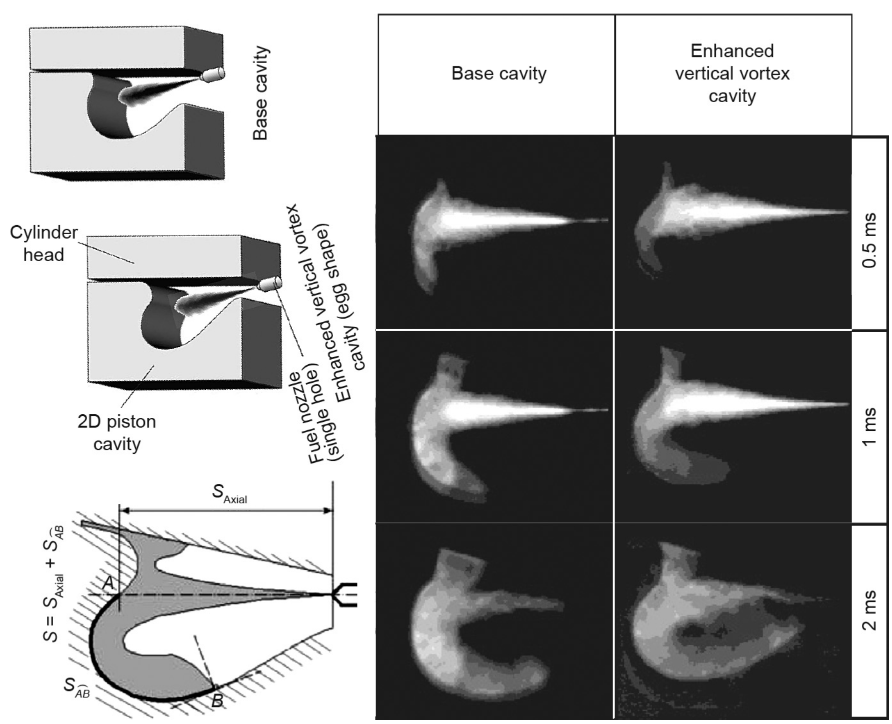


Fig. 36. Vertical vortex spray along the bottom wall of the combustion cavity (modified from Ref. [32]).

Fig. 26 illustrates the spray combustion in a direct-injection (DI) diesel engine. Two possible ignition positions, the set-off position of the flame, and five kinds of diesel spray flame are indicated here. The five flames are:

(1) Free diesel flame before wall impingement;

(2) Side wall impingement spray flame;

(3) Bottom wall impingement spray flame (turn-back spray flame);

(4) Spray-to-spray interaction flame (mutual interaction flame);

(5) Cylinder head impingement spray flame (top land spill-over flame).

It is very difficult to identify these flames separately in direct combustion photographs obtained from an optical engine; however, they can easily be separated in an analysis of numerical simulation results. Each flame contributes heat release, heat loss through the wall, and undesirable emission formations. However, the contribution manner is different for each flame. The development of each flame is strongly related to the spatial movement of the fuel spray. Thus, spray attitude control or spray dispersion control in the combustion space becomes a key process in combustion design.

When a diesel spray develops along a wall surface, deviated development occurs due to the Coanda effect of the flow [33].

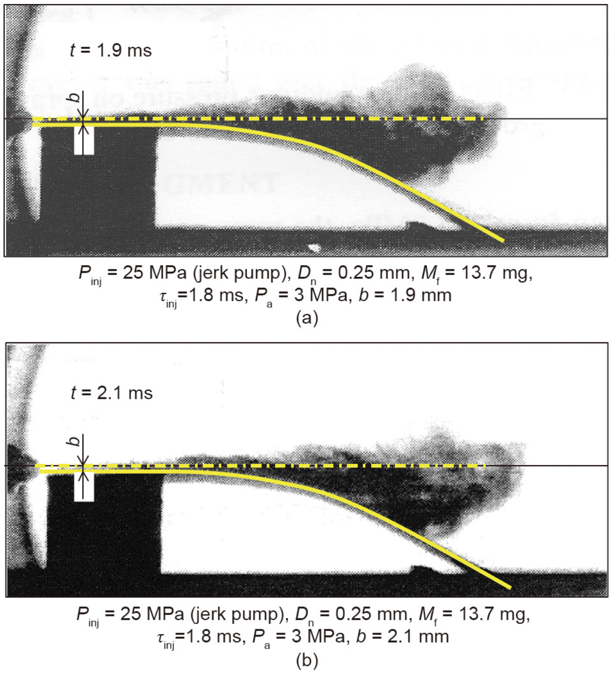


Fig. 37. Diesel spray with the (a) weak and (b) strong Coanda effect. τ_{inj}: injection duration [33].

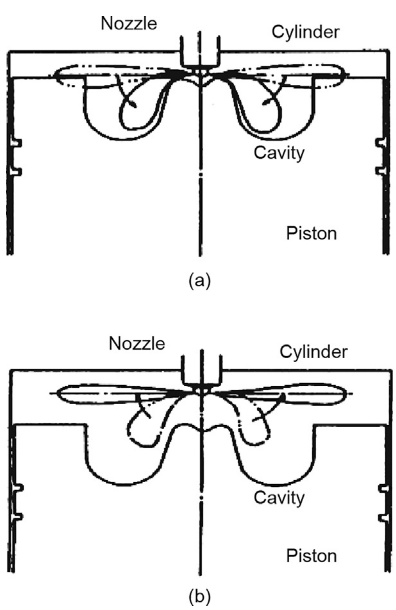


Fig. 38. The conceptual idea of diesel spray controlled by the Coanda effect of the piston surface [33]. (a) Spray with the Coanda effect; (b) free spray.

Fig. 37 [33] provides typical evidence of this effect, as observed in the spray development on a curved surface. When the spray is injected along a curved wall, the spray trajectory is deviated in the wall direction by the force of the Coanda effect. It is considered that the bulk movement of the spray is similar to a gaseous jet; thus, the spray movement can be controlled in numerous ways using the aerodynamic effect of the wall. Fig. 38 [33] illustrates the conceptual idea of spray attitude control by means of the Coanda effect. Here, adjustments in the injection timing result in the on–off control of the Coanda effect. In this way, spray dispersion in the bottom direction could be obtained by the Coanda effect, whereas top land dispersion of the fuel spray could be promoted when the Coanda effect is not induced.

4.7. Air flow

Air flows such as swirl, squish, and tumble have well-known effects on spray dispersion. Many trials have been done on the effective utilization of air flow. Detailed descriptions of these effects can be found in the literature; however, they are not within the scope of this paper and are thus not included here. The combination of a smart injector and controlled air flow will greatly advance improvements in engine combustion.

5. Conclusion

The ICE requires further development in order to fill the role of the main power source of transportation vehicles. Many kinds of improvement have been attempted for cutting-edge engine technologies. However, these technological improvements will stagnate in the near future because most engine technologies are classified as mature technologies. In order to break through this stagnation in technological development, new ideas and new technologies from other fields of technology must be incorporated into the field of engine technology.

As a first step in this endeavor, this article discusses the possibility of active spray attitude control for future fuel spray combustion technology in smart compact ICEs. However, many new technologies are required in order to achieve this aim. For example, nozzle geometry and cavitation control during the injection period need a high-response micro actuator. Furthermore, MEMS technology is one candidate for a breakthrough technology that should be incorporated into the field of engine technology.

Artificial spray attitude control is an attractive concept for a breakthrough technology that is relevant to the smart injector. This perspective review reports some conceptual ideas on this topic, but does not explain the technologies required to achieve them nor discuss expected improvements. In order to develop practical breakthrough technologies, new technologies must be surveyed and young engineers and researchers must be fostered to meet this challenge.

Acknowledgements

This perspective review summarizes this author's long period of research work under old supervisors and was developed with the help of research colleagues. This author is sincerely grateful.

References

[1] Findings and recommendations. Summary of major findings [Internet]. Seattle: The Allen Institute for Artificial Intelligence; [cited 2019 Apr 25]. Available from: https://www.semanticscholar.org/paper/1.0-Findings-and-Recommendations-11.1-Summary-of/6c1eb848e832847eff7de73a59e8568e4d7f707e/figure/3.
[2] Arai M. Physics behind diesel spray and its combustion. Saarbrucken: Lambert Academic Publishing; 2016. p. 299–334.
[3] Arai M. Physics behind diesel sprays. In: Proceedings of the 12th International Conference on Liquid Atomization and Spray Systems; 2012 Sep 5; Heidelberg, Germany; 2012. p. 1–18.
[4] Noboru U. How far extreme-high pressure fuel injection have an effect on diesel combustion improvement? Mechan Engineer Cong 2014:W071003. Japanese.
[5] Agarwal AK, Singh AP, Maurya RK, Shukla PC, Dhar A, Srivastava DK. Combustion characteristics of a common rail direct injection engine using different fuel injection strategies. Int J Therm Sci 2018;134:475–84.
[6] Payri R, Salvador FJ, Martí-Aldaraví P, Vaquerizo D. ECN spray G external spray visualization and spray collapse description through penetration and morphology analysis. Appl Therm Eng 2017;112:304–16.
[7] SAE Standard: J2715_200703. Gasoline fuel injector spray measurement and characterization. Pittsburgh: SAE International; 2007.

[8] Singh AK, Lanjewar AM, Rehman A. Direct fuel injection system in gasoline engine—a review. Int J Innovat Technol Explor Engineer 2014;4(4): 21–8.

[9] Ebara T, Amagai K, Arai M. Image analysis of a diesel spray impinging on a wall. In: Proceedings of the 7th International Conference on Liquid Atomization and Spray systems; 1997 Aug 18–22; Seoul, Korea; 1997. p. 527–44.

[10] Leng X, Jin Y, He Z, Long W, Nishida K. Numerical study of the internal flow and initial mixing of diesel injector nozzles with V-type intersecting holes. Fuel 2017;197:31–41.

[11] Leng X, Jin Y, He Z, Wang Q, Li M, Long W. Effects of V-type intersecting hole on the internal and near field flow dynamics of pressure atomizer nozzles. Int J Therm Sci 2018;130:183–91.

[12] Yoshimura K, Hosaka T, Yasukawa Y, Ishii E, Ogura K. Effect of off-axis valve motion on spray shape of fuel injection. In: Proceedings of the 26th Symposium (ILASS-Japan) Atomization; 2017 Dec 19–20; Tokyo, Japan; 2017.

[13] Morgan TB, Bothell JK, Li D, Heindel TJ, Aliseda A, Machicoane N, et al. Feasibility of monochromatic X-ray imaging of the near-field region of an airblast atomizer. In: Proceedings of the 14th Triennial International Conference on Liquid Atomization and Spray Systems; 2018 Jul 22–26; Chicago, IL, USA; 2018.

[14] Matusik KE, Sforzo BA, Seong HJ, Duke DJ, Kastengren AL, Ilavsky J, et al. X-ray measurements of fuel spray specific surface area and sauter mean diameter or cavitating and non-cavitating diesel sprays. In: Proceedings of the 14th Triennial International Conference on Liquid Atomization and Spray Systems; 2018 Jul 22–26; Chicago, IL, USA; 2018.

[15] Torelli R, Sforzo BA, Matusik KE, Kastengren AL, Fezzaa K, Powell CP, et al. Investigation of shot-to-shot variability during short injections. In: Proceedings of the 14th Triennial International Conference on Liquid Atomization and Spray Systems; 2018 Jul 22–26; Chicago, IL, USA; 2018.

[16] Le D, Pietrzak BW, Shaver GM. Dynamic surface control of a piezoelectric fuel injector during rate shaping. Control Eng Pract 2014;30:12–26.

[17] Ferrari A, Novara C, Paolucci E, Vento O, Violante M, Zhang T. A new closed-loop control of the injected mass for a full exploitation of digital and continuous injection-rate shaping. Energy Convers Manage 2018;177:629–39.

[18] Payri R, Bracho G, Gimeno J, Bautista A. Rate of injection modelling for gasoline direct injectors. Energy Convers Manage 2018;166:424–32.

[19] Arai M, Shimizu M, Gakumasawa H, Hiroyasu H. Attitude of high speed liquid jet controlled by internal cavitation in a nozzle. In: Proceedings of the 6th International Conference on Liquid Atomization and Spray Systems; 1994 Jul 18–22; Rouen, France; 1994. p. 286–93.

[20] Oda T, Ohnishi K, Gohda Y, Sumi T, Ohsawa K. Internal flow visualization a large-scaled VCO diesel nozzle with eccentric needle. In: Proceedings of the 12th Triennial International Conference on Liquid Atomization and Spray Systems; 2012 Sep 2–6; Heidelberg, Germany; 2012.

[21] He Z. Visual experiment of cavitating flow in a real-size diesel injector nozzle and les modeling of cloud cavitation shedding. In: Proceedings of the 6th Engine Researchers Forum; 2015 Jul 24–26; Shanghai; China; 2015.

[22] He Z, Guo G, Tao X, Zhong W, Leng X, Wang Q. Study of the effect of nozzle hole shape on internal flow and spray characteristics. Int Commun Heat Mass Transf 2016;71:1–8.

[23] Zhang X, He Z, Wang Q, Tao X, Zhou Z, Xia X, et al. Effect of fuel temperature on cavitation flow inside vertical multi-hole nozzles and spray characteristics with different nozzle geometries. Exp Therm Fluid Sci 2018;91:374–87.

[24] Nakase Y. Visualization technology of spray and combustion. In: Proceedings of the 25th Internal Combustion Engine Symposium; 2014 Nov 26–28; Tsukuba, Japan; 2014.

[25] Xu M. Development of advanced laser diagnostics to investigate the unique atomization and vaporization processes of flash boiling sprays. In: Proceedings of the Gordon Research Conference, Laser Diagnostics in Combustion; 2013 Aug 11–16; Waterville Valley, NH, USA; 2013.

[26] Zeng W, Xu M, Zhang G, Zhang Y, Cleary D. Atomization and vaporization for flash-boiling multi-hole sprays with alcohol fuels. Fuel 2012;95:287–97.

[27] Wang Z, Dai X, Liu F, Li Z, Wu H. Breakup of fuel sprays under cavitating and flash boiling conditions. Appl Therm Eng 2018;143:22–33.

[28] Li T, Dong X, Hung DLS, Li X, Xu M. Analysis of evaporation characteristics and heat transfer for flash-boiling sprays. Int J Heat Mass Transfer 2018;127:244–54.

[29] Chiba T, Saito M, Arai M. Behavior of diesel sprays in various ways of inter-spray impingement. In: Proceedings of the ILASS-Asia 2000; 2000 Dec 17–22; Tsukuba, Japan; 2000.

[30] Ko K, Huh J, Arai M. Diesel spray behavior and adhering fuel on a recessed wall. SAE Technical Paper 2003:2003–01–1834.

[31] Ko K, Arai M. Diesel spray impinging on a flat wall. Part I: characteristics of adhered fuel film in an impingement diesel spray. At Sprays 2002;12(5–6): 737–52.

[32] Shimo D. Research on improvement of diesel combustion by controlling distributions of mixture concentration/temperature and ignition-heat release rate [dissertation]. Hiroshima: Hiroshima University; 2013. Japanese.

[33] Arai M, Amagai K, Ebara T. Attitude control of a diesel spray under the Coanda effect. SAE Technical Paper 1994:941923.