Research on the Effect of Water Injection Pressure on Knocking Combustion of a Direct Injection Gasoline Engine

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ABSTRACT: In this study, the research method of numerical simulation is used to explore the inhibition of different water injection pressures on knock combustion of turbocharged direct injection gasoline (GDI) engines by coupling computational fluid dynamics with a chemical-kinetics model. First, the ignition advance angle and compression ratio are increased to induce the GDI engine to knock, and then the influence of the water injection pressure on the in-cylinder, evaporation of water, and the knock of the gasoline engine are analyzed. The simulation results show that, compared with no water injection, the direct injection of water in the cylinder can significantly reduce the knock intensity. When the water injection pressure is greater than 40 bar, the knock intensity is less than 2 and the knocking is completely suppressed. In this work, the effects of different water injection pressures on knocking are explored by analyzing the effects of water injection pressure on water atomization, in-cylinder combustion, and the knocking mechanism. On the one hand, the evaporation rate of water increases with increasing water injection pressure and the quality of the liquid film generally improves. On the other hand, direct water injection can significantly reduce the distribution of CH$_2$O in the end mixture, thereby reducing the generation of H$_2$O$_2$ and further suppressing the spontaneous combustion of the end mixture. At the moment of knock, when the water injection pressure is greater than 40 bar, the detonation mechanism of the no. 7 monitoring point does not produce a sudden change in HCO radicals. The water spray can effectively reduce the NO$_x$ emission, and the NO$_x$ emission under the water spray pressure of 120 bar is the lowest. However, after spraying water, it will increase CO emissions.

1. INTRODUCTION

Current research on gasoline engines aims to improve their power performance and fuel economy while reducing pollutant emissions. Gasoline direct injection (GDI) engines can realize these goals well. Not only can GDI produce considerable torque at low speeds but it can also maintain torque over a wide range of speeds. At the same time, GDI does not increase the power of gasoline engines at the expense of increasing fuel consumption and emissions.¹,² However, knocking combustion is prone to occur as the compression ratio and load of the GDI engine increase.

The cause of gasoline deflagration is the rapid spontaneous combustion of the end mixture. In the case of strong deflagration, the engine power will decrease, the work will become unstable, the speed will decrease, and the engine will vibrate greatly.³ Knock is a major obstacle that limits the increase in engine compression ratio. At present, the measures to prevent knocking combustion mainly include using fuel with a higher octane number, adding antiknock materials, and selecting the best ignition advance angle.⁴,⁵ In addition, water injection is a simple and effective measure to alleviate engine knock. Because water has a large latent heat of vaporization, its evaporation and heat absorption in the cylinder can effectively cool the in-cylinder mixture and reduce the combustion temperature in the engine cylinder. These above implementations all have a positive effect on the suppression of engine knock and the increase in engine output.

Engine water injection technology mainly includes port water injection (PWI), direct water injection (DWI) into the cylinder, and fuel emulsification technology.⁶ Direct water injection into the cylinder has the following advantages compared with the other two methods: the injection time is more flexible because it is not limited to the opening and closing times of the intake valve; in addition, spraying water directly into the cylinder can improve the water atomization effect, which causes less water consumption and a good cooling effect.⁷ This has been confirmed by Boretti.⁸ He compared the effects of PWI and DWI on engine knock and combustion and finally suggested that DWI has a higher fuel conversion efficiency due to the steam expansion that follows water vaporization.

Different amounts of spray water will affect the initial conditions and emissions of the mixed gas in the cylinder. Too much
water injection may cause the water in the cylinder to atomize too late, making fuel mixing insufficient. Therefore, many scholars have investigated this topic. Kim et al.\textsuperscript{9} studied the effect of DWI on gasoline engines through experiments and found that increasing the injected water mass resulted in further spark advance without knock occurrence and provided room for further brake-specific fuel consumption reduction. Wei et al.\textsuperscript{10} used the computational fluid dynamics (CFD) method to inject different proportions of water into a GDI engine to explore its impact on engine performance and emissions. The results indicated that 15% water injection by mass combined with fuel gave the best engine performance due to the increase in the indicated mean effective pressure and efficiency resulting from the cooling of certain parts of the engine. Water injection also caused a decrease in NO\textsubscript{x} emissions, as well as soot emissions. Pei et al.\textsuperscript{11} and Liu et al.\textsuperscript{12} measured the effects of water injection on the knocking and combustion processes of a GDI engine with a high compression ratio (CR). Pei et al. found that when the water injection ratio is increased to 50%, engine knock drops by 82.7% and the indicated specific fuel consumption drops by 9.9%. Additionally, Liu et al. found that when the water/fuel ratio is increased from 0.1 to 0.5, the knock limit spark advance can be extended to varying degrees. In addition, the coefficient of variation in the indicated mean effective pressure (IMEP) drops to 1.15% as the knock limit spark advances when the water/fuel mass ratio is up to 0.5. Li et al.\textsuperscript{15} discovered that as the water ratio increases, the knock intensity decreases. As the water ratio increases from 5 to 25%, NO\textsubscript{x}, CO, and UHC will decrease with the increase in water ratio, but the soot emissions will increase. Chen et al.\textsuperscript{18} compared WI and EGR through experiments. They finally found that, compared with EGR, the main

Table 1. Basic Parameters of the GDI Engine

| parameter          | value |
|--------------------|-------|
| number of cylinders| 1     |
| cylinder bore/mm   | 76    |
| stroke/mm          | 82.6  |
| connection rod length/mm | 139.3 |
| displacement/L     | 0.5   |
| compression ratio  | 9.5   |

Table 2. Experimental Operating Conditions of the GDI Engine

| parameter                | value  |
|--------------------------|--------|
| crank speed/rpm          | 2000   |
| spark time/°CA           | 725.7  |
| fuel injection time/°CA  | 440    |
| fuel injection duration/°CA | 52.02 |
| total fuel injection mass/mg | 65.02 |

Table 3. Numerical Calculation Submodels

| models               | setting                        |
|----------------------|--------------------------------|
| turbulence model     | $k$ two-equation model         |
| fuel break model     | RT-KH model                    |
| collision model      | NTC collision model            |
| fuel collision model | wall film model                |
| combustion model     | SAGE model                     |
| NO\textsubscript{x} model | extended Zeldovich model |
| soot model           | Hiroyasu model                 |

Table 4. Knock Conditions of the GDI Engine

| parameter          | value  |
|--------------------|--------|
| compression ratio  | 10.3   |
| spark time/°CA     | 718    |
| equivalence ratio  | $1.1 \pm 0.01$ |
| total fuel injection mass/mg | 65.0258 |
| fuel injection time/°CA | 440.25 |

Figure 1. Geometric model of the GDI engine.

Figure 2. Comparison of the mean pressure between the experiment and simulation (CR = 9.5; ST = 725.7 °CA); (a) under 2000 rpm; (b) under 5600 rpm.

Figure 3. Schematic diagram of monitoring points.
superiority of WI is reduced NO\textsubscript{x} emissions without sacrificing fuel economy until the water mass reaches 50% of the fuel mass.

The timing of water injection is closely related to the atomization of water in the cylinder. Therefore, many scholars have conducted research on the water spray timing of DWI. Fratita et al.\textsuperscript{22} found that injecting the water before the start of the combustion delays the start of the combustion by up to 2.3 crank angle degrees (°CAs) and alters the combustion time. When the water is injected well before ignition, the combustion is slightly shortened, but when the injection takes place right before ignition, the combustion is significantly extended. Both Wang et al.\textsuperscript{19} and Wu et al.\textsuperscript{20} studied the effects of water injection timing on the combustion and emissions of natural gas engines. Wang et al. proved that the peak combustion pressure and peak combustion temperature were slightly decreased with a slowing of the water injection timing. Furthermore, by delaying the water injection timing, the volumetric efficiency increased slightly and NO\textsubscript{x} emissions decreased. The results of Wu et al. indicated that proper water injection timing (WIT) can not only effectively reduce knock intensity (KI) and NO\textsubscript{x} emission but also further improve thermal efficiency and realize high CR in spark-ignition natural gas engines. The knock intensity reaches its minimum and the IMEP and ITE reach their maximum at $-150$ °CA. With the delay of WIT, the water dilution and cooling effects are strengthened, and the CA50 is impeded, as found by Zhang et al.\textsuperscript{21} through the experiment of the GDI engine. Indicated thermal efficiency (ITE), NO\textsubscript{x}, CO, and HC emissions are reduced. ITE is higher than the test basis at a WIT
of $-100$ $^\circ$CA ATDC. IMEP is increased by 9.5%, and ITE is increased by 3.5% with a WIT of $-60$ $^\circ$CA ATDC.

Through experiments, Fabian and Cordier et al.\textsuperscript{24,25} found that increasing the injection pressure within a certain range is beneficial to the atomization and evaporation of water droplets, which will eventually lead to a difference in exhaust temperature.

In terms of the pressure of PWI, Rocha et al.\textsuperscript{26} determined through experiments that water injection time and water injection pressure have a greater impact on fuel consumption when the IMEP is 8 bar than when the IMEP is 5 bar. Meanwhile, Li et al.\textsuperscript{27} found that the KI of the GDI engine was the lowest when the water injection pressure was set at 5 bar. During this time, the work cycle volume is the highest and the emissions of NO\textsubscript{x} and HC are the lowest.

In addition to the water injection strategy mentioned above, the installation location of the water injector has also received attention from scholars. Raut and Mallikarjuna\textsuperscript{28} believed that CFD was used to study the influence of the position and

![Figure 6. Pressure curve (a) and PP\textsubscript{max} (b) at each monitoring point (CR = 10.3; ST = 718 $^\circ$CA).](https://doi.org/10.1021/acsomega.2c02220)
direction of the water injector on the water evaporation and emission characteristics of GDI engines. Finally, the optimal design was as follows: the water injector was installed between the exhaust valves at a distance of 29 mm from the spark plug and the direction was 24°. At this time, the indicated average effective pressure is improved by 9.2%, NOx is reduced by 48.2%, and soot is reduced by 22.6%.

In summary, water injection can effectively suppress the engine’s knocking tendency, as well as improve engine power and economy and reduce emissions. However, current scholars have seldom studied the water injection pressure of the DWI of GDI engines. The water injection pressure can directly affect the trajectory of the water movement in the cylinder. The higher the water injection pressure is, the larger the spray cone angle and penetration distance of the water droplets are and the greater the influence of the water moving at its own speed is. The more that the spray cone angle and penetration distance of water droplets increase with increasing water injection pressure, the greater the influence of the corresponding water movement at its own speed. On one hand, at present, the research on the effect of different water injection strategies of DWI on the knocking of GDI engines is not unified. On the other hand, the research on DWI is limited to the physical aspect and does not focus on the chemical reaction aspect, and the research on knock mechanism is lacking. During knocking combustion, peroxides and aldehydes are produced in the low-temperature multistage ignition process. Therefore, this study will select the specific model of the GDI gasoline engine and characterize the knock by the KI value combined with the generation of aldehydes and HCO radicals. Therefore, the effects of the water injection pressure of DWI on the combustion, knocking and emission of the engine were explored from both physical and chemical aspects.

2. CONSTRUCTION OF THE NUMERICAL MODEL OF THE GDI ENGINE AND KNOCK SIMULATION ANALYSIS

2.1. Geometric Model and Numerical Model of the GDI Engine. The geometric model, basic parameters, and operating conditions of the GDI engine are shown in Figure. 1, Table 1, and Table 2. In the numerical simulation, the selection of each submodel is very important, such as the turbulence model, spray model, combustion model, and so on. The turbulence model selected in this work is the RNG k−ε two-equation model, and the spray model is the discrete droplet model. Additionally, the SAGE combustion model is well adapted to various reactions. It has a higher degree of rationality for combustion simulation and can describe in detail the influence of different processes on the combustion process. The selection of each submodel is shown in Table 3. The surrogate of gasoline fuel consists of n-heptane, isoctane, and toluene in proportions of 17, 69, and 14%, respectively, and the chemical mechanism of the surrogate includes 113 components and 201 reactions, which can better describe combustion in the engine cylinder.

2.2. Verification of the Numerical Models. Figure. 2 shows the comparison of the mean pressure between the experiment and the simulation. It can be seen from the figure that the in-cylinder pressure curve of the experimental results is very close to that of the simulation results, and the deviation between the two is less than 5%. On the basis of this, it can be considered that the calculation model of this study can simulate the operating conditions of the GDI gasoline engine.

2.3. Numerical Simulation Analysis of Knock. To explore the effect of the direct injection of water in the cylinder to suppress knocking, this study is carried out at a compression ratio of 10.3 and a spark timing (ST) of 718 °CA, which causes the GDI gasoline engine to knock. Its operating conditions are shown in Table 4. To evaluate the degree of knock at different working conditions, the KI is defined as follows:

\[
KI = \frac{1}{N} \sum_{i=1}^{N} PP_{max,i}
\]  

In the above formula, KI represents the strength of knocking. The larger the value of KI is, the more obvious the trend of knocking. \(PP_{max,i}\) represents the difference between the peak of the pressure change curve at the monitoring point and the peak of the in-cylinder mean pressure. When KI is greater than 2, the gasoline engine knocks. Therefore, after analyzing the results of the simulation, eight monitoring points are uniformly selected in the area near the cylinder wall. The specific positions of the monitoring points are shown in Figure. 3.

3. RESULTS AND DISCUSSION

3.1. Determination of the Time and Location of Knock. The combustion of hydrocarbon fuels is the result of a series of chemical reactions. When the fuel is burned, \(\text{CH}_2\text{O}\) is first decomposed in the low-temperature reaction stage and the OH radical is decomposed by the reaction \(\text{H}_2\text{O}_2 + (M) = \text{OH} + \text{OH}(M)\) in the high-temperature stage. After the reaction \(\text{CH}_2\text{O} + \text{OH} = \text{HCO} + \text{H}_2\text{O}\), \(\text{H}_2\text{O}\) is oxidized by \(\text{OH}\) radicals to generate \(\text{HCO}\) radicals. Finally, after the reaction of \(\text{HCO} + \text{OH} = \text{CO} + \text{H}_2\text{O}\) is completed, a large amount of \(\text{CO}\) is generated, thereby releasing heat.

To determine the knock mechanism, the combustion at the monitoring points was analyzed from the point of chemical kinetics. Figure 4 shows the distribution field diagram of the temperature field, where \(\text{HCO}\) radicals and \(\text{OH}\) radicals are at 731–734 °CA. It can be seen from the figure that the in-cylinder temperature and the \(\text{OH}\) radicals gradually increase as combustion progresses. This is consistent with the study by Kawahara et al. where \(\text{OH}\) radicals are indicators of low-temperature chemical to high-temperature spontaneous combustion reactions. At 734 °CA, the temperature near monitoring
Figure 8. Pressures of eight monitoring points under different water injection pressures (CR = 10.3; ST = 718 °CA).

Figure 9. \( P_{\text{max}} \) (a) and KI (b) under different injection pressures (CR = 10.3; ST = 718 °CA).

Point no. 7 is higher than the temperature in other areas. From the distribution of HCO radicals in the combustion chamber, it can be seen that, at 732 °CA, HCO in all directions of the combustion chamber is not much different from that of the wall.
At 733 °CA, the HCO radicals distribution at monitoring point no. 7 obviously changes abruptly. Combined with the distribution of OH radicals, it can be seen that, after the reduction of the HCO radicals, the OH radicals increase significantly. This is consistent with the conclusion of Merola et al.38 who concluded that when knocking occurs, HCO radicals appear in the knocking area first, followed by a large number of OH radicals appearing in the knocking area. On the basis of the flame propagation process diagram in Figure 5, it can be seen that, at 733 °CA, the flame has not yet reached the exhaust side. At 734 °CA, there was a hot spot at monitoring point no. 7 before the flame reached the cylinder wall, which means that the end mixture near monitoring point no. 7 had spontaneous combustion occurring at 734 °CA. It can be seen that the change in radicals in the cylinder can reflect the combustion situation in the cylinder, which is of great significance for analyzing the knocking of the engine.

When the engine knocks, the macroscopic aspect, fluctuations in pressure can be observed. Figure 6a is a comparison diagram of the change curve of each monitoring point and the average pressure in the cylinder under knocking conditions to more intuitively illustrate the intensity of engine knocking. Various monitoring points have different degrees of fluctuation compared to the average pressure in the cylinder. The monitoring point with the largest pressure fluctuation is monitoring point no. 7. The peak pressure of monitoring point no. 7 is 12 MPa higher than the average pressure peak. Monitoring point no. 8 follows, and its pressure peak exceeds the average pressure in the cylinder by 10 MPa. Robert et al.40 believe that the exhaust temperature is much higher than the intake temperature during the combustion process, and the terminal mixture near the exhaust valve is more likely to be heated and spontaneously ignited. Monitoring points 7 and 8 are both located on the exhaust side, which is consistent with Robert’s research. Combined with the $P_{\text{max}}$ under the eight monitoring points in Figure 6b, it can be seen that the $P_{\text{max}}$ of monitoring point no. 7 is also the largest. According to the above formula, the KI value of the engine at this time is 6.4, and it can be inferred that the engine has knocking.

### 3.2. Influence of Water Injection Pressure on Knocking

In this study, five water injection pressures of 40, 60, 80, 100, and 120 bar were studied. To explore the effect of water injection pressure on combustion, knock, and emissions, the results without water injection were also studied for comparison. The geometric model with the injector is shown in Figure 7. The relevant parameters of water injection are shown in Table 5, while the other parameters of the engine are consistent with Table 1 and Table 2.

#### 3.2.1. Analysis of Knock Intensity

The pressure change curve of each monitoring point under different water spray pressures is shown in Figure 8. The peak pressure of each monitoring point decreases significantly after water spraying, and the fluctuation range also decreases substantially, showing that water spraying can significantly suppress the trend of knocking.

The $P_{\text{max}}$ under different injection pressures is shown in Figure 9a, and the maximum $P_{\text{max}}$ without water injection is as high as 12 MPa at monitoring point no. 7. When the water injection pressure is 40 bar, the maximum value of $P_{\text{max}}$ is 2.9, and the value of $P_{\text{max}}$ is significantly reduced after injection. Figure 9b shows the KI under different water injection pressures. It can be seen from the figure that water injection can considerably reduce KI. The KIs under different water spray pressures are as follows: no water injection > 40 bar > 60 bar > 80 bar > 120 bar > 100 bar. This is the distribution of turbulent kinetic energy (TKE) before ignition because KI is related to the intensity and duration of the water’s disturbance to the mixture in the cylinder. For low turbulent kinetic energy, increasing the turbulent kinetic energy is conducive to flame propagation. As the water injection pressure increases, the water in the mixed gas area at the end of ignition continues to decrease and the mass of water droplets colliding with the wall also increases. Therefore, the water spray pressure should not be too large. The KI decreases with increasing spray pressure when the water injection pressure is less than 100 bar. When the KI is close to 2 and the injection pressure is 40 bar, the engine is in a critical knock state. When the spray pressure is more than 40 bar, no knock occurs because the KI is much less than 2. The water injection pressure has almost no effect on KI when the pressure is greater than 80 bar, and when the water injection pressure is 100 bar, the KI of the engine is the smallest.

In order to investigate the combustion stability in the cylinder of this study, the pressure changes in 11 consecutive cycles with water injection pressure of 100 bar are plotted, as shown in Figure 10a. It can be seen from the figure that the fluctuation range of the maximum combustion pressure is 16−18.5 MPa and the position of $P_{\text{max}}$ also changes. The IMEP calculated from the in-cylinder pressure is shown in Figure 10b, and its fluctuation range is 1.19−1.33 MPa. Coefficient of variance (COV) is used as a measure of engine combustion stability and is calculated as follows:

$$\text{COV} = \frac{\sigma_{\text{IMEP}}}{\text{IMEP}} \times 100\%$$

#### Table 5

| Water Injection Pressure (bar) | IMEP (MPa) |
|------------------------------|------------|
| 0                            | 0.8        |
| 40                           | 0.6        |
| 60                           | 0.5        |
| 80                           | 0.4        |
| 100                          | 0.3        |
| 120                          | 0.2        |

**Figure 10.** In-cylinder mean pressure (a) and IMEP (b) under 11 cycles of calculation (CR = 10.3; ST = 718 °CA).
The COV calculated according to the IMEP of Figure 10b is 4.12%. The in-cylinder combustion is considered as stable until COV_{IMEP} exceeds 5%. Therefore, direct water injection can not only suppress knocking but also has better combustion stability.

### 3.2.2. Movement of Water in the Cylinder

In this section, the effects of different water injection pressures on engine knock...
will be explained from the aspects of water atomization and mixing in the cylinder. First, during DWI, the water is atomized, evaporated, mixed into the fuel and air in the cylinder, and finally combusted with the fuel. Therefore, the degree of atomization of water directly determines the degree of fuel combustion. Figure 11a shows the trajectory of water and Figure 11b shows the liquid film quality in the cylinder under different water injection pressures during 660°–718° CA. Figure 11a shows that the distribution area of water in the cylinder increases with increasing spray pressure and that the evaporation rate of water also increases. This occurs because the higher the spray pressure of the water is, the larger is the spray cone angle of the water drop and the greater is the penetration distance of the water mist. The longer the water droplet’s own velocity plays a dominant role in the movement process, the more conducive it is to the uniform distribution of water. Before the ignition moment (718° CA), there is still some water near the spark plug that has not evaporated when the spray water pressure is 40 bar. The unevaporated water may affect the flame propagation in the early stage of ignition. There is little water distribution near the spark plug when the spray water pressure is greater than 40 bar, which will not hinder the spread of the flame. In addition, the unevaporated water is basically distributed near the cylinder wall, which is beneficial for reducing the temperature of the mixture at the end and suppressing the occurrence of knocking. The quality of the liquid film formed by the water colliding with the cylinder wall under different injection pressures is shown in Figure 11b. As the injection pressure increases, the peak value of the liquid film quality also increases. When the spray water pressure is 80 bar, it decreases slightly, which may be related to the disturbance in the cylinder. Because the spray cone angle and penetration distance increase with the water injection pressure, the initial water mist’s own speed dominates and the water diffusion speed increases, causing more water to collide with the cylinder wall. Therefore, as the water injection pressure increases, the atomization effect of the water is improved, resulting in better mixing within the cylinder.

The equivalence ratio distribution reflects the uniformity of the mixing of fuel and air in the cylinder, which affects the complete combustion of the fuel. The equivalence ratio distributions under different water injection pressures are shown in Figure 12a. The equivalence ratio distribution is the most uneven when the water injection pressure is 40 bar. When the water injection pressure is greater than 100 bar, the distribution of the equivalence ratio in the central area of the cylinder is relatively uniform compared to some areas of the cylinder wall that are not uniform. Therefore, in all water spraying conditions, the KI of the water spray pressure of 40 bar is the largest and the KI of 100 bar is the smallest. The TKE distribution under different injection pressures is shown in Figure 12b. As the spray pressure increases, the evaporation rate of water increases with the speed of water movement. The disturbance effect of water on the cylinder will be strengthened when the water injection pressure is increased, so the TKE at the center of the cylinder before ignition increases with increasing water injection pressure. However, the evaporation rate of water increases with increasing water injection pressure, and as a result, the duration of the disturbance of water in the cylinder is shorter. Therefore, the perturbation time of the cylinder center decreases with increasing water injection pressure and the TKE of the cylinder center decreases slightly before ignition. The high TKE distribution area in the center of the cylinder occurs at pressures of 40, 60, 80, 100, and 120 bar. Because the high TKE in the center of the cylinder is beneficial to flame propagation and reduces the preparation time for the terminal mixture to spontaneously ignite before the flame front arrives, the distribution of high TKE in the center of the cylinder under different water injection pressures is the same as the KI.
of vaporization of water is very large and liquid water can absorb a large amount of heat released during the combustion process. Conversely, water is a triatomic gas with a large specific heat capacity, which increases the specific heat capacity of the gas in the cylinder. Both of these aspects help to reduce the temperature and pressure peaks in the cylinder. In addition, some chemical reactions will be restricted by water and thus inhibit a series of chain reactions, thereby limiting the generation of some radicals and active groups.

Figure 14a shows the heat release rate (HRR) under different water injection pressures. The peak value of the HRR decreases significantly after water injection. The peak value of HRR is larger when the water injection pressure is 40 bar. Indicating that it produces local heat release during the combustion process, which is also the reason why its KI value is higher than that under other water injection pressures. The peak values of instantaneous heat release rates under other water spray pressures are not much different. Figure 14b shows the heat release (HR) under different water injection pressures. The HR after spraying is much lower than that without water spraying. The combustion duration was 6 °CA without water injection and 8–9 °CA after water injection. Therefore, water injection will increase the combustion duration, thereby reducing the preparation time for the autoignition of the terminal mixture.

3.2.4. Analysis of the Knock Mechanism. Peroxides and aldehydes produced by the low-temperature multistage ignition process were detected in the spontaneous ignition area near the cylinder wall in related experiments. The following discussion will analyze the impact of low-temperature chemical reactions on the ignition process.

The quality changes of CH$_2$O and H$_2$O$_2$ in the cylinder under different water injection pressures are shown in Figure 15. It can be seen that the peaks of CH$_2$O and H$_2$O$_2$ are significantly reduced after spraying water. Both CH$_2$O and H$_2$O$_2$ reach the maximum peak when the water injection pressure is 40 bar. This is the same as the change trend of the HRR peak value in Figure 14a, which can also properly illustrate the important factors of CH$_2$O and H$_2$O$_2$ that cause a change in the heat release in the cylinder. In addition, the low-temperature reaction will produce a large amount of CH$_2$O and H$_2$O$_2$. These two types of radicals have a strong relationship with the low-temperature reaction. Due to the influence of the heat and
pressure propagated by the flame, the terminal mixture will have different degrees of low-temperature reactions before the flame reaches it. When this happens, the interacting gas may ignite spontaneously, so water spraying can suppress the generation of internal objects. Therefore, the water spray can inhibit the generation of these two types of radicals in the cylinder. However, which part of the low-temperature reaction is specifically suppressed requires further analysis.

Figure 16 shows the distribution of CH$_2$O in the cylinder under different spray pressures (CR = 10.3; ST = 718 °CA). Water spraying can obviously inhibit the low-temperature chemical reaction of the terminal mixture, thereby reducing the spontaneous combustion of the terminal mixture and inhibiting the tendency of knocking.

Figure 17. HCO radicals can mark the position of the end mixture where spontaneous combustion begins.
occurs because HCO radicals will be generated in the front of the flame. From the previous analysis, it can be seen that the time and location of knocking are 733–734 °CA and monitoring points no. 7 and 8, respectively. At 733 °CA, only the flame fronts of monitoring points no. 6 and no. 7 in the unsprayed condition changed abruptly. This indicates that spontaneous combustion occurred on the cylinder wall surface. When the water spray pressure is 40 bar, a sudden change occurs in the flame front near monitoring points no. 7 and 8 at 735 °CA. When the spray pressure is 60 bar, the flame front near the area at monitoring point no. 7 undergoes a sudden change. Since the knocking time has passed at this time, the change in HCO radicals at this time is only generated by the oxidation of CH₂O by OH radicals.

3.3. Influence of Water Injection Pressure on Cycle Work. The $p-V$ diagrams under different water spray pressures are shown in Figure 18a. In order to quantitatively analyze the cycle work of the GDI gasoline engine, the closed curves in the figure are integrated and their respective areas are obtained to obtain the cyclic work capacity under different water injection pressures, as shown in Figure 18b. It can be seen that after water spraying, the cycle work is smaller than that without water spraying. On the one hand, the water injected into the cylinder will absorb the heat in the cylinder, which will significantly reduce the average temperature and pressure in the cylinder. On the other hand, water injection will increase the combustion duration of the engine, which will reduce the isovolume of the cylinder.
Comparing the cycle work under different water injection pressures, it can be found that the cycle work increases with the increase of water injection pressure. Because the water injection pressure increases, the atomization of the water is better, which is beneficial to the improvement of the engine power performance. The terminal mixture clearly ignited spontaneously when the water injection pressure is 40 bar. Due to the impact of the pressure wave generated by the self-ignition of the terminal mixture on the piston, some fuels do some useless work, so the cycle workload is minimal. Although the cycle work decreases after water spraying compared with that without water. The cycle work cannot be improved by using water spraying technology alone. However, under the experimental condition (compression ratio = 9.5; ignition time = 725.7 °CA), the cycle work is 901.0 J. When the water injection pressure is greater than 40 bar, the knocking has been completely suppressed and the cycle work is greater than 1020 J. Especially when the water injection pressure is 120 bar, the cycle work is 1028.9 J. Therefore, the combination of water injection, increasing the compression ratio, and pre-ignition can improve the cycle work of the gasoline engine.

3.4. Influence of Water Injection Pressure on Emission.

Figure 19 shows the mass change curve and cumulative amount of NO\textsubscript{x} under different water injection pressures. Figure 19a shows that the mass of NO\textsubscript{x} first increases to a peak and then slowly decreases. Since this study mainly uses high-temperature NO, the NO emission mechanism used in this study is the extended Zeldovich reaction mechanism. Therefore, the main factors affecting NO are oxygen concentration and temperature. After the spark plug is ignited, the temperature in the cylinder continues to rise. In the case of sufficient oxygen, the higher the temperature is, the faster the reaction speed is and the faster the generation speed of NO\textsubscript{x} is. When the temperature exceeds 1800 K, the formation rate of NO\textsubscript{x} increases rapidly with increasing temperature. The quality of NO\textsubscript{x} will decrease because the formation reaction of NO\textsubscript{x} is reversible. As the piston descends, the temperature in the cylinder decreases and the reverse reaction is dominant. Since the in-cylinder temperature is significantly reduced by water injection, both the peak value of NO\textsubscript{x} and the final generation quality after water injection are significantly reduced compared to that without water injection.

First, the effect of temperature on NO\textsubscript{x} emissions was analyzed. The temperature distribution under different water injection pressures is shown in Figure 20. The high-temperature area of the temperature field after water injection drops significantly, and the high-temperature duration also decreases slightly. The total amount of NO\textsubscript{x} first increased with increasing water injection pressure and then decreased with increasing water injection pressure. NO\textsubscript{x} emissions are highest at a water injection pressure of 80 bar, since, at 745 °CA, there are more high-temperature areas in the cylinder at an 80 bar injection pressure than at other operating conditions. This phenomenon is more pronounced at 755 °CA.

The oxygen concentration also has a certain influence on the formation of NO\textsubscript{x}. Figure 21 shows the oxygen concentration distribution at different water injection pressures. The oxygen-enriched area in the cylinder is slightly reduced after water injection. The liquid water injected into the cylinder absorbs the heat released by combustion and transitions into water vapor, thereby diluting the oxygen concentration to a certain extent. Comparing the working conditions of different water injection pressures, it can be seen that as the water injection pressure increases, the oxygen-enriched area increases slightly at first and reaches a peak at 80 bar. Subsequently, the oxygen-enriched area decreases slightly as the water injection pressure increases. Therefore, the NO\textsubscript{x} emission is also the highest when the water injection pressure is 80 bar and the lowest when the pressure is 120 bar.

Figure 18. p–V diagram (a) and cycle work (b) under different water injection pressures (CR = 10.3; ST = 718 °CA).

Figure 19. NO\textsubscript{x} emissions (a) and cumulative mass of NO\textsubscript{x} (b) under different water injection pressures (CR = 10.3; ST = 718 °CA).

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The mass change curve of CO under different water injection pressures is shown in Figure 22a. It can be seen that the quality of CO increases slowly at first and then increases rapidly. After reaching the peak, the CO under different working conditions will decrease to varying degrees. This is because the temperature in the cylinder rises very slowly in the early stage of ignition, so the generation of CO is relatively slow. In the later stage of combustion, the flame spreads rapidly, the temperature in the cylinder rises rapidly, and the generation rate of CO increases rapidly. The slight decrease in the peak CO value is due to the fact that part of the CO is oxidized to CO\(_2\) at the later stage of combustion. It can be seen from the figure that after water spraying, the emission of CO increases. It can be seen from Figure 22a that, after water injection, the average temperature in the cylinder is significantly reduced, resulting in a large amount of CO that cannot be oxidized to CO\(_2\). So CO emission will increase after spraying water. However, different water injection pressures have little effect on the formation quality of CO shown in Figure 22b.

4. CONCLUSION
This study sets five water injection pressures of 40, 60, 80, 100, and 120 bar and compares them with the unsprayed conditions.
The in-cylinder distribution of water mist before ignition and the changes in low-temperature reactants during knocking were analyzed, and the influence of different water injection pressures on combustion and knocking was explored.

1) Compared with unsprayed water, the KI of the GDI engine is significantly reduced after spraying water. When the water injection pressure is greater than 40 bar, the KI is much less than 2 and knock is completely suppressed. This is because WI inhibits the generation of knocking by inhibiting the low-temperature chemical reaction and the generation of knocking mechanism. Compared with that in the unsprayed condition, the water spray significantly reduced the CH₂O distribution in the end mixture. When the water injection pressure is greater than 60 bar, the detonation mechanism of monitoring point no. 7 has no mutation of HCO radicals.

2) The evaporation rate of water and the quality of the liquid film increase with increasing injection pressure. Since the high TKE in the center of the cylinder is conducive to flame propagation and reduces the preparation time for the terminal mixture to spontaneously ignite before the flame front arrives, the high TKE distribution area in the center of the cylinder is consistent with that of the KI: 40, 60, 80, 100, and 120 bar.

Figure 21. O₂ concentration distribution of O₂ under different water injection pressures (CR = 10.3; ST = 718 °CA).
(3) Although the cycle work after water injection is smaller than that without water injection, the combination of appropriate water injection strategy, increasing compression ratio, and ignition advance can effectively increase the cycle workload. DWI can reduce in-cylinder NO\textsubscript{x} emissions, either by reducing the in-cylinder temperature and high-temperature duration or by reducing the in-cylinder oxygen concentration. Under the water injection condition, except when the water injection pressure is at 80 bar, the NO\textsubscript{x} decreases with increasing water injection pressure. However, DWI significantly increases CO emissions compared to nonwater injection.

5. DEFICIENCIES OF THE RESEARCH IN THIS ARTICLE AND FUTURE PROSPECTS

(1) In this work, the effect of direct water injection in the cylinder on combustion and emissions is investigated under low-speed and full-load conditions. Therefore, in the following work, in order to obtain the general law of direct water injection in the cylinder in suppressing knocking, improving engine performance, and reducing emissions, research should be carried out under more working conditions.

(2) Since increasing the compression ratio by reducing the clearance volume will cause the mesh to interfere with the relevant components, the adjustment range of the compression ratio in this work is limited. Therefore, in the following work, the GDI engine model with a higher compression ratio should be established to further improve the engine efficiency.

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Figure 22. CO emissions (a) and cumulative mass of CO (b) under different water injection pressures (CR = 10.3; ST = 718 °CA).

Notes
The authors declare no competing financial interest.

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■ ABBREVIATIONS
CFD, computational fluid dynamics; CR, compression ratio; DWI, direct water injection; GDI, gasoline direct injection; HRR, heat release rate; IET, indicated thermal efficiency; IMEP, mean effective pressure; KI, knock intensity; PWI, port water injection; ST, spark timing; TKE, turbulent kinetic energy; WIT, water injection time

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