

A Review of Cavitation Phenomenon and Its Influence on the Spray Atomization in Diesel Injector Nozzles

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Abstract

In view of the combustion efficiency and emission performance, various new clean combustion modes put forward higher requirements for the performance of the fuel injection system, and the cavitating two-phase flow characteristics in the injector nozzle have a significant impact on the spray atomization and combustion performance. This article comprehensively discusses and summarizes the factors that affect cavitation and the effectiveness of cavitation, and presents the research status and existent problems under each factor. Among them, viscosity factors of diesel fuel are a hot research topic that researchers are passionate about, and physical properties of diesel fuel still have the value of further in-depth research. However, the importance of material surface factors ranks last since the nozzle material was determined. Establishing a more comprehensive cavitation-atomization model considering various factors is the focus of research on cavitation phenomena. The improved model can ultimately serve high combustion efficiency and great emission performance.

History

Received: 31 May 2023
 Revised: 09 Aug 2023
 Accepted: 04 Dec 2023
 e-Available: 15 Dec 2023

Keywords

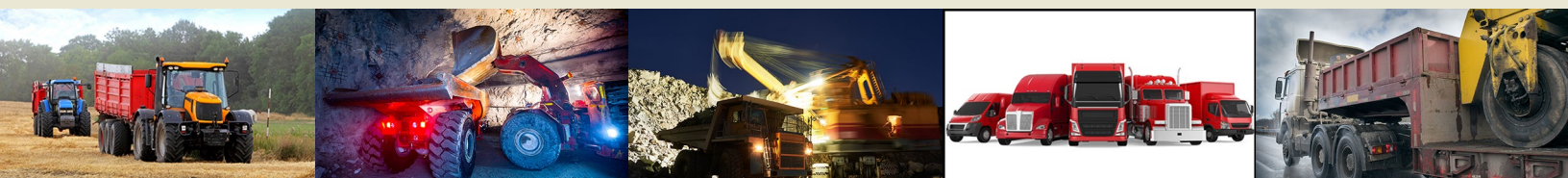
Diesel nozzle, Cavitating form, Geometry-induced cavitation, String cavitation, Spray atomization

Citation

Cao, T. and Qu, P., "A Review of Cavitation Phenomenon and Its Influence on the Spray Atomization in Diesel Injector Nozzles," *SAE Int. J. Commer. Veh.* 17(1):67-89, 2024, doi:10.4271/02-17-01-0005.

ISSN: 1946-391X
 e-ISSN: 1946-3928

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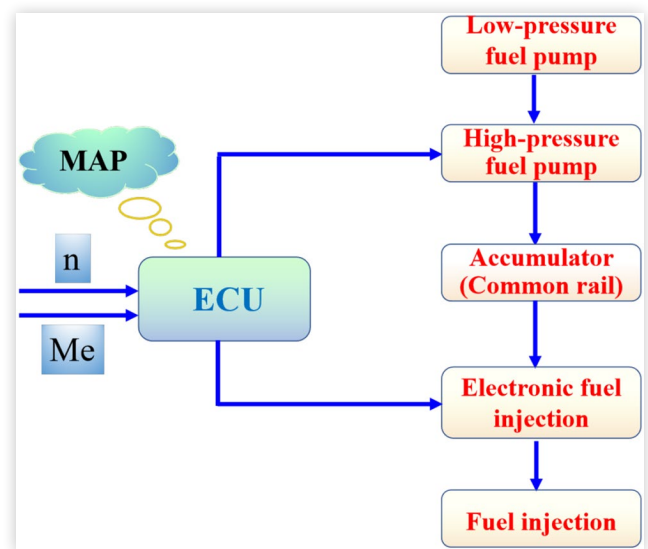


1. Introduction

Nowadays, cars have become a necessity of high-quality life with developing of the consumer level. Among them, conventionally fueled vehicles powered by internal combustion engines account for the majority, indicating that the automobile industry has a high dependence and demand for fossil fuels [1]. Excessive fossil fuels cause problems such as excessive carbon emissions, which runs counter to the goal of carbon neutrality set by countries around the world. And the internal combustion engine produces many harmful substances, such as carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter [2]. Therefore, the development of near-zero emission internal combustion engine has become a key research topic in order to cope with the more and more stringent emission regulations.

Internal combustion engine is a kind of thermal engine, which converts the heat energy released by the combustion of fuel into kinetic energy during the working process [3]. Common internal combustion engine is mainly divided into gasoline engine and diesel engine. Among them, the diesel engine has obvious advantages, such as high thermal efficiency and low fuel consumption. With the promotion of “energy-saving” and “environmental protection” concept, fuel economy and emissions cleanliness gradually become the primary factor to consider in the diesel engine design, and diesel fuel economy and pollutant emissions content is mainly affected by combustion characteristics in the cylinder [4]. Therefore, the combustion performance is enhanced through optimizing the diesel fuel system, thus reducing vehicle emissions. In this context, electronically controlled fuel injection technology has quietly emerged, gradually occupying the mainstream market through continuous improvement (Figure 1).

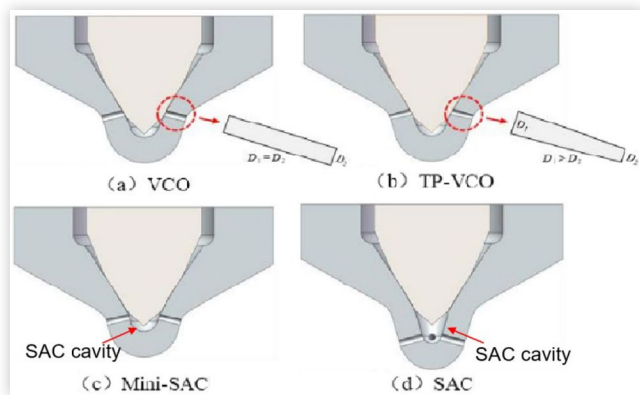
FIGURE 1 The schematic of electronic control injection system of diesel engine.



So far, the most advanced electronically controlled fuel injection system and electronically controlled high-pressure common-rail system have been developed by the Bosch company. The high-pressure common-rail system is equivalent to the “heart” and “brain” of the internal combustion engine, which realizes flexible control of injection timing, regularity, and duration as a landmark technology to improve fuel economy and reduce pollutant emissions [5]. China is the main application market of diesel engines in the world [6]. Wuxi Oil Pump Nozzle Research Institute in China has been committed to the development of common-rail fuel injection system, but there is still a certain gap in the performance and function compared with other advanced products from the Bosch company [7]. German Robert Bosch and Delphi Parker Electric have occupied the vast share of the domestic and foreign markets [8]. In addition, all high-efficiency combustion technology requires more accurate control of fuel injection and atomization characteristics, which also puts forward higher requirements for high-pressure common-rail fuel injection system. Therefore, it is necessary to carry out research on the internal flow of the diesel nozzle to achieve accurate control of the fuel flow and subsequent spray atomization, and provide theoretical guidance for further independent research on the common-rail fuel injection system.

The diesel nozzle is the most critical core component in the common-rail fuel injection system, and its position determines its role as a connecting link, which not only connects upstream fuel flow, but also determines the spray atomization in the cylinder [9]. When the needle valve is seated, the confined space around the needle valve head is called a pressure chamber, or a SAC cavity [Figure 2(c) and 2(d)]. According to the relative position of the nozzle and the head, the nozzle is divided into SAC cavity (area around needle tip) nozzle and VCO (valve covered orifice) nozzle, as shown in Figure 2(a) and 2(d). The current common nozzle structure is the combination of the above two nozzles, namely Mini-SAC nozzle [Figure 2(c)], which avoids the disadvantages of VCO nozzle and SAC cavity nozzle, has achieved remarkable results in efficient and clean energy. In addition, the tapered nozzle is beneficial to inhibit the geometry-induced cavitation and promote string cavitation, which develops the TP-VCO nozzle, as shown in Figure 2(b).

FIGURE 2 Four typical nozzle head structure.



The flow characteristics of the diesel fuel is the key index to evaluate the fuel circulation and the near-field spray atomization, which is related to the accuracy and stability of the fuel injection system. Cavitation phenomenon is the most common in two-phase flow in the nozzle, with the high Reynolds number and strong compression. The cavitating flow and spray atomization is related to the fuel economy and the emission of pollutants. It is helpful to study a cavitating two-phase flow and spray characteristics in the nozzle hole to improve fuel economy and reduce pollutant emission.

2. Introduction to Cavitation Phenomenon in Nozzles

2.1. Definition of Cavitation

Cavitation phenomenon is widely present in ship engineering, water conservancy machinery, environmental protection, aerospace, and medical [10]. The initial discovery of cavitation dates back to more than 100 years ago. In 1893, the British found that the navigation speed of destroyers had dropped unreasonably, and inspection confirmed pits, holes, and cracks in the propeller blades. At this point, human beings first intuitively realized the cavitation phenomenon, and began to pay attention to its impact in various industries. In daily life, the most familiar gas-liquid phase is in either gasified or liquefied form, and the two are mutually reversible. The cavitation inception to cavitation collapse can be considered to have experienced a transformation between gasification and liquefaction. Cavitation inception corresponds to the gasification, and cavitation collapse corresponds to the liquefaction.

The gasification contains two forms, evaporation and boiling. These two gasification methods are now compared with cavitation inception, so as to have a deeper understanding of cavitation phenomenon. Location of occurrence: The evaporation occurs on the surface of the liquid, while boiling and cavitation occur inside the liquid. Temperature range: The evaporation is constantly carried out at room temperature, and the boiling requires triggering conditions, that is, the liquid needs to reach the boiling point temperature. The cavitation inception is related to temperature but not absolute. Once other conditions such as injection pressure are met, cavitation can also be observed at room temperature. The intensity from high to low is boiling, cavitation, and evaporation, which can be seen from their respective occurrence conditions. In addition, the dynamic factors of all three are related to pressure and temperature, Table 1.

The pure liquid has no condition to produce cavitation, but there are always large and small cavitation cores inside the real liquid. Cavitation nucleus is divided into “active nucleus” and “inert nucleus,” the latter mainly contains dust and other small solid particles, which has no practical effect

TABLE 1 Differences among cavitation inception, evaporation, and boiling.

| Items | Cavitation inception | Evaporation | Boiling |
|----------------|-----------------------------------|----------------------|---------------------|
| Location | In the liquid (local area) | Liquid surface | In the liquid |
| Temperature | Room temperature/high temperature | No effect | Boiling temperature |
| Intensify | Medium | Low | High |
| Dynamic factor | Pressure | Pressure/temperature | Temperature |

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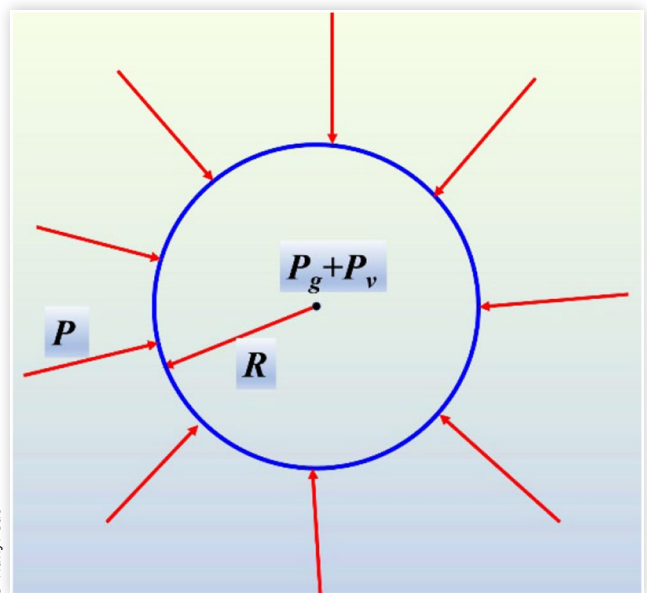
on cavitation primary. The “active core” mainly includes the free bubbles contained in the liquid, its source is external gas or the transformation of the liquid dissolved gas as the dissolved conditions change, and the free bubbles ultimately play a role in the cavitation inception. These free bubbles form gas-liquid interfaces inside the liquid, and the actual location of cavitation inception is precisely on the gas-liquid interface formed by these bubbles. It should be pointed out that cavitation is not composed of one or two cavitation bubbles, but rather the comprehensive results of many cavitation bubbles with the group bubbles. As shown in Figure 3, taking a single bubble as an example, a single bubble itself has an equilibrium theory, which follows the following equation:

$$P_g + P_v = P + \frac{2\tau}{R} \quad \text{Eq. (1)}$$

$$P_g = P_{g0} \left(\frac{R_0}{R} \right)^3 \quad \text{Eq. (2)}$$

$$P_v = P_v(T) \quad \text{Eq. (3)}$$

FIGURE 3 Balance diagram of single bubble.



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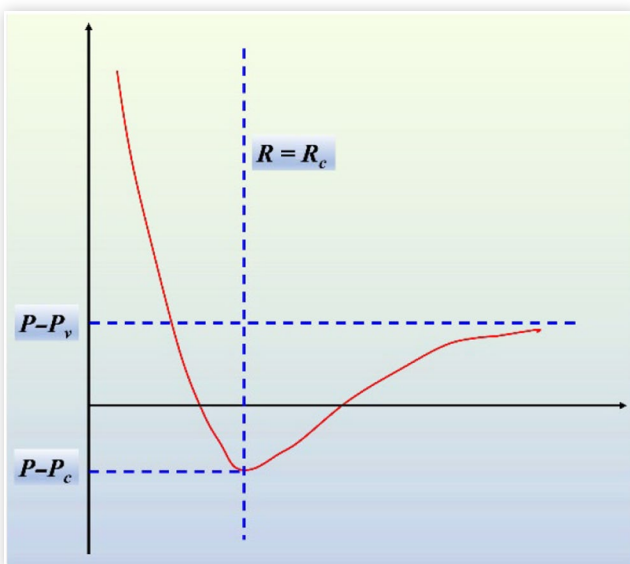
Among them, P_g is the internal pressure of the bubble, P_v is the saturated vapor pressure, P_{g0} is the initial pressure inside the bubble, T is the surface tension coefficient, R_0 is the initial size of the bubble, and P is the external pressure of the bubble.

Combining the three equations gives a $P = P(R)$ curve (Figure 4), and R_c is the critical radius. With the line $R = R_c$ as the limit, the left area means that the bubble is in equilibrium and keeps the same; the right area of the bubble means that the equilibrium is broken, and the bubble has the opportunity to grow and develop inside the liquid. What plays a leading role in this process is Equation 3, so an important prerequisite for the initial onset of cavitation is that the external pressure of the bubble is reduced to below the critical pressure of the bubble.

In short, the main points of cavitation inception are attributed to the following points:

1. The medium of cavitation is liquid phase and only liquid phase. It should be noted that the liquid phase refers to not only a liquid, but also a solid or gas liquefied into a liquid phase;
2. The cavitation phenomenon is essentially a phase transition, which is a change between the liquid and its steam. The bubbles are not a cavitation phenomenon that shrink due to external pressure changes or dissolution;
3. Compared with boiling phenomenon, the dynamic factor generated by cavitation is the result of changes in fluid dynamics parameters (pressure reduction in local areas caused by fluid flow), while boiling phenomenon is the result of changes in thermodynamic parameters;
4. The occurrence of local areas is a unique feature of cavitation phenomenon. Due to the difference of pressure gradient, only a small part of areas may occur and its adjacent areas are completely unaffected;

FIGURE 4 Equilibrium curve of single bubble.



5. The phenomenon of cavitation is a process that undergoes a series of state changes from inception to development, and then to collapse.

In summary, the definition of cavitation is given: the phase transition between liquid and steam occurs in a local region of the fluid under the influence of fluid dynamics parameters, and it includes the phase transition between gas and liquid, as well as the phase transition between liquid and gas.

2.2. The Three Elements and Judging Methods

The three elements of cavitation inception are cavitating nucleus, low-pressure area, and timescale, as shown in Figure 5.

The cavitating nucleus is a prerequisite for cavitation phenomenon. The tensile strength is theoretically between -132 MPa and 1400 MPa in a pure fluid without a cavitating nucleus, so it is usually not “fractured” to provide a prerequisite for cavitation inception. In the actual fluid, there must be “weaknesses” that make their own tensile strength reduce significantly. These “weaknesses” are caused by the so-called cavitating nucleus [1]. If the cavitating nucleus is the primary internal cause of cavitation, then the low-pressure area is the external cause of cavitation. The cavitating nucleus only continues to grow and develop when there is a low-pressure area in its space, and even undergo a liquid to gas phase transition after exceeding the critical radius of cavitation occurrence, which is cavitation inception. Therefore, cavitation inception demands a certain time of low pressure, so that the vacuoles (bubbles that dissolve inside the fuel) has enough time to grow beyond the critical radius. Therefore, cavitation inception needs a certain amount of low-pressure timescale

FIGURE 5 Three elements of cavitation inception.

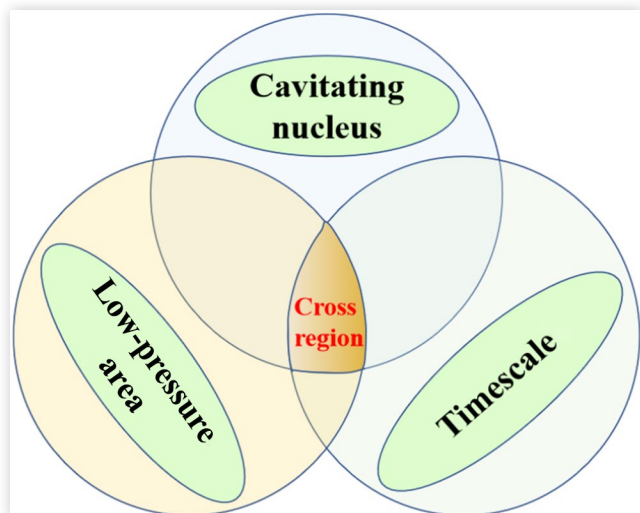
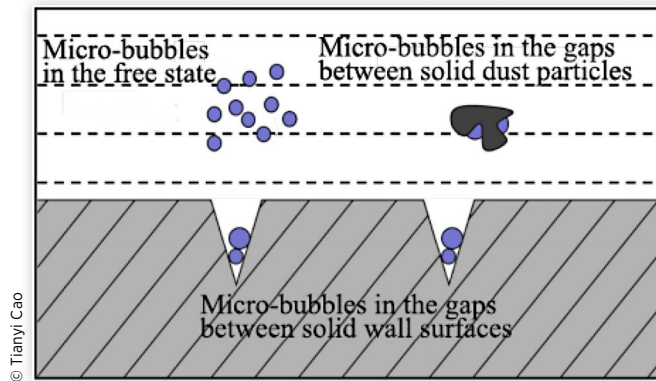


FIGURE 6 Existing form of non-condensation gas in liquid.

to allow the vacuoles to have enough time to grow beyond the critical radius state, which is showed as “cross region” in Figure 5. Otherwise, if the volume of bubble simply increases under pressure difference without the liquid–gas phase transition, it cannot be considered as cavitation inception.

Cavitation nuclei are relatively extensive in liquids, including dissolved gases and charged ions, as well as dust particles or microorganisms. However, the main factor is the non-condensation gas in the liquid that has a practical effect on cavitation inception [12]. As shown in Figure 6, non-condensation gas mainly exist in three forms: micro-bubbles in the free state, micro-bubbles in the gaps between solid dust particles, and micro-bubbles in the gaps between solid wall surfaces. When the low-pressure zone and low-pressure action time are met, cavitation inception occurs based on these micro-bubbles. Among them, undissolved single bubbles and aerated bubbles belong to a type of free micro-bubbles and play the role of cavitation nuclei.

The change in pressure field causes growing difference of gas nuclei, thereby affecting the inception and development of different cavitation forms. For string cavitation, the low-pressure region is inside the vortex, and the lowest pressure position is at the center of the vortex core. The vortex flow field where the string cavitation occurs promotes the precipitation of dissolved gases in the fuel, transforming them into free gases. Subsequently, free gas is collected at the center of the vortex. In addition, the unique role of the vortex flow field gathers the gas core inside the vortex, increasing the action time of the gas core at low pressure, and thus enabling the inception and development of string cavitation. For geometry-induced cavitation, the low-pressure region is located in the disturbance region at the wall, and the lowest pressure position

is located on the wall. Free gas is easily carried out of the nozzle by upstream flow, significantly shortening the low-pressure action time. At the same time, there is also a force in the flow field near the wall that pushes the gas core outward. The schematic of cavitation inception with two forms is shown in Figure 7. Therefore, a thorough understanding of the prerequisites for cavitation inception under two different cavitation forms is necessary, which is beneficial for analyzing and understanding the various changes in cavitation forms under different operating conditions.

The change in flow coefficient is used to determine the moment of cavitation inception [13]. In the single-phase flow stage, as the injection pressure increases, the flow coefficient slightly increases linearly. However, when the injection pressure increases to the point where cavitation inception occurs in the nozzle, the effective flow area of the fuel decreases, and the flow coefficient decreases conversely. As a result, the curve of flow coefficient with the injection pressure shows a significant turning point. The critical cavitation number corresponding to this turning point is usually used as a method to determine cavitation inception. This method is not limited to a certain form of cavitation (as long as cavitation occurs, the flow coefficient changes). Therefore, most research in this field uses the judgment method to determine the two cavitating forms, geometry-induced cavitation and string cavitation.

2.3. Classification of Cavitation Form

The appearance presented by cavitation phenomenon are usually referred to as cavitation form, which exhibits significant differences in cavitation morphology under different fuel operating conditions and developing stages. Cavitation phenomenon often occurs in liquid with high flow rates or on the outer surface of solids with relative motion. The article mainly discusses the cavitation phenomenon that occurs during the fuel flow inside the nozzle, belonging to the former. The inception and development of cavitation phenomena show transient characteristics, which are extremely difficult to directly capture in practical engineering operations. However, the unique sound accompanying cavitation can be heard, or spot-like marks or cracks on the surface of the equipment can be observed during regular inspection of the instrument. Unfortunately, this only captures the traces of its existence, making it difficult to provide practical assistance for the prevention and prediction of cavitation. Therefore, it is

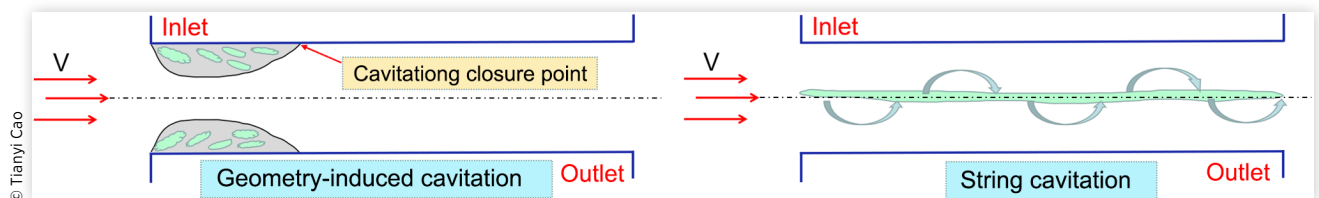
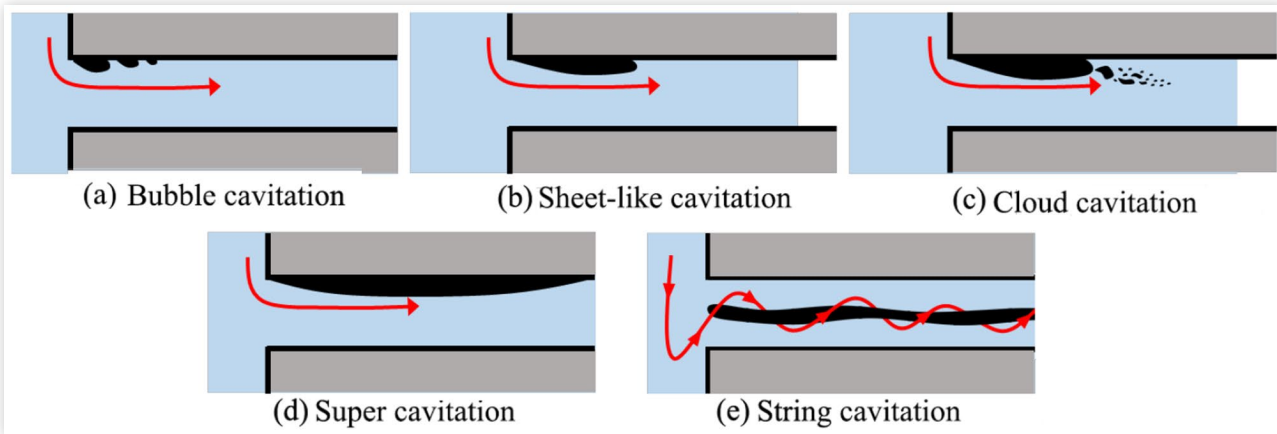
FIGURE 7 Schematic of cavitation inception with two forms.

FIGURE 8 Classification of geometry-induced cavitation and string cavitation in nozzles.

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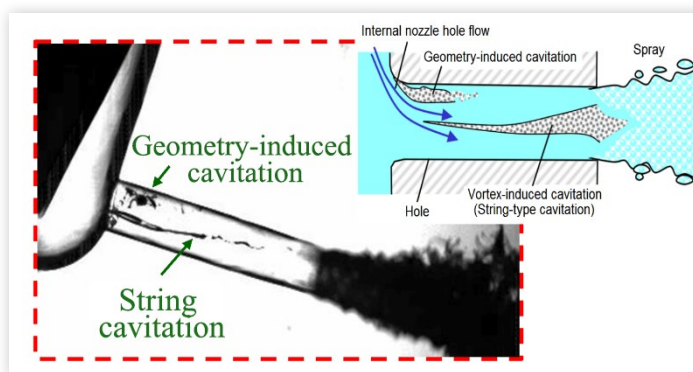
necessary to clearly capture the morphological changes from the inception to development of cavitation in order to make breakthroughs on cavitation research. The researchers captured the morphological characteristics of bubbly cavitation and string cavitation in ship experiments [14].

The bubble-like cavitation shown in Figure 7 is only one of the forms included in geometry-induced cavitation. The cavitation phenomenon is often caused by the flow contraction at the nozzle inlet and the presence of a low-pressure zone for wall backflow, leading to the initial formation of cavitation. Subsequently, it further extends and develops toward the nozzle outlet, where various typical cavitation forms appear. High-speed fuel generates strong vortices in the flow due to the flow channel structure, and the low-pressure center causes another form of string cavitation (referred to as string cavitation), as shown in Figure 8. The cavitation caused by nozzle structure is also known as geometry-induced cavitation, which includes bubble cavitation, sheet-like cavitation similar to some thin sheets, irregular cloud-like cavitation at the tail of cavitation, and super-cavitation where the main body has developed to the nozzle outlet. The cavitation form is effectively controlled through injection pressure and structural parameters. This cavitation form adheres to the wall surface at the nozzle inlet from the moment it appears, which leads

to a direct impact on the wall surface as cavitation bubbles collapse, significantly shortening the service life of the nozzle [15].

Geometry-induced cavitation and string cavitation often coexist in the diesel nozzle, as shown in Figure 9. From the perspective of the three elements of cavitation inception, the differences between two cavitating forms are mainly reflected in:

1. The locations of low-pressure areas. For geometry-induced cavitation, it mainly refers to the phenomenon of fuel entering the nozzle and causing flow contraction at the nozzle inlet, resulting in an increase in flow velocity and a decrease in pressure. This leads to the formation of a reflux zone at the wall above the nozzle inlet due to flow separation, thus resulting in lower pressure in the reflux zone and cavitation phenomenon. The low-pressure zone is mainly located in the wall reflux zone on the nozzle inlet. The string cavitation induced by vortices and the low-pressure region are mainly located inside the vortex field, which is at the center of the vortex core.
2. Low-pressure action time and cavitation nuclei. The vortex flow field where string cavitation occurs promotes the precipitation of dissolved gases in the

FIGURE 9 Geometry-induced cavitation and string cavitation in diesel nozzle.

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fuel, transforming them into free gases. Subsequently, free gas is collected at the center of the vortex, where it converges and stabilizes, increasing the reaction time of the gas core at low pressure, resulting in the inception and stable development of string cavitation. For geometry-induced cavitation, the low-pressure region is located in the reflux region where flow separation occurs near the wall. The flow field has a force that pushes the gas core toward the outside, even if it is far from the low-pressure reflux region. At the same time, free gas is easily carried by upstream flow and sprayed out of the nozzle, shortening the time the gas core spends in the low-pressure region.

Therefore, it is necessary to further focus on string cavitation based on sufficient research on geometry-induced cavitation, and to study the interaction and influence between these two forms of cavitation that coexist in the nozzle.

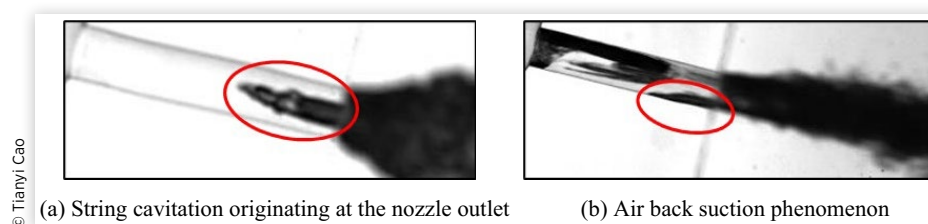
Unexpected phenomena often occur, whether in real applications or experimental diesel nozzles. For example, the string cavitation that starts at the nozzle outlet and then develops toward the nozzle inlet has been referred to as the air reverse suction phenomenon in previous studies. It was found that the gas phase starting from the central axis position of the nozzle outlet is also the string cavitation phenomenon, rather than air reverse suction in the simulation study of our research group using a convergent nozzle [16]. There is a large low-pressure area on the cross section of the nozzle outlet, thus a transition happening from the liquid phase to the gas phase in the central low-pressure area after the fuel spraying out the nozzle. At the same time, the cavitating vapor phase is inverted and sucked into the nozzle under the significant low-pressure region. Compared to the phenomenon of air reverse suction, the article believes that it is more consistent to refer to it as string cavitation starting at the nozzle outlet, as shown in Figure 10(a). Correspondingly, the pressure region at the nozzle wall is exactly the opposite, with an increasing pressure distribution from the nozzle inlet to the nozzle outlet. Therefore, if it is observed that cavitation starts at the nozzle outlet and then moves against the wall toward the nozzle inlet, it can be called cavitation reflux, as shown in Figure 10(b). The discovery of new cavitating forms is of great significance for research into the near-field spray stability and combustion efficiency.

2.4. Impact and Application of Cavitation

Traditionally, cavitation is often considered an abnormal phenomenon. It causes strong disturbance to the surrounding fluid as the volume and form changes, increasing the instability of fluid flow during the cavitating inception and development. Therefore, cavitation phenomenon is considered as a disturbance source. Cavitation bubbles have the characteristic of group bubbles, which collapses in high-pressure areas. The micro jets and shock waves generated by the group bubbles cause damage to the material surface, and the accumulation over time ultimately leads to fatigue damage of the material. Therefore, cavitation phenomenon is also considered as a source of material damage [17]. At the moment of rupture, cavitation bubbles emit pulse-like noise often referred to as “cavitation noise” due to sudden changes in pressure distribution [18], so cavitation phenomenon is also regarded as a radiation source of noise. The morphological changes of cavitation at each stage generates pressure fluctuations and has a significant impact on the flow pattern [19]. Therefore, cavitation phenomenon is also considered as an excitation source of vibration.

With the increasing deepening of research on cavitation phenomenon, scholars have discovered its other side and utilized it in various fields. For example, the energy released during the rupture of cavitation bubbles is used to break the walls of yeast microbial cells, which consumes much less energy than the commonly used mechanical wall breaking method [20]. The cavitation effect is applied to the extraction of oil and natural gas. The rock breaking efficiency of cavitation is improved by coupling the pulse wave around the flow surface with self-oscillating cavitation, and it is also beneficial for the purification of the exploration well bottom [21]. In addition, the cavitation effect is also applied in the field of cleaning and cutting. As a new type of jet technology, cavitation jet clean rust and sludge on various equipment at lower jet pressures efficiently. In addition, the most effective application of cavitation phenomenon is the promotion and development of super-cavitation underwater vehicles. The use of super-cavitation to wrap an underwater vehicle in it adds a new medium—air/water vapor—between the vehicle and water, significantly reducing the resistance of the underwater vehicle during travel [22]. It contributes to the initial breakup

FIGURE 10 String cavitation and air suction at the nozzle exit of diesel engine.



when the cavitation area in the nozzle hole extends to the nozzle outlet, thus optimizing spray atomization.

In addition to the conventional wall sheet cavitation phenomenon, there are also special flow phenomena such as cloud cavitation, residual bubbles, and vortex-induced string cavitation in the nozzle of the injection system. Currently, there is relatively little research on the latter at home and abroad. Therefore, it is very necessary to integrate and summarize the current research status of various special flow phenomena in the nozzle of high-pressure common-rail fuel injection system and their effects on spray atomization under the visualized test platform and high-precision numerical simulation methods. Based on the current summary, it can provide both theoretical guidance for achieving the accuracy and consistency of the high-pressure common-rail fuel injection system on fuel injection and spraying control, and important application value for the research of fuel injectors, creating academic value of cavitation two-phase flow theories and spray atomization.

3. Research Status of Cavitating Flow in Diesel Nozzle at Home and Abroad

The main research points in this text are twofold: the factors that affect cavitation phenomena and the effectiveness of cavitation. The former belongs to the precause of cavitation and can directly affect the occurrence and development of cavitation. The latter belongs to the result of cavitation or the manifestation of cavitation effects. This text has been adjusted based on this methodology, and the selected studies are also included in the above two points. Second, a unified methodology for cavitation capture has been provided to clarify the methodology and criteria. The details are as follows:

MATLAB software is used to independently write a post-processing solution program to extract the specific data information (cavitation intensity, spray angle, etc.) in the original image. Taking string cavitation as an example, string cavitation intensity (I_{string}) is defined as follows:

$$I_{string} = \frac{S_{string}}{S_{hole}} \quad \text{Eq. (4)}$$

where S_{string} represents the cross-sectional area of cavitation in the hole and S_{hole} represents the area of the hole in a two-dimensional image. The hole area is obtained from the diameter and length, and the area of string cavitation is to be solved by MATLAB process. Specifically, subtract the transient cavitation images using the previously saved blank background images in the loop program, and then overlay the images for binary processing to obtain the cavitation area.

3.1. Influence of Cavitation Flow and Research Status

The inception and development of cavitation (geometry-induced cavitation, vortex string cavitation) are mainly influenced by three factors: viscosity, medium, and surface. Researchers have conducted relevant research on the three factors in the early stage and revealed the inception and development of cavitation.

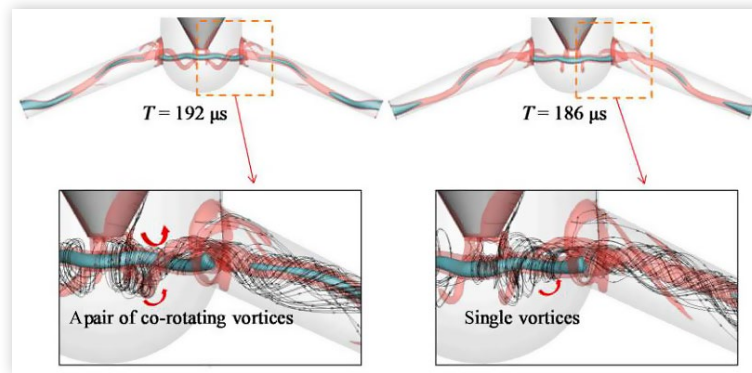
3.1.1. Viscous Factors Viscous factors mainly include two categories: geometric factors and hydrodynamic factors.

1. Geometric factors

The geometric factors mainly include the nozzle structure, such as the inclination angle and the nozzle shape. Many researches have been carried out on the cavitating characteristics induced by geometric factors that further improve the spray effect.

Kang et al. [23] compared the accuracy of cavitating prediction based on elliptical and rectangular geometric conditions in airfoils and propellers. The acceptance angle index better predicted the cavitation inception in elliptical shapes. Kuiper et al. [24] explored the possibility of suppressing vortex cavitation by considering changes in geometric parameters in the tip region. Guan et al. [25] explored the influence of nozzle inlet and nozzle inclination angle on string cavitation. The results showed that the chaotic vortex near the nozzle entrance and the large nozzle inclination angle both hindered the string cavitation (Figure 11).

In terms of the cavitating development, Gavaises et al. [26] utilized high-speed imaging visualization technology to study the cavitating structure inside the conical nozzle of diesel engines. Conical holes suppressed the geometry-induced cavitation at constant needle lift, but they contribute to the inception and development of string cavitation, especially at low needle lifts. At the same time, vortex structures were observed between holes in the SAC cavity, and it was elucidated as the development mechanism of string cavitation between holes. Zhang et al. [27] numerically simulated the cavitating flow with taper coefficients and needle lifts as variable parameters in a dual-row diesel engine. The results indicated that a decrease in taper coefficients results in a decrease in the cavitation area on the nozzle wall and a contraction toward the cavitation inception (Figure 12). Payri et al. [28] studied the influence of conicity on the cavitating flow and spray behavior in the diesel nozzle. The cylindrical hole was conducive to the development of cavitation, while the convergent nozzle hole played a restraining role. Rastogi et al. [29] summarized the influence of nozzle structures (conicity, inlet fillet, and aspect ratios) on cavitating development, and introduced three new methods for measuring geometrical dimensions. At the same time, Mitroglou et al. [30] utilized a high-speed visualization system to study the cavitation phenomenon on the transparent nozzle, revealing the possibility of cavitation occurring at specific locations and the location differences of periodic changes. Deng Haipeng et al. [31] studied the influence of structural parameters such

FIGURE 11 Vortex visualized and vapor iso-surface at two instants.

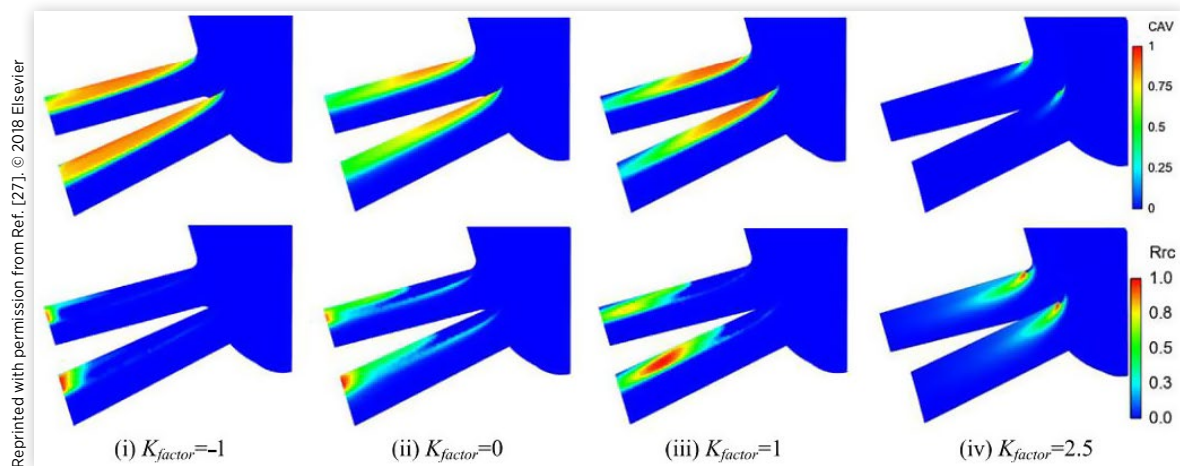
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as aspect ratios and inclination angle on cavitating flow during the movement of the needle valve. The results indicated that increasing the hole size led to the expansion of the cavitation area, and the overall position of cavitation shifted inward from the nozzle wall. Cioncolini et al. [32] tested and studied the complete form of super-cavitating development with aspect ratios and wall thicknesses in the conical nozzle. Cavitation number increased at the beginning and end of super-cavitation with the hole size and wall thickness.

In addition, factors such as SAC volume structure and needle lift are also research hotspots. Roth et al. [33] observed the development of cavitation in the six-hole nozzle on a refractive index matching test bench and elucidated the influence of SAC volume inside the nozzle. Cao et al. [34] built a visual internal flow and spray test bed to conduct a comparative study on cavitation phenomenon with needle lifts. The results showed that the needle lift can significantly affect cavitation patterns, along with its corresponding pressure fluctuations and the spray angle. Chen et al. [35] used a prototype transparent nozzle to investigate the string cavitation induced by vortex in the nozzle hole. The nozzle with VCO and Min-sac

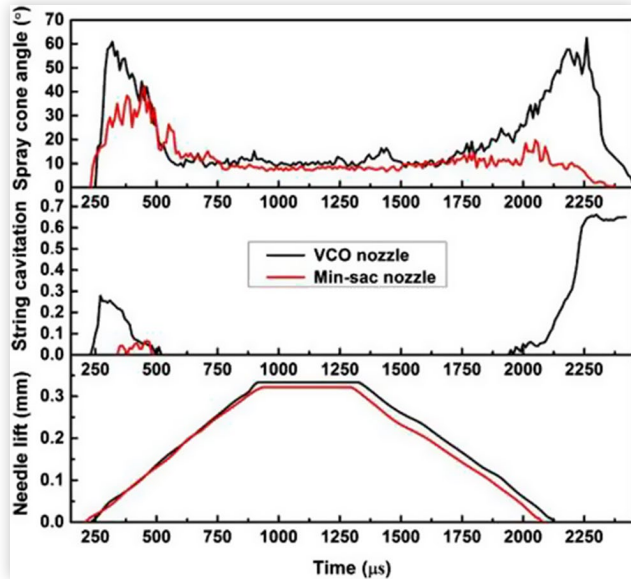
volume were more conducive to the string cavitation compared to the nozzle with SAC cavity (Figure 13). Lenik et al. [36] constructed a new type of electronically controlled fuel injector with a pressure storage chamber. It was promoted that the development of cavitation inside the hole increases the cross-sectional area of the throttle hole or the effective volume of the pressure storage chamber.

Andriotis et al. [37] homed in on the development of cavitation with a transparent injector in a low-speed two-stroke diesel engine (Figure 14). The frequency of string cavitation was related to the Strouhal number of vortices in the SAC chamber, and it is also constrained by the needle lift and the geometric parameters of the nozzle. Watanabe et al. [38] used a micro-PIV device and CFD simulation method to study the flow characteristics of vortices in diesel engine nozzles. By changing the shape of the needle head, the control of the eddy current structure in the SAC cavity was achieved, thereby changing the string cavitation pattern in the hole. Salvador et al. [39] found significant differences in cavitation and turbulence development under different needle lifts on porous nozzles at fixed needle lift. Battistoni [40] and Wang et al. [41]

FIGURE 12 Cavitation distribution in the nozzle with different taper coefficients.

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FIGURE 13 String cavitation and spray cone angle of the VCO and Min-sac volume.



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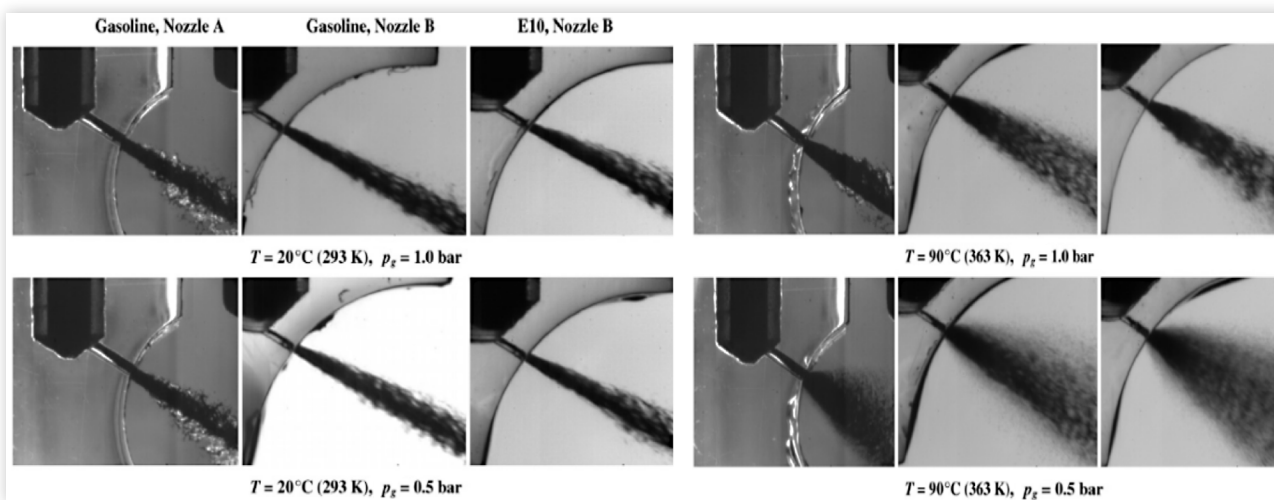
compared the hole-to-hole string cavitation with eccentric conditions and elaborated the causes of the eccentric needle valve. Prasetya et al. [42] studied the development of string cavitation inside the nozzle on a small bladder diesel engine and found that vortices formed in the SAC cavity at low needle lifts, and the initial stage of string cavitation tended to develop steadily when the vortex intensity increased to a certain extent.

2. Hydrodynamic factors

Scholars have conducted extensive research on fluid dynamics factors. It is generally believed that injection pressure and back pressure belong to the category of fluid dynamics factors. The factors of needle movement have gradually been classified into this category with the continuous

deepening of research. Reid et al. [43] observed the repeated inception and development of hole-to-hole cavitation in an optical diesel nozzle. The hole-to-hole cavitation was proved to be independent of upstream injection pressure and cavitation number. B. Yin et al. [44] simulated the cavitating two-phase flow characteristics in the diesel nozzle. An increase in injection pressure was beneficial for the inception and development of cavitation, and super-cavitation patterns were observed at higher injection pressures, while an increase in ambient pressure hindered the persistence of cavitation. Kawahara et al. [45] combined a two-phase flow mixing model with a cavitation model to explore the near-field spray atomization in diesel engines. The cavitation in the nozzle developed into super-cavitation when the injection pressure rises to a certain value, and a new spray model was proposed. Dong et al. [46] studied the spray characteristics of the external axle needle injector and the V-shaped nozzle through comparative analyses. The traditional injection parameters such as injection pressure and back pressure had very limited effect on the spray angle of the external axle needle injector. Payri et al. [47] found that there was a lag effect in the inception and development of cavitation with the back pressure using the visual experimental methods. Arcoumanis et al. [48] studied the effects of Reynolds number, cavitation number, and eccentricity of the needle valve on cavitating flow in a scaled-up transparent injector. The cavitation pattern starting from the nozzle inlet mainly depended on the cavitation number rather than the Reynolds number or eccentricity of the needle valve, but significant differences in cavitation pattern was caused by the eccentricity of the needle valve. Devassy et al. [49] discussed the influence of cavitation on the three-dimensional needle valve movement. Research showed that the cavitation effect exacerbated the phenomenon of needle valve eccentricity in a piezoelectric common-rail diesel engine injector. Kim et al. [50] studied the influence of needle valve position and nozzle length-width ratio on the cavitating development in the nozzle. The eccentricity of the needle valve caused

FIGURE 14 The effect of fuel temperature on internal flow and spray under different kinds of fuel and back pressures.



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hydraulic overturning, which occurred in the spray hole on the side near the needle valve. Eccentricity of the needle valve caused hydraulic flipping, which occurred in the nozzle near the needle valve side.

In summary, the influence of viscous factors on cavitation phenomenon is extremely significant. And there are differences in the effects of viscous factors on various stages of cavitation development. In the same nozzle, the combination of different viscous factors can produce different cavitation forms. For example, combining low needle lift with high injection pressure will produce string cavitation. After increasing the needle lift, string cavitation can transition to geometry-induced cavitation, further demonstrating the significant influence of viscosity factors. Similarly, appropriate viscosity factor plays a decisive role in inhibiting cavitation but improving the spray atomization. In addition, viscous factors are the research focus that researchers pay the most attention to during the entire process of cavitation occurrence and development. One reason for this is that viscous factors such as nozzle geometry and injection pressure are easily obtainable and controllable, making them the preferred test conditions. Another reason is that viscous factors can directly control the direction of cavitation development and obtain the research results that researchers expect. However, a relatively complete cavitation prediction model has not been established based on geometric structures or external pressures under the extensive research status of geometric factors and hydrodynamic factors, which are also a research point that researchers need to explore under the current rich data.

3.1.2. Medium Factors The medium factors of cavitation two-phase flow in diesel engine nozzles mainly include two aspects: fuel properties and gas content.

1. Fuel properties

Currently, scholars have little research on the physical properties of the fuel inside the diesel nozzle, especially the fuel temperature. The precise control of fuel temperature is an urgent problem to be solved in the technology used in diesel engine injectors. During a single injection process, diesel fuel needs to flow through components such as the fuel tank, common rail, and fuel injector, and it is difficult to control the temperature losses along the way. The fuel temperature inside the nozzle varies with the operating conditions of the diesel engine, ranging from 0°C to 150°C. The significant temperature difference changes the fuel saturation vapor pressure, viscosity, density, and other physical parameters [51], and then affects the flow characteristics in the diesel nozzle and the spray combustion characteristics in the combustion chamber. Therefore, the study of fuel temperature has its unique practical significance. Su et al. [52] studied the influence of fuel temperature on the spray atomization of soybean oil methyl ester (SME). The size of spray droplets increased in both axial and radial directions with the fuel temperature, and the fuel evaporation effect developed. Serras et al. [53] compared and analyzed fuel characteristics of gasoline, isooctane, ethanol, and butanol at 20°C and 90°C, and revealed the influence of physico-chemical properties on

spray characteristics in DISI engine. Aleiferis et al. [54] found that the influence of fuel temperature was very significant on the cavitation flow inside the transparent nozzle, and higher fuel temperature significantly promoted the initial fragmentation of fuel injection, as shown in Figure 14. Wang et al. [55] determined that the cavitation inception was significantly affected by fuel temperature, that is, it was liable to be born with increasing temperature in a single nozzle. However, the super-cavitation was almost unaffected by fuel temperature. Zhou et al. [56] found that increasing the temperature promotes the development of string cavitation, and the string cavitation intensity increased exponential growth with the fuel temperature in scaled-up and prototype transparent nozzle.

From the thermodynamic effects of cavitation, it can be seen that the energy of the latent heat is only provided by the surrounding liquid for bubble growth in liquids, so the liquid near the two-phase region is cooled. In addition, the expansion effect of fuel affects temperature differences in the two-phase region due to the decrease in pressure, according to the Joule–Thomson effect. Furthermore, the enormous shear force generated by the nozzle wall causes a viscous heating effect as the injection pressure increases, leading to an increase in enthalpy and fuel temperature. Petkovšek et al. [57] confirmed the thermodynamic effects with the two-dimensional temperature of cavitating flow in a Venturi tube. The results indicated that the magnitude of temperature drop depended on the size and growth of bubbles. Arienti et al. [58] pointed out that the fuel temperature at the nozzle outlet deviated from the fuel tank temperature within 15°C under adiabatic wall conditions. The increase in temperature was attributed to two aspects: the expansion of the liquid phase caused by pressure difference and the increase in enthalpy caused by viscosity. Through numerical simulation, Yu et al. [59] found that the increase of sensible heat enthalpy and condensation enthalpy caused by shear force increased the temperature of jet surface in the nozzle hole, thus affecting the evaporation of spray atomization. Payri et al. [60] investigated the effect of thermal efficiency on fuel injectors. High injection pressure increased the range of fuel temperature drop in the nozzle. When the fuel temperature exceeded the critical value of 283 K at the nozzle inlet, the fuel become subcooled during the steady-state injection phase, while below the critical value caused laminar or transitional flow states, leading to fuel heating. Liang et al. [61] concluded that the cavitation thermal effect had a significant impact on the structure and detachment dynamics of the cavitation cavity, based on modal decomposition methods. Slender cavities appeared along the wall under isothermal conditions, while thick cavities appeared under thermal conditions. The thermal effect enhanced the vorticity gradient in the cavitation cavity, and the large vorticity gradient had an impact on the detachment of small-scale cavitation cavities.

2. Air content

It is mainly concentrated in hydraulic machinery that aerate air through ventilation operations such as water turbines. Its main purpose is to suppress cavitation effect, reduce flow noise, and lower flow resistance. In the diesel

nozzle, the effective use of ventilation can also inhibit cavitation erosion and promote spray atomization. However, there are few reports on this aspect due to high injection pressures and high sealing requirements in diesel injection systems. As mentioned above, gas nucleus is one of the most important preconditions for cavitation inception and plays a decisive role in the subsequent cavitating development. In engineering practice, it is often necessary to use ventilation method to suppress or promote the cavitation phenomenon, and the air bubbles in the upstream play the effect of initial gas nucleus.

Ji et al. [62] conducted numerical simulations of natural and ventilated cavitation based on the theory of cavitation nuclei. The results indicated that the improved model obtained changed in bubble size and shape under natural and ventilated cavitation conditions. Harish et al. [63] added high-pressure air from the top cover of the turbine to the runner, and measured the pressure pulsation signal and vibration signal of the unit after ventilation. There was no resonance phenomenon in the unit after pressure ventilation treatment, and the vibration of the generator frame was within the allowable range. Qian et al. [64] analyzed the relationship between pressure fluctuations in the flow channel of Francis turbine and the intake air volume. The main shaft hole inlet reduced the pressure difference in the horizontal section of the draft tube, thereby reducing the low-frequency pressure fluctuations in the draft tube. Liao et al. [65] studied the effect of ventilation on the vortex belt of draft tube in the center hole of the water turbine spindle based on the water-air two-phase flow model. The research showed that if the ventilation rate was too small, the gas was less with entering the central vortex zone of the straight cone section, which suppressed the water flow. Excessive ventilation also reduced the cross-sectional area of water flow. Jin et al. [66] studied the influence of four kinds of center holes on pressure pulsation of the tailpipe in the Francis flow turbine. The pressure vibration was reduced by air inflowing through center hole under part-load condition. Luo et al. [67] studied the unsteady characteristics of vortex band structure and the basic mechanism of air vortex interaction in the draft tube of Francis turbine. The inlet air from the center of the main shaft alleviated pressure fluctuations caused by the vortex belt, and the proper inlet air volume changed the structure and distribution of the vortex belt, thus alleviating pressure fluctuations in the draft tube. Kim et al. [68] used a new modified numerical calculation method to simulate the multi-phase flow of Francis turbine ventilation in view of the spiral cavitating vortex band under low load conditions. The pressure pulsation induced by the vortex zone was effectively suppressed by aerating air into the draft tube. The flow pattern changed substantially in the draft tube when the ventilation volume become larger, and the pressure fluctuation was suppressed.

In summary, the physical properties of diesel fuel can be obtained by changing the temperature or mixing fuel in the medium factor. The key parameters under this factor are actually viscosity and saturated vapor pressure. Therefore, the influence of fuel physical properties on cavitation phenomenon mainly targets the transition points of cavitation, such

as cavitation inception and cavitation collapse, while for the stage of cavitation development, only promoting or inhibiting effects can be observed, and boundary properties are not applicable to this stage. For ventilation operations in air content, ventilation effectively suppresses the pressure pulsation induced by the trailing vortex zone and increases the flow stability. At the same time, pressure distribution in the flow field has a profound influence on the development and cavitating form in the flow field. Therefore, ventilation has important application potential for flow stability in diesel engine. However, there are few literature reports on the influence of ventilation on the nozzle flow and spray atomization in diesel nozzle, and the mechanism of its influence remains unclear on geometry-induced cavitation and string cavitation.

3.1.3. Material Surface Factors The material surface refers to the inner wall of the nozzle for cavitation phenomenon in diesel nozzles, and material surface factors are manifested in the difference in wall roughness. Geometry-induced cavitation adheres closely to the wall from its inception, so it is significantly affected by surface factors. Scholars have already obtained clear results on it in experiments. Duke et al. [69] conducted comparative experiments on nozzle materials (metal and transparent) on the premise of ensuring that the nozzle dimensions were identical with synchrotron radiation X-ray imaging technology. The results were consistent with previous predictions, and it showed significant differences that the distribution of geometry-induced cavitation within material nozzles. The inception and development of string cavitation are far from the wall surface, so its related variation is not radically affected by surface factors.

Overall, the research work on material surface factors focuses on the exploration of nozzle materials in the early stage. Now that the material of nozzle hole has been determined, the related research has been rarely mentioned on cavitating two-phase flow in injector nozzle. But it is undeniable that it has certain influence on cavitation phenomenon, especially the inception and development of geometry-induced cavitation.

3.2. Cavitation Effect and Research Status

The cavitating two-phase flow directly affects the stability of the entire injection system in the diesel nozzle, the precise control of the injection quantity, and the instability of spray atomization. To summarize, its impact is reflected in the following four aspects:

1. Circulation characteristics. Cavitation inception compresses the liquid in the surrounding space and changes the flow cross section and flow area of the fuel inside the nozzle, further affecting the circulation characteristics.
2. Cavitation erosion characteristics. The shock wave and micro-jet caused by the cavitation collapse damages the inner wall of diesel nozzle, causing

cavitation damage. In serious cases, it leads to the failure of diesel injector. Even in light cases, it also changes the fuel injection and spray atomization of diesel nozzle.

3. Pressure fluctuation characteristics. The cavitating transient state causes pressure fluctuations in the injection system, which is manifested in the flow stability and spray atomization near the nozzle.
4. Spray atomization characteristics. The inception and development of cavitation show the maximum disturbance at the nozzle outlet, which affects the spray atomization and subsequent combustion characteristics.

Of these four effects, the first three are unfavorable to the fuel injection system, while the last one is favorable. Therefore, it is very necessary to comprehensively analyze and evaluate the cavitation effect of diesel nozzle on the injection system with regard to four factors. Researchers from home and abroad have carried out relevant studies on these four kinds of cavitation effects, which are arranged as follows.

3.2.1. Circulation Characteristics The accurate flow coefficient model is helpful to predict and evaluate the injection volume under different working conditions. Cavitation makes the effective flow area smaller in the nozzle, thus affecting the flow coefficient. Qiu et al. [70] studied the influence of back pressure on the development of cavitation in the nozzle, and obtained the fuel flow with the super-cavitation. Under the condition of super-cavitation, the flow in the nozzle had blocking effect, and the back pressure had little effect on the mass flow rate, but the flow coefficient decreased with the back pressure. Brusiani et al. [71] compared the effects of cylindrical and conical holes on cavitating development based on the 3D transient multi-phase method. Loss rate of mass flow decreased significantly with the cross-sectional area lessening in nozzle hole. Han et al. [72] coupled the mixed multi-phase model with the cavity model and explored the cavitating flow in the variable cross-section nozzle. It was uniform that the velocity gradient distribution of the divergent nozzles at the outlet, which was conducive to the flow coefficient.

Hassan et al. [73] used a mixed multi-phase cavitating model to study the cavitating flow in the conical nozzles. The development of cavitation was weaker in the convergent hole than that in the cylindrical hole under the same operating conditions, while the average flow velocity and flow coefficient were higher than those in the cylindrical hole at the outlet. Desantes et al. [74] elucidated the influence of average flow density at the nozzle outlet, as well as the reasons for the increase in outlet flow velocity in cavitating development through the empirical models.

Zhou et al. [75] obtained the flow coefficient of each hole by establishing transient measurement system. The transient flow coefficients of each hole were constantly changing with similar rules. However, the flow coefficient is different at the same injection condition. He et al. [76] also found that the flow coefficient in the convergent hole was larger than that in

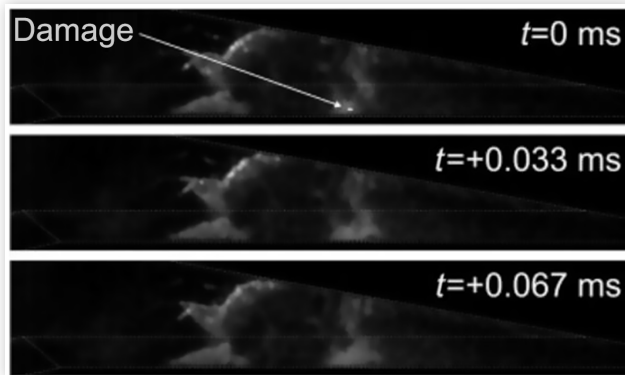
other holes at the same injection condition. Tang Zerun et al. [77] studied cavitating flow under different openings. The flow coefficient first remained stable, then slightly increased, and sharply decreased at last. Tao et al. [78] conducted numerical simulations on V-shaped ball valves with different structures. A change in valve opening would lead to a decrease in the flow resistance coefficient and an increase in the flow coefficient of the V-shaped ball valve. Tang et al. [79] proposed a diagonal ladder triangular flow curve to express the development and changes of blocked flow in the throttle hole plate and discovered the limitations and stepped characteristics in the blocked flow. Ou et al. [80] studied the cavitating flow of coal liquefaction regulating valve. The flow rate curve followed a parabolic pattern, and the flow capacity increased with opening. Morii et al. [81] found that the cavitating performance curve is more prone to fracture under high flow rates. Flow instability occurred under high flow conditions with the continuous development of cavitation areas.

In fact, the flow coefficient is a parameter that directly reflects the flow capacity of the nozzle hole. Therefore, the influence of cavitation development on the flow characteristics can be obtained through the variation of flow coefficient in the nozzle orifice. In this way, the measurement and balance of flow characteristics and spray atomization effect can be obtained after accurately controlling the cavitation morphology through the various factors mentioned above. Under the premise of ensuring the flow characteristics of the nozzle hole, great injection effect and high combustion efficiency are ultimately achieved.

3.2.2. Cavitation Erosion Characteristics Cavitation erosion refers to the damage caused by cavitation collapse to the material wall, which is an external manifestation accompanying the disappearance of cavitation. Therefore, scholars usually associate it with cavitating development. Yabuki et al. [82] studied the cavitating erosion of metal materials in corrosive environments and obtained the cavitation rate based on the polarization curve under cavitating conditions. When the cavitating characteristics length accounts for more than one-third, cavitation slump exhibited discontinuity. Furthermore, cavitating collapse and perish played a positive role during the spray atomization [83].

Ebrahim et al. [84] explored the cavitating erosion in a two-dimensional flat simplified nozzle. The cloud cavitation fell off and collapsed at the outlet inside the divergent nozzles. Therefore, the cavitation erosion area was concentrated at the hole outlet. Kambara et al. [85] established a new method for predicting cavitation through the relationship between cavitating phenomenon and cavitating erosion damage. The damage was relatively high, which was caused by sheet cavitation collapse to the wall at large needle lifts. At the same time, the location and intensity of cavitation were predicted by calculating the number of local sheet cavitation collapse. Dular et al. [86] attached thin copper foil to the wall of a hydrofoil and studied the cavitating erosion effect on two-dimensional hydrofoil structures. It was established that a relationship between cavitation effect and cavitation erosion

FIGURE 15 Damage appearance at cavitation cloud separation from side view.



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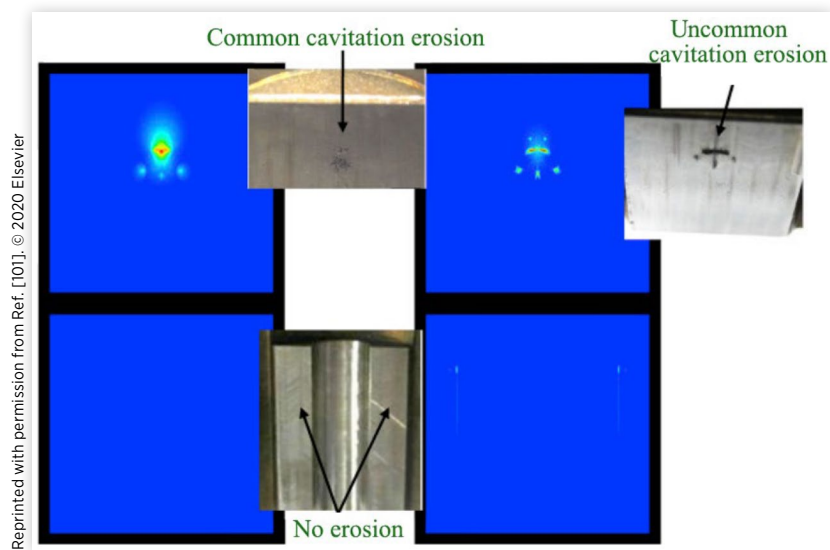
damage is evaluated by measuring the surface damage of hydrofoils and the cavitation wear. Subsequently, they also finished the tests on the surface of the transparent Venturi tube. Wall damage only occurred when the cloud cavitation collapsed. The size of the cloud cavitation and its distance from the wall rarely affected the cavitation erosion damage [87], as shown in Figure 15. At the same time, two shapes of cavitation erosion collapse were also captured by high-speed cameras, namely spherical cavitation cloud and horseshoe-shaped cavitation cloud [88]. In addition, the influence of temperature parameters on cavitation erosion was investigated with polished aluminum samples. The cavitation erosion was the most serious at 60°C [89]. In addition to pasting thin soft materials to change the mechanical properties of the wall surface, some researchers also adopted wall surface treatment. Wo et al. [90] studied the cavitation erosion at the needle valve sealing surface by using scanning electron microscopy. It was found that the cavitation erosion of the low hardness sealing surface was higher than that of the high hardness sealing surface. Porš et al. [91] compared cavitation erosion in diesel nozzles before and after heat treatment. It resulted in greater cavitating wear, due to the decrease in hardness after heat treatment.

In engineering, it is hoped that cavitation erosion is accurately predicted when it occurs, including the time and location of the occurrence, so as to improve the design and reduce the damage. Cavitation erosion significantly reduces the structural integrity and operation efficiency of propellers. Bark et al. [92] developed a new method to predict the risk of cavitation erosion with propellers and rudders in the face of the increasingly prominent cavitation erosion. Watanabe et al. [93] proposed a new predictive model for the cavitation erosion occurring at the propeller blades to address the issue of inconsistency between cavitation area and cavitation erosion area, which provided a theoretical reference for the design of the new propeller series. Melissaris et al. [94] studied the cavitation erosion of KCD-193 propeller blades using mean-field pressure as the driving force after cavitation collapse. By calculating the potential power of the first layer

unit in contact with the blade surface, it was preliminarily estimated that the damage of cavitation erosion is found in high-risk areas on the blade. In addition to predicting erosion damage on propeller blades, Stockner et al. [95] provided a method for predicting the cavitation erosion occurring on the surface of fluid power components.

High-precision prediction results can be obtained by analyzing the standard deviation of parameters such as average pressure and average porosity at the location where cavitation occurs. Patella et al. [96] proposed a method for predicting the damage of cavitation erosion by simulating cavitation flow characteristics. To this end, a numerical method was developed for coupling cavitation flow model and erosion model, and pitting experiments were conducted with a three-dimensional laser profilometer to evaluate cavitation pits. Bergels et al. [97] proposed an erosivity index based on material surface pressure load and material yield stress, which predicted the minimum bubble size and position at the beginning of cavitation erosion. Peters et al. [98] used the information in the flow solver to predict the cavitation effect, and the predicted results were in good agreement with the experiment. Geng [99] and Steller [100] established the predicting model in cavitation erosion risk for energy transport, then the research models were predicted and prospected in this field. Brunhart et al. [101] studied the fluid mechanics of the thin gap in the high-pressure fuel pump. Two evaluation criteria were determined by comparing the CFD results of damaged and undamaged designs, as shown in Figure 16. In addition, some scholars have attempted to directly suppress the cavitation erosion. Cai et al. [102] reduced cavitation erosion of the output valve in derived buff-type buffer from engineering perspectives, such as parts design and machining accuracy.

The pressure at the nozzle outlet is relatively high, so cavitating bubbles collapse near the area, resulting in cavitation erosion. In this case, cavitation erosion has a significant influence on the near-field spray atomization. Ignaciuk et al. [103] determined that the cavitation was mainly in the check valve after microscopic diagnosis, and the fuel injection was significantly reduced after cavitation erosion. Cristofaro et al. [104] studied the influence of cavitation erosion in diesel injectors on spray atomization. The fuel injectors that experienced cavitation erosion had a wider spray diffusion range and better spray atomization. Besides the injector nozzle, cavitation erosion can also be produced in the cylinder liner of diesel engine. Yu [105] and Xia et al. [106] compared cavitation corrosion samples from vibration equipment with corrosion samples in diesel engine cylinder liner with visualization technology. The results indicated that the corrosion of diesel engine cylinder liners was caused by cavitation erosion, and the main dynamic factor was the vibration of the cylinder walls. In addition, researchers have also investigated the cavitation erosion of different media after mixing operation [107, 108]. Instantaneous pressure waves and sound waves were generated when cavitation bubbles collapsed. Regarding this, Reisman et al. [109] used visual experimental methods to study the effect of cloud cavitation and cavitation erosion. Cloud cavitation rupture and collapse generated shock waves

FIGURE 16 Comparison of simulated cavitation and experimental cavitation.

and sound waves. At the initial fragmentation, the high-pressure area of cloud cavitation generated large pulse surface pressure waves, which had a much greater effect than the cloud cavitation in a discontinuous form. Gavaises et al. [110] estimated the flow parameters corresponding to different extent of cavitation erosion by normalizing the flow field throughout the entire injection period, including the acoustic signal generated when cavitation bubble ruptured.

In summary, there is a certain understanding of the research on cavitation erosion effect, but there are still many deficiencies and shortcomings [111]. Scholars have summarized the research work on cavitation erosion in recent years and pointed out the advantages and disadvantages of various experimental methods and numerical predicting models, providing new ideas for further research on cavitation erosion effect [104].

3.2.3. Pressure Fluctuation Characteristics The gas phase area occupied by cavitation compresses the fuel in the surrounding space when cavitation inception occurs within the nozzle, causing the fuel to shift. As mentioned earlier, the cavitation inception is transient. Similarly, the differences in cavitation form also affects the surrounding fuel. It also has transient characteristics due to being completed on the basis of high injection pressure and micro-scale nozzles. It is precisely that the pressure fluctuations are caused by the strong transient state during the inception and development of cavitation inside the nozzle. It is uncontrollable that the research on pressure fluctuations. For example, the vibration of the device itself and the injector body leads to additional pressure fluctuations, which makes it difficult to distinguish or even cover up the pressure fluctuations caused by differences in cavitation form. Cavitation has an impact on the spray atomization for the cavitating two-phase flow in the diesel engine nozzle, including the generated pressure fluctu-

ations. However, there is still a lack of research on the pressure fluctuations under different cavitation conditions.

Wang et al. [112] studied the fluctuation of injection pressure and unstable cavitation phenomenon in diesel engine nozzles using a dual fluid model. The liquid tension was sufficient to maintain the growth of localized cavitation bubbles in the re-circulation zone at the nozzle inlet. Therefore, the content of cavitation bubbles only slightly changes with the fluctuation of inlet pressure in this region. The team also used the same method to study the fragmentation and detachment of sheet/cloud cavitation. Significant quasi-periodic pressure fluctuations were captured throughout the entire cavitation area under the conditions of state/cloud cavitation. In addition, Liang et al. [113] obtained similar results from the influence of sine wave pressure fluctuations on cavitation characteristics in valves.

The pressure fluctuation characteristics inside the nozzle directly reflect the stability of fuel flow, and more specifically, it can reflect the oscillation caused by cavitation on the nozzle. This oscillation can directly affect the peripheral contour of the near-field spray jet, and then determine the atomization effect of the initial spray. It is worth noting that the pressure fluctuation caused by cavitation has little effect on the main spray beam, especially at high injection pressure, due to the limitation of pressure fluctuation magnitude.

3.2.4. Spray Atomization Characteristics The combustion efficiency in the combustion chamber is directly affected by the spray atomization in diesel engine nozzle. Scholars also attach importance to the spray atomization. Previous studies have shown that the fuel flow is one of the direct incentives for spray atomization. Therefore, most scholars still regard the cavitation phenomenon in the hole as the research premise even focusing on the development of spray morphology. Cui et al. [114] tested the near-field spray

atomization with transparent nozzles as early as the 1990s. The main reason affecting the spray shape was not the air resistance in the traditional concept, but the cavitating form in the nozzle hole. Ueki et al. [115] explored the mechanism of near-hole atomization with numerical simulation methods. Spray atomization had a strong dependence on the cavitating flow inside the nozzle and the flowing conditions at the nozzle outlet. Som et al. [116] found that conical degree of the nozzle hole and hydraulic grinding weakened the cavitation effect and turbulence intensity, thereby suppressing the initial fragmentation effect of the spray. Hwang et al. [117] studied the near-field spray characteristics in the nozzle based on the marine diesel engine test rig. The fuel temperature directly affected the fragmentation, diffusion, and evaporation of the jet beam, and listed the fuel temperature as one of the most important test parameters for developing the combustion system. Örley et al. [118] studied the cavitation phenomenon in the rectangular nozzle and the initial breakup of the liquid jet. It induced turbulence fluctuations and spray instability leading to the collapse of the cavitation area near the outlet and the entrained air. Sun [119] discussed the effect of cavitation number on cavitation phenomenon inside the nozzle hole. Cavitation number was an important factor restricting the spray atomization of near-hole fuel jets. Battistoni et al. [120] used the large eddy simulation (LES) model to study the transient characteristics of the spray jet with the in-nozzle flow and the needle valve movement. It was found that the bubbles left in the SAC cavity affected the initial spray morphology and aggravated the spray instability. Gao et al. [121] used the backlight photography technology to study the cavitation phenomenon in the nozzle and the spray structure near the hole. As the outer area of the spray was subject to air resistance, the residual bubbles were compressed at the initial stage of spraying and then expanded again to form an umbrella spray (Figure 17). Zhang et al. [122] coupled the internal cavitating flow with the spray jet, and the cavitating cloud cluster separated from the nozzle would collapse near the upper surface of the spray jet, thus enhancing the combustibility of the adjacent jet. Therefore, the appearance of cavitating

clouds formed an asymmetric jet structure, which improved the near-field spray atomization.

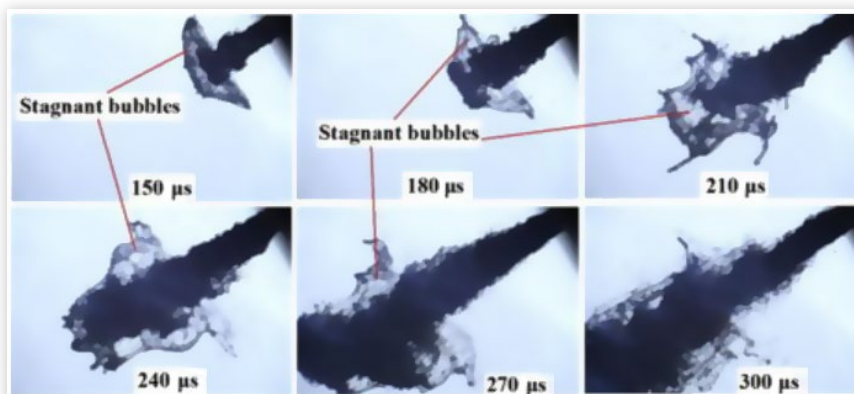
In addition, some scholars have conducted direct research on spray characteristics. Shinjo et al. [123] studied the initial atomization effect of high-speed spray jet in air. The formation of liquid filaments outside the spray was caused by the enrolling of liquid jet tip and the disturbed surface of liquid core. Ghiji [124] and Ding [125] conducted experimental and numerical research on primary atomization of high-pressure diesel engines. They found that the early liquid jet front had an umbrella-shaped structure, which was consistent with the experimental results. At the same time, they also observed the internal morphology of the dense area of spray, and analyzed the formation mechanism of initial fragmentation and early spray angle.

In fact, the parameters of spray atomization, such as spray penetration and spray fragmentation, are the most important factors that directly affect combustion efficiency. However, on the premise that the cavitation phenomenon exists in the nozzle hole, it is necessary to link spray atomization with the cavitation flow in the hole, based on the fact that there is a high correspondence between cavitation development and near-field spray atomization. Therefore, it is particularly necessary to summarize and discuss the influence of cavitation on near-hole spray atomization.

4. Insufficient Research on Cavitating Flow in Diesel Nozzles

In summary, there has been extensive research on geometry-induced cavitation induced by nozzle geometric factors (such as nozzle hole structures), and effective control can be achieved by changing the nozzle structures. It has been observed that another string cavitation is induced by vortex flow inside the

FIGURE 17 Morphology evolution in near-nozzle region under 40 MPa.



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nozzle with the deepening of research on the internal flow. But there is relatively little research on this aspect, especially since two cavitating forms often coexist in the nozzle, and it is still unclear what is the mutual influence and interaction between two cavitating forms.

It has been widely known that viscous factors (geometric structure factors, dynamic factors) affect the inception and development of cavitation, while there is little research on the medium factors (fuel temperature, gas content) and wall factors. The influence of wall factors is relatively small, which is normally ignored in current research. The inception and development of different cavitating forms affect the flow coefficient, injection pressure, and spray atomization in diesel engine nozzle. At present, it is mainly carried out around these aspects that the research on the cavitating flow in the nozzle. The impact on pressure fluctuations has been more concerned in the fuel injection system by the business community in recent years. Therefore, the current insufficient research is as follows:

1. Research on the influence of medium factors on fuel temperature. Diesel fuel rubs with the fuel pipe and nozzle wall under the action of viscosity and strong compressibility, causing significant fuel temperature rise. Currently, relevant papers mostly focus on the cavitating flow in ambient temperature fuel without considering the cavitation phase transition driven by both temperature and pressure. Therefore, it is necessary to explore the cavitating two-phase flow under the dual action mechanism of temperature and pressure.
2. Research on medium factors under the influence of gas content. It is common that the impact of air content on cavitation in hydraulic machinery such as water turbines, and there are also studies on suppressing cavitation and reducing drag by injecting more air. In the study of cavitation phenomenon in diesel nozzle, the different bubble content affects the cavitation inception and even the pressure distribution of the flow field, thus determining the subsequent spray characteristics. However, it is still unclear that the influence of different gas contents in the fuel medium on the changes in its internal cavitating form and the mechanism of action between different cavitating forms, due to high injection pressures and high sealing in diesel engine. It is necessary to use ventilation to change the gas content in the system for relevant research.
3. Study on the effect of cavitating flow in the nozzle on near-field spray. The researchers mainly focus on the spray atomization, such as spray shape and spray breaking effect. The research on spray characteristics under the string cavitation is also limited to geometric factors such as spray angle. It is still insufficient that the internal structure of spray, especially the internal structure of spray under string cavitation.

4. Research on the effect of cavitation flow on system pressure fluctuations. Current research on pressure fluctuations mainly adopts numerical simulation methods due to the geometric size of diesel nozzle in diesel engine nozzles. The influence of different cavitation forms (geometry-induced cavitation and string cavitation) on pressure fluctuations needs further exploration during their inception and development. Similar to the cavitation effect, the pressure fluctuation at the nozzle outlet directly affects the spray stability, which is not conducive to the fine control of the fuel injection.

5. The Future Research Trends on Cavitating Flow in Diesel Nozzles

First, the new generation of internal combustion engines require the fuel and gas to be evenly mixed in a shorter time, which promotes further improvement of the fuel injection system, making it develop ultra-high injection pressure and small hole diameter [126]. At this time, the fuel is bound to have severe friction with the flow passage wall, causing a sharp rise in fuel temperature. The change in temperature alters the thermodynamic parameters such as fuel saturation, vapor pressure, and viscosity, exhibiting significant thermodynamic effects. However, current research is mostly conducted at room temperature on cavitation phenomena in diesel engine nozzles. Therefore, scholars need to explore the cavitating flow under high-temperature conditions, providing data support for improving the high-temperature two-phase flow model.

Second, the cavitation form is easy to change during fuel injection, causing disturbance to the surrounding fuel. This disturbance is manifested in pressure fluctuation, which aggravates the instability of near-field spray. However, current researches are mostly about the influence of various factors on cavitation forms. It is necessary to conduct relevant researches on the pressure fluctuations caused by cavitation forms, which is conducive to exploring stable near-field spray atomization.

In addition, gas should be injected into the pipeline in engineering practice and exist in the form of bubbles in the nozzle. The gas volume promotes or inhibits the cavitation in the nozzle, which has unique practical value in industry, which is something researchers still need to explore.

At last, researchers should further study the string cavitation extending to the nozzle outlet for the string cavitation caused by vortex, exploring the development of spray morphology. It is widely hoped that there is an effective way to improve combustion efficiency by investigating the contact area between spray droplets and surrounding air.

6. Conclusion

The cavitation phenomenon in the nozzle hole of a diesel engine directly affects the overall combustion efficiency and emission performance. The specific manifestations of cavitation phenomenon can be divided into geometry-induced cavitation and string cavitation, with relatively little research on the latter. This article summarizes the factors that affect cavitation phenomenon and the effects of cavitation phenomenon.

Among the factors affecting cavitation phenomena, although the research scope on viscosity factors is the most extensive, a relatively complete cavitation prediction model has not been established. Without considering external factors, changing the physical properties of fuel can also control the development of cavitation, among which ventilation operation can significantly suppress cavitation. Material surface factors can be considered last, provided that the nozzle material is determined.

For the effect of cavitation phenomenon, the flow coefficient and pressure fluctuation can serve as indicators of changes in cavitation morphology, while cavitation effect is one of the significant negative effects of cavitation phenomenon. Most attention should be paid to the spray atomization, since it is a factor directly related to combustion efficiency and emission performance. The concepts discussed above are important basis for integrating the concept of cavitation inside nozzles, and have important reference significance for establishing effective cavitation-atomization models.

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Abbreviation and Nomenclature

| Alphabet | Physical meaning |
|----------|--------------------------------------|
| D | Hole diameter |
| D_{in} | Hole inlet diameter |
| D_o | Hole outlet diameter |
| H | Needle lift |
| I | Cavitation intensity |
| K | Cone coefficient of nozzle hole |
| L | Hole length |
| L/D_o | Length/diameter ratio of nozzle hole |
| P | External pressure of bubbles |
| P_0 | Injection pressure |

| | |
|------------|----------------------------------|
| P_1 | Back pressure |
| P_g | Internal pressure of bubbles |
| P_{inj} | Injection pressure |
| P_v | Saturated vapor pressure |
| R | Bubble radius |
| Re | Reynolds number |
| S | Two-dimensional cavitation area |
| SAC | Nozzles with pressure chamber |
| S_{hole} | Two-dimensional hole area |
| T | Fuel temperature |
| V | Fuel velocity |
| VCO | Nozzles without pressure chamber |
| θ | Spray angle |

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