Numerical simulation of the influence of fuel temperature and injection parameters on biodiesel spray characteristics

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Abstract
The purpose of this study is to investigate the effects of fuel temperature and nozzle length-diameter ratio (L/D) on biodiesel spray characteristics, under high injection pressure and high ambient pressure, by numerical method. The analysis of spray characteristics is carried out in conjunction with the transient flow inside nozzle. To achieve this, three-dimensional calculation grids of spray nozzle and spray domain were setup, and the needle movement was achieved by dynamic mesh technique. The reliability of spray models was validated by experimental results. It was established that the variation in spray tip penetration (STP) and Sauter mean diameter (SMD) is similar at different initial conditions. The STP increases at a faster rate initially and then slows down, whereas the SMD gradually decreases with time after the injection. In addition, a sensitivity analysis of the effects of injection parameters on biodiesel spray characteristics was conducted. Compared to the nozzle L/D, injection pressure and fuel temperature have a greater impact on biodiesel spray characteristics. The increase in injection pressure has a significant effect on the velocity distribution, STP and SMD. When the injection pressure is increased from 100 to 200 MPa, the maximum velocity of the spray core zone increases by 33.96%, the STP increases by 27.17%, and the SMD reduces by 14.81%. Furthermore, an increase in fuel temperature mainly affects the concentration distribution and the SMD of atomized droplets. When the fuel temperature is increased from 300 to 350 K, the maximum concentration of axial spray center lowers by 25.41%, and the SMD decreases by 17.19%. However, the increase of L/D chiefly impacts the concentration of axial spray center, but has little effect on other spray parameters. When the nozzle L/D is increased from 4 to 8, the maximum concentration of axial spray center increases by 20.29%.

Keywords
biodiesel, fuel temperature, injection pressure, length-diameter ratio, numerical simulation, spray characteristics
1 | INTRODUCTION

With increasing industrialization and greater usage of automobiles, the supply of fossil fuels such as petroleum and natural gas may eventually dwindle, and many countries are conducting research on clean alternative fuels for automobiles. Biodiesel is a green and renewable energy, and it is produced from vegetable oils, animal fats, waste cooking oils, microalgae oil, etc. Biodiesel can be mixed with diesel in different proportions, and the fuel blends can be used in a diesel engine without major structural modifications, making it an attractive alternative to traditional mineral diesel.1-7 The physicochemical properties of biodiesel, which are different from those of diesel, do influence the fuel spray behavior. Previous research has revealed that the spray quality of biodiesel is inferior to diesel owing to its higher density, kinematic viscosity, and surface tension.8-12 Furthermore, quality of fuel atomization greatly influences the combustion characteristics and pollutant emissions of a diesel engine. Homogeneous air-fuel mixture can decrease the particulate matter (PM) emissions and increase the combustion efficiency of a diesel engine. The variations in fuel temperatures and injection parameters impact the spray behavior of biodiesel. Therefore, to improve spray quality of biodiesel, it is necessary to quantitatively analyze the effect of fuel temperature and injection parameters on the spray characteristics of biodiesel.

Some researchers have investigated the biodiesel spray characteristics from different perspectives through both experimental and simulation methods. The influence of fuel properties on the spray characteristics has been investigated in some literature.13-19 Their results revealed significant differences in injector internal flow and spray characteristics between biodiesel and diesel. The cavitation and turbulence levels of biodiesel are lower than those of diesel. The injection velocity and mass flow rate are lower for biodiesel, and biodiesel should be injected at about 60 K higher temperature as compared to diesel.20 Furthermore, the atomization quality of biodiesel is inferior to diesel. The spray tip penetration (STP) and Sauter mean diameter (SMD) are greater, while dispersion area and spray cone angle (SCA) are smaller, for biodiesel. In addition, the effects of fuel temperature and ambient gas temperature on spray characteristics of biodiesel were studied by experimental and numerical analyses.21-24 It was found that an increase in ambient temperature (from 300 to 450 K) has a greater impact than an increase in fuel temperature (from 300 to 360 K), on the spray liquid tip penetration, and high-quality air-fuel mixture can be generated when the fuel temperature and ambient air temperature both increase. With the increase in fuel temperature, the STP and SMD of biodiesel gradually decrease. However, the STP, SCA, and the distribution of evaporated fuel mass increase as the ambient air temperature increases. The effects of injection pressure and ambient pressure on biodiesel spray behavior were revealed in some studies.25-31 The results show that higher fuel injection pressure results in longer STP, smaller SMD, higher spray velocity, and more turbulent kinetic energy than that at lower injection pressures, while the SCA shows no significant change at different injection pressures. Furthermore, with the increase in ambient pressure, the STP and SMD decrease, the SCA obviously increases, and the cavitation intensity inside the injector nozzle is lower. Moreover, the effects of nozzle tip configurations on the spray characteristics were investigated, and the spray behaviors of three nozzles with cylindrical, conical, and conical-cylindrical configurations were tested and discussed in the literature.19,32 The results reveal that for a given mass flow rate, the conical nozzle shows a better atomization efficiency with smaller SMD than cylindrical and conical-cylindrical nozzles. It also exhibits higher air-to-liquid mass ratios, higher airflow rates, lower discharge coefficients, and higher air and liquid injection pressures than the other nozzles tested.

Overall, these previous literatures analyze the effects of fuel properties, ambient temperature, fuel temperature, ambient pressure, and injection pressure on the spray characteristics or the flow inside the nozzle by experimental or numerical methods. While the injection pressures and the ambient pressures of some studies are relatively lower, which are out of step with the modern high-intensity diesel engines, and relatively few studies deal with the coupling analysis of the biodiesel transient flow inside nozzle and its spray behavior. The cavitation and turbulent in the nozzle, as well as injection velocity and mass flow rate at the nozzle exit, have significant effects on the fuel spray and atomization. Therefore, it is necessary to conduct the coupling analysis of inner nozzle flow and spray behavior. Furthermore, with the increase in the engine power density, the injection pressure and ambient pressure of turbocharged diesel engine become increasingly higher. Therefore, this work focuses on the coupling analysis between cavitation flow inside the nozzle and the spray characteristics under high injection pressure and ambient pressure conditions. The three-dimensional calculation grids of nozzle hole and spray domain were setup by Gambit software, and the needle movement was achieved by the dynamic mesh technique. The analysis of biodiesel spray characteristics is carried out with respect to the transient flow inside the nozzle because the fuel injection velocity and mass flow rate at the exit of nozzle are changing constantly from the opening to closing of needle valve. The cavitation flow model and spray calculation model were established using the FLUENT software. Meanwhile, spray simulation results were compared with experimental results to validate the reliability of the numerical simulation models. Afterward, the effects of different injection parameters, such as injection pressure, nozzle hole length-diameter ratio, and fuel temperature on the STP, SMD, injection velocity, and concentration...
distribution of biodiesel are compared and analyzed. Finally, the sensitivity analysis of the effects of injection parameters on biodiesel spray characteristics was conducted.

2 | COMPUTATIONAL GRIDS AND PARAMETERS SETTING

2.1 | Computational grids

In this study, a standard single-hole nozzle was used in the experiment and simulation, as shown in Figure 1. In the spray experiment, the high-speed camera and the Malvern laser PSA were placed on the side of fuel spray. In order to record the SCA and the STP at different injection time, determine the SMD of atomized droplets at different positions, and avoid the impacts of the overlapped spray from multi-hole nozzle on the test results, a single-hole nozzle was usually used for easier testing. Furthermore, the simulation results should be validated by the test results, so a model of single-hole nozzle was also established in the simulation process. The diameter $D$ of the nozzle hole is 0.315 mm, the length $L$ is 1.89 mm, the curvature radius $R$ of the transition fillet is 0, and the maximum lift $h$ of needle valve is 0.25 mm.

The three-dimensional calculation grids of the nozzle were setup by Gambit software. The 3-D nozzle is more consistent with the structure of the actual nozzle, as computing resources permit. In addition, the 3-D nozzle is convenient for the researchers to track the pressure distribution, the velocity distribution, and the cavitation distribution on the different cross section of the nozzle, and the calculation results can be expressed in the form of a cross-sectional nephogram.

The files of user-defined function (UDF) about needle movement were compiled, and the needle movement rule was defined in the UDF file. The file is a subprogram written in C code language, which can be called in FLUENT software through setting program link. The needle movement rule is shown in Figure 2. The initial lift of needle valve was 0.016 mm, and the maximum lift was 0.25 mm. The initial rise velocity of the needle was 0.186 m/s, which increased to 0.42 m/s. The needle descent velocity was 0.489 m/s, and the total duration of movement of needle was 1.41 mseconds.

The grid updating technology of dynamic layers was used to achieve the needle movement, and the influence of the needle movement on the transient cavitation flow inside the nozzle was investigated by the dynamic mesh technique. The nozzle configuration is a regular circular shape. In order to save computer resources and accelerate calculation speed, 1/4th nozzle was used for generating mesh without affecting the computational accuracy, as shown in Figure 3A. Considering the fuel flow characteristics inside nozzle, the mesh was densified in those places, such as the entrance and the exit of nozzle, near the wall surface, and boundary layer. Nozzle calculation grids of different needle lifts are shown in Figure 4.

According to the STP and SCA obtained from the spray experiment, the calculation grids of spray domain were created to ensure spray penetration. The spray calculation domain was set to a cylinder with a radius of 200 mm and a height of 400 mm, after which the structured grids of the cylinder were generated by Gambit software, as shown in Figure 3B. The nozzle exit was located at the center of the top surface of the cylinder. Considering the spray development characteristics, the calculation grids were densified near the nozzle exit and the cylinder axis.

![FIGURE 1 Schematic of two-dimensional nozzle section. Note: D is nozzle diameter, L is nozzle length, R is transition fillet radius, and h is maximum lift of needle valve](image)

![FIGURE 2 Needle movement rule](image)
In this study, the mesh quality test was carried out by the method of Grid Convergence Index (GCI), which was a method based on Richardson extrapolation for estimating grid discrete error. Five sets of meshes with the different refinement levels were established for the tested nozzle in this paper, the node number in the five sets of meshes was 1.21, 1.52, 1.72, 2.01, and 2.32 million, respectively. The velocity of the nozzle exit was considered as the important characteristic parameters for the numerical simulation of the inner flow of the nozzle, and the velocity parameters with five sets of meshes were calculated, respectively. The results showed that the flow velocity increased monotonously with the refinement of grids, as shown in Figure 5. When the number of nodes increases from 1.21 to 1.72 million, the flow velocity increases significantly. While the number of nodes reaches 1.72 million, the flow velocity tends to be stable. Then, the GCI method was adopted to estimate mesh discrete error, and the GCI of the nozzle with 1.72 million nodes is 0.76%. In order to economize computing resources, the nozzle with a relatively small number of 1.72 million nodes was selected for the final numerical simulation. Similarly, the Sauter mean diameter was considered as the characteristic parameters for the simulation of fuel spray. The calculated GCI was 0.27% when the number node of the spray domain is 960,000, which can meet the requirement of mesh convergence. Therefore, the total number of calculation grids for the injector nozzle and the spray domain were 1,720,000 and 960,000, respectively.

### 2.2 Boundary conditions

In the numerical simulation of nozzle internal flow, the inlet and outlet of the nozzle were set to pressure boundary. The inlet pressure of nozzle was set as fuel injection pressure, the outlet pressure of nozzle was set as ambient pressure, and the wall surface of nozzle was set to no-slip velocity boundary. The top surface, the bottom surface, and the circumferential surface of spray domain were set to the fixed wall boundary in the numerical simulation of biodiesel spray characteristics. Furthermore, the boundary type of bottom surface was set to “escape,” and the boundary type of surrounding wall was set to “reflect.”

First, the numerical calculation of transient flow inside nozzle was conducted. Then, the calculation results at the nozzle outlet were used as the initial conditions of the spray numerical computation, which made the spray simulations more accurate.

### 2.3 Fuel property parameters

The biodiesel used in this study was produced from soybean oil by transesterification with methanol. It was composed of various fatty acid methyl esters with different carbon chain lengths, and its composition was examined by gas chromatography, as shown in Table 1. The soybean biodiesel contains 89.76% fatty acid methyl ester, in which more than
30.26% are saturated fatty acid esters and unsaturated fatty acid esters account for 59.51%. Linoleic acid esters, oleic acid esters, and palmitic acid esters are the major components of biodiesel from soybean oil.

The physicochemical properties of biodiesel were tested according to the national standard test methods, and compared with that of diesel, as shown in Table 2. The test results show that the density of soybean-based biodiesel is about 4.6% higher than that of mineral diesel. The viscosity of biodiesel is approximately 62.8% higher than that of diesel. The surface tension of biodiesel is approximately 7.1% higher than that of diesel. The distillation temperature of biodiesel is significantly higher than diesel, and its saturated vapor pressure is clearly lower than diesel. Therefore, the evaporation and atomization properties of biodiesel are inferior to those of diesel, thereby making it necessary to adjust injection pressure and fuel temperature to improve the spray quality of biodiesel.

In this study, the biodiesel is considered to be an incompressible fluid whose physical properties do not change with the increasing injection pressure. However, the physical properties of biodiesel vary greatly with temperature. At different temperatures, the fuel density, kinetic viscosity, surface tension, and saturated vapor pressure are shown in Table 3. The fuel density and the kinetic viscosity are measured with the national standard method, the surface tension and the saturated vapor pressure are estimated on the basis of literature data and empirical formula.

### CALCULATION MODEL

The numerical calculation process was divided into two phases: the computation of transient flow inside the nozzle and the simulation of spray behavior outside spray domain. Prior to biodiesel spray simulation, the authors carried out the computation and validation of transient flow inside the nozzle, and

### Table 1 Fatty acid composition of the biodiesel from soybean oil

| Type of fatty acid   | Carbon chain | (By mass)/% |
|---------------------|--------------|-------------|
| Dodecanoic          | C12:0        | 0.21        |
| Myristic            | C14:0        | 0.71        |
| Palmitic            | C16:0        | 15.26       |
| Palmitoleic         | C16:1        | 0.80        |
| Heptadecanoic       | C17:0        | 8.90        |
| Stearic             | C18:0        | 3.92        |
| Oleic               | C18:1        | 17.83       |
| Linoleic            | C18:2        | 34.45       |
| Linolenic           | C18:3        | 4.67        |
| Arachidic           | C20:0        | 0.35        |
| Eicosenoic          | C20:1        | 0.38        |
| Behenic             | C22:0        | 0.65        |
| Docosadienoic       | C22:1        | 0.22        |
| Lignoceric          | C24:0        | 0.26        |
| Tetracosenoic       | C24:1        | 1.16        |
| Unknown components  |              | 10.23       |
| Total               |              | 100         |

### Table 2 Physicochemical properties of mineral diesel and biodiesel from the soybean oil

| Item                              | Biodiesel | Diesel | Test method |
|-----------------------------------|-----------|--------|-------------|
| Density (@20°C) [kg/m³]           | 878       | 836    | GB/T1884    |
| Kinetic viscosity (@20°C) [mPa·s] | 5.47      | 3.58   | GB/T265     |
| Surface tension (@20°C) [10⁻³ N/m]| 28.63     | 26.55  | -           |
| Saturated vapor pressure (@20°C) [kPa] | 2.43 × 10⁻⁵ | 1.28 | -           |
| Flash point [°C]                  | 160       | 64     | GB/T261     |
| 10% Distillation temperature [°C] | 328       | 218    | GB/T6536    |
| 50% Distillation temperature [°C] | 337       | 272    | GB/T6536    |
| 90% Distillation temperature [°C] | 354       | 338    | GB/T6536    |

### Table 3 Fuel properties of biodiesel at different temperatures

| Fuel temperature [K] | Density [kg/m³] | Kinetic viscosity [mPa·s] | Surface tension [10⁻³ N/m] | Saturated vapor pressure [kPa] |
|----------------------|-----------------|---------------------------|----------------------------|--------------------------------|
| 293                  | 878             | 5.47                      | 28.63                      | 2.43 × 10⁻⁵                    |
| 300                  | 871             | 5.15                      | 28.28                      | 2.65 × 10⁻⁵                    |
| 320                  | 861             | 3.31                      | 27.79                      | 3.19 × 10⁻⁵                    |
| 350                  | 848             | 1.95                      | 26.79                      | 28.95 × 10⁻⁵                   |
the relevant results can be found in the relevant literature. Computation of unsteady multiphase flow inside the nozzle was achieved by Eulerian-Eulerian method. From the time of needle opening to the time of closed position, the injection velocity and mass flow rate at the nozzle exit are changing over time, and the calculation results of internal nozzle flow are stored in a profile file. Afterward, this file was called when the spray characteristics of biodiesel were calculated, and this was used as the initial condition of spray calculation to arrive at the spray characteristics of biodiesel were calculated, and this was stored in a profile file. Afterward, this file was called when the time, and the calculation results of internal nozzle flow are

### 3.1 Governing equations

The basic governing equations for biodiesel spray calculation are continuity equation, momentum conservation equation, and energy conservation equation. The filter equations are Equations (1), (2), and (3), respectively.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \bar{u}_i)}{\partial x_i} = 0 \tag{1}
\]

where \( \rho \) is the density, \( t \) is the time and \( \bar{u}_i \) is the velocity component in the \( x_i \) direction.

\[
\frac{\partial (\rho \bar{u}_i)}{\partial t} + \frac{\partial (\rho \bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \bar{u}_i}{\partial x_j} \right) - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}
\]

where \( p \) is the pressure on the micro-unit, \( \mu \) is the kinetic viscosity, and \( \tau_{ij} \) is the viscous force component owing to the molecule viscosity on the surface of the micro-unit.

\[
\frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho \bar{u}_i T)}{\partial x_i} = \text{div} \left[ \frac{h}{c_p} \text{grad} T \right] + S_T \tag{3}
\]

where \( c_p \) is the specific heat capacity, \( T \) is the temperature, \( h \) is the heat transfer coefficient of the fluid, and \( S_T \) is the viscous dissipation.

### 3.2 Turbulence model

The Realizable \( k - \varepsilon \) turbulence model was used in this study, and it was a new improved turbulence model. A new transport equation is introduced when expressing the turbulence dissipation rate, and the constraints on the Reynolds stress are satisfied, so that the Reynolds stress is consistent with the real turbulence. Where turbulence kinetic energy (TKE) is defined as follows:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho \bar{u}_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_k}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + G_k - \rho \varepsilon \tag{4}
\]

The turbulence dissipation rate is Equation (5).

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \bar{u}_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_k}{\sigma_k} \frac{\partial \varepsilon}{\partial x_j} \right) \tag{5}
\]

\[
+ \rho C_1 \varepsilon \mu - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon}}
\]

where \( k \) is turbulence kinetic energy, \( \varepsilon \) is turbulence dissipation rate, \( \bar{u}_i \) is time-averaged velocity, \( \mu \) and \( \mu_k \), respectively, represent fluid viscosity and kinetic viscosity, \( G_k \) represents the turbulence kinetic energy caused by the average velocity gradient, \( C_1 = \max (0.43, \frac{\nu}{\eta + \frac{1}{C_2}}) \), \( C_2 \), \( \sigma_k \), and \( \sigma_\varepsilon \) represent model constants, and their empirical values are 1.9, 1.0, and 1.2, respectively.

### 3.3 Spray calculation modeling

The fuel spray is composed of fuel droplets, air and fuel vapor, and it belongs to multiphase flow with discrete phases. The discrete droplet model (DPM) is widely used in fuel spray simulation. The DPM is developed by the Euler-Lagrangian method. The method considers fluid as a continuous phase and directly solves fluid parameters by the Navier-Stokes equation in the Euler coordinate system. The droplets are regarded as a discrete phase, and the orbit of the discrete droplets is solved by integrating the differential equation of droplet force in the Lagrangian coordinate system. Fuel spray and atomization undergo processes such as droplet breakup, collision, and polymerization. To improve the accuracy of numerical calculation, it is necessary to make appropriate selection of the spray sub-models of droplet breakup and droplet collision.

The FLUENT software provides four droplet breakup models: TAB model, WAVE model, KH-RT model, and SSD model. Among these, both KH-RT model and WAVE model can be applied to fuel spray calculation. The KH-RT droplet breakup model was established by the disturbance wave instability theory of gas-liquid interface, and the model was further developed based on the Wave model. The Wave model does not consider the effects of turbulence and cavitation on the droplet breakup of spray flow. Compared to the WAVE model, the KH-RT model is more suitable for high-pressure spray simulation, and its simulation accuracy is higher.
of motion. Furthermore, when the instability of KH wave reaches a certain level, the droplet will break up. In addition, when inertial force is produced owing to density difference between the fuel droplet and the air, the Rayleigh-Taylor (RT) disturbance waves will appear on the leeward side of the droplets, and the RT waves will further break the droplets into smaller size.

During the process of fuel spray, collision will occur when the distance between two droplets is very small. After collision, the droplets may be aggregated into larger droplets or broken into smaller droplets. In this study, the O’Rourke algorithm was used to simulate the collision of droplets with statistical characteristics. This algorithm is widely used in spray simulation and has second order accuracy in space. Simulating the number of collisions that can occur between N unsteady droplets, the calculation frequency is \( \frac{1}{2} N^2 \) for each simulation step. However, the number of fuel droplets for one spray reaches several millions, and the computational effort required is very large. The O’Rourke Collision model uses a method of tracking droplet particle groups to effectively reduce the computational effort. This method is based on the following two basic assumptions: (a) When a random method is used to estimate the number of collisions, consideration need not be given to whether the orbits of droplet particle groups overlap at the same time, and (b) Collisions occur only when two droplets are in the same mesh elements.\(^{41}\)

After the fuel droplets are injected into the combustion chamber, their motion is affected by a turbulent vortex, which causes the motion track to shift from a straight line to a non-smooth curve.\(^{42}\) This phenomenon is called turbulent droplet dispersion. According to the motion feature of the droplets during the process of spray, it is necessary to introduce the model of turbulent droplet dispersion in the spray simulation. There are two common turbulent diffusion models: particle cloud model and discrete random walk (DRW) model. The particle cloud model determines the turbulent droplet diffusion in an average orbit by solving the average motion equation of the droplets, but this model cannot be used for unsteady droplets motion. On the other hand, the DRW model considers the effect of instantaneous turbulence velocity on the droplet motion orbit by a random method, and it also considers the interaction between the droplet and the discrete vortex. Therefore, the DRW model was selected for computing the turbulent diffusion of spray droplets.

**TABLE 4** Principal equations of droplet breakup model

| Equation | Description |
|----------|-------------|
| \( \tau_{KH} = \frac{B_0 \Lambda_{KH}}{d_{ax, KH}} \) | KH-RH Model (Kelvin-Helmholtz instability) |
| \( \Omega_{KH} = \sqrt{\frac{0.34 + 0.38 \Omega_1}{(1 + 0.1)(1 + 1.2)}} \sqrt{\frac{\rho}{\rho_0}} \) | |
| \( \tau_{RT} = \frac{\Omega_{KH}}{2} \) | KH-RH Model (Rayleigh-Taylor instability) |
| \( \Lambda_{KH} = \frac{9.05(1 + 0.458 u_0^2)(1 + 0.477 u_0^2)}{(1 + 0.378 u_0^2)^2} \) | |

**FIGURE 6** Schematic of the spray test system

3.4 | Model validation

A standard single-hole nozzle with hole diameter of 0.315 mm was used in the biodiesel spray experiment. Under conditions of an injection pressure of 30 MPa, an ambient temperature of 293 K and an ambient pressure of 0.1 MPa, the STP of biodiesel at different times was tested by a high-speed camera, and the mean diameter of atomized biodiesel droplets was measured by Malvern laser particle size analyzer. Figure 6 presents the schematic diagram of the experimental system. Meanwhile, both the simulation parameters and the experimental parameters were set to the same values, and the accuracy of the spray model was verified by comparing the simulation results with the experimental results.

The numerical and experimental spray configuration at different injection times were compared, as shown in Figure 7. The spray configuration of numerical simulation and test measurement is similar at the same injection time. The farther away from the nozzle outlet, the more dispersed is the fuel spray, and the axial and radial spray development trend of numerical simulation is consistent with that of test results.

The MATLAB software was used to analyze and process the spray images captured by the high-speed camera,
and the STP of biodiesel at different injection times was measured. The comparison of simulation results and experimental results for the biodiesel STP is shown in Figure 8. Simulation curve and experimental curve of the STP have the same tendency, which is rapid increase at first followed by a slower rate of increase. Furthermore, the simulation and experimental results vary by <5%. It indicates that the above spray calculation models meet the simulation requirements.

The mean diameters $D_{32}$ and $D_{43}$ of the atomized droplets were measured by a Malvern laser particle size analyzer. They were compared with the simulation results, as shown in Figure 9. The error between the simulation results and the experimental results for the mean diameters $D_{32}$ and $D_{43}$ are 4.03% and 5.31%, respectively. Thus, the reliability of the spray calculation models is further verified.

4 | RESULTS AND DISCUSSION

4.1 | Influence of injection pressure on biodiesel spray characteristics

The ambient pressure is set to 5 MPa, the hole diameter is 0.315 mm, the ratio of hole length to diameter is 6, fuel temperature is 320 K, and the fuel injection pressure is adjusted to 100, 150, and 200 MPa, respectively. The graph of biodiesel STP with time under different injection pressures is shown in Figure 10. The STP at different injection pressures shows a rapid growth trend at the early stage and a trend to slow down toward the middle to late stages. This is because the fuel has a higher initial velocity at the exit of nozzle, and the entrainment of the initially atomized fuel in the ambient gas is not strong, causing the STP to increase rapidly in the early stages. However, with the passage of time after initial injection, the atomized droplets continuously exchange energy with ambient gas, and the kinetic energy and velocity of the atomized fuel droplets decrease owing to air resistance. Moreover, the air entrainment effect is intensified over time, the fuel spray expands in the radial direction and the axial velocity reduces, leading to the growth of STP gradually slowing during the middle to late spray stages. Furthermore, with increasing injection pressure, the initial kinetic energy and initial velocity of atomized droplets increase, so the STP of biodiesel increases significantly.

The SMD of biodiesel at different injection pressures is shown in Figure 11. With the passage of time, the SMD gradually decreases. This is because there is a large difference in speed between the moving droplets and the surrounding air, and the droplets are broken into smaller sized particles owing to the air shear forces. Moreover, as the fuel spray moves forward, the entrainment effect is intensified, the fuel spray expands in the radial direction, the droplet breakup is promoted, and the number of smaller droplets increases, leading to a reduction in the SMD of biodiesel. After the injection pressure is increased, the jet velocity is accelerated, the cavitation flow inside nozzle is strengthened, and the breakup of fuel droplets is promoted owing to cavity collapse. In addition, with the increase in injection pressure, the turbulence kinetic energy is enhanced at the exit of the nozzle, which can promote the breakup of fuel droplets. When the injection pressure is elevated from 150 to 200 MPa, the degree of SMD reduction decreases with increase in injection pressure. This occurs because when the injection pressure is increased to a certain extent, the droplet breakup will be restrained by the physiochemical properties of fuel such as density, viscosity, surface tension, and so on. In addition, with increase in
injection pressure, the probability of droplets collision and coalescence is increased, so the degree of SMD reduction decreases.

The velocity contour maps of the X-Y plane at different injection pressures are shown in Figure 12. The velocity distribution at different injection pressures was found to be similar. The velocity at spray core zone is the highest. Spray exterior zone is affected by air resistance and entrainment effect, and the velocity of atomized droplets gradually decreases. The velocity of atomized droplets becomes progressively lower as their axial distance from the nozzle exit increases. This happens because the initial velocity of droplets is high at the initial spray stage, and as the spray keeps forward moving, the velocity of the spray front is gradually reduced owing to air resistance and entrainment effect. In addition, as injection pressure increases, the maximum velocity of the spray core zone increases significantly, and the area occupied by high-velocity droplets also increases. This is because as injection pressure increases, the initial velocity of the droplets increases. Furthermore, the cavitation flow inside nozzle is intensified with the increase in injection pressure, and the initial velocity is further enhanced owing to cavity collapse.

Local amplification vector graph of biodiesel velocity field in the X-Y plane, under 200 MPa injection pressure, is shown in Figure 13. The spray front pushes air out continuously, while the rear of the spray constantly draws air in, so an entrainment vortex is generated on the outside of the spray. The atomized droplets of peripheral spray exchange energy with ambient air owing to entrainment effect, and consequently, the kinetic energy and movement velocity of atomized droplets decrease.

The concentration contour maps of X-Y plane at different injection pressures are shown in Figure 14. Under different injection pressures, the concentration of the spray core zone is higher than the spray peripheral zone. The further the axial distance from the nozzle exit, the lower is the concentration. The radial direction expands from the spray core zone to peripheral zone, and the concentration gradually decreases. This is because the peripheral fuel spray is split into many small droplets due to air disturbance and entrainment effect, and the small droplets quickly evaporate into fuel vapor; therefore, the concentration of the fuel droplets at the peripheral zone is lower than that at spray core zone. As the injection pressure increases, the maximum concentration at the spray core zone gradually decreases, and the region of high concentration value also reduces. This is because as the injection pressure increases, the initial velocity of droplets becomes larger, which promotes the fragmentation and atomization of droplets. The size of atomized droplets is smaller, and their evaporation rate is faster. Therefore, the spray concentration decreases with the increase in injection pressure.

4.2 Influence of hole length-diameter ratio on the biodiesel spray characteristics

The injection pressure is 200 MPa, the ambient pressure is 5 MPa, the fuel temperature is 320 K, the hole diameter is 0.315 mm, the length of the hole is increased gradually, and the hole length-diameter ratio is set to 4, 6, and 8, respectively. The STP curves of different length to diameter ratios are shown in Figure 15. It is seen that the STP of biodiesel decreases slightly with the increase in the length-diameter ratio of nozzle. When the nozzle diameter is constant and the nozzle length is increased, the friction between the fluid and the wall increases, the flow resistance increases, the cavitation flow inside nozzle is restrained, and the disturbance strength is lessened at the exit of the nozzle. Therefore, the initial velocity of droplets and the STP of biodiesel decrease.
However, the nozzle diameter remains constant, and the structure at the inlet and outlet of the nozzle is not changed; therefore, the influence of the length-diameter ratio on the cavitation flow inside nozzle and the velocity at the exit of nozzle is limited, and consequently, the degree of STP reduction is relatively smaller.

The SMD of biodiesel at different length-diameter ratios is shown in Figure 16. The SMD of atomized biodiesel droplets gradually increases with the increase in length-diameter ratio. This is because the fuel flow inside the nozzle is more stable when the length of nozzle is increased. The turbulence and cavitation flow in the nozzle are restrained, and the strength of disturbance at the exit of nozzle is weakened; hence, the SMD of atomized droplets increases with increase in nozzle length.

The velocity contour maps of different length-diameter ratios in the X-Y plane are shown in Figure 17. With the increase in length-diameter ratio, the maximum velocity at spray cone zone decreases, and the region of high-velocity value also decreases at the axial spray center. This is because the friction between the fuel and the wall increases with the increase in length-diameter ratio, and the momentum loss of atomized droplets increases due to the increased flow resistance. Moreover, the cavitation and turbulence inside the nozzle are restrained owing to the increase in the length-diameter ratio, the strength of disturbance is lessened at the exit of the nozzle, and the initial velocity of atomized droplets reduces. Therefore, the maximum velocity of atomized droplets decreases, and the area occupied by high-velocity droplets also decreases with increasing length-diameter ratio.

The concentration contour maps of different length-diameter ratios in X-Y plane are shown in Figure 18. With increase in length-diameter ratio, the maximum concentration of the spray core zone increases, and the region of high concentration value expands. The friction between the fuel and the wall increases with the increase in length-diameter ratio, the initial velocity of the fuel droplets decreases, and the cavitation flow inside nozzle is weakened. The breakup of droplets is suppressed by the above factors; hence, the concentration of spray core zone increases with the increase in length-diameter ratio.

### 4.3 Influence of fuel temperature on biodiesel spray characteristics

The injection pressure is 200 MPa, the ambient pressure is 5 MPa, the nozzle diameter is 0.315 mm, the nozzle length-diameter ratio is 6, and the fuel temperature is regulated to...
300, 320, and 350 K, respectively. The STP of biodiesel at different fuel temperatures is compared, as shown in Figure 19. The STP of biodiesel gradually decreases with the rise in fuel temperature. This is because the fuel density, kinematic viscosity and surface tension reduce with rising fuel temperature, and the breakup and evaporation of fuel droplets become easier. This results in the increase in vapor pressure of biodiesel fuel, and gas-phase resistance increases due to increased degree of atomization, so the velocity attenuation of atomized biodiesel droplets is quicker, and hence, the STP of biodiesel reduces with the increase in fuel temperature.

The SMD of biodiesel at different fuel temperatures is compared, as shown in Figure 20. The SMD of biodiesel decreases markedly with increasing fuel temperature. The cavitation flow inside the nozzle is motivated owing to the rise in fuel temperature, the turbulence kinetic energy at the exit of nozzle increases because of cavity collapse, which is beneficial to initial atomization. In addition, with increasing fuel temperature, the maximum velocity of spray core zone decreases, and the area occupied by high-velocity droplets also reduces. This is because higher fuel temperature results in the increase in internal energy of fuel molecules, which accelerates their movement velocity causing an increase in random motion. Therefore, air entrainment near the spray boundary is intensified, and the momentum loss of spray increases due to gas-liquid interactions. In addition, increasing fuel temperatures result in a decrease in fuel kinematic viscosity and surface tension, making the breakup and atomization of fuel droplets easier. Consequently, a large number of smaller fuel droplets are produced, and the velocity attenuation of smaller size droplets is faster under the action of ambient gas.

The velocity contour maps of X-Y plane at different fuel temperatures are compared, as shown in Figure 21. With increasing fuel temperature, the maximum velocity of spray core zone decreases, and the area occupied by high-velocity droplets also reduces. This is because higher fuel temperature results in the increase in internal energy of fuel molecules, which accelerates their movement velocity causing an increase in random motion. Therefore, air entrainment near the spray boundary is intensified, and the momentum loss of spray increases due to gas-liquid interactions. In addition, increasing fuel temperatures result in a decrease in fuel kinematic viscosity and surface tension, making the breakup and atomization of fuel droplets easier. Consequently, a large number of smaller fuel droplets are produced, and the velocity attenuation of smaller size droplets is faster under the action of ambient gas.

The concentration contour maps of X-Y plane are compared at different fuel temperatures, as shown in Figure 22. With increasing fuel temperature, the maximum concentration of spray core zone reduces, and the high concentration region also decreases at the axial spray center. This is because as the fuel density, kinematic viscosity, and surface tension decrease with increasing fuel temperatures, the droplets evaporation becomes more achievable, and the evaporation rate is faster, leading to an apparent decline in the maximum concentration of axial spray center.

4.4 Comprehensive analysis of various factors

The degree to which various factors influence biodiesel spray characteristics is compared in Table 5. When injection pressure is increased from 100 to 200 MPa, the maximum velocity of atomized biodiesel droplets increases by 33.96%, the maximum STP increases by 27.17%, the SMD decreases by 14.81%, the maximum concentration of axial spray center reduces by 7.1%, and the overall spray quality of biodiesel is significantly improved. Moreover, when nozzle diameter is constant and the length-diameter ratio is increased from 4 to 8, the concentration of spray axial center undergoes the greatest change and rises by 20.29%, the maximum STP decreases by 9.02%, the SMD increases by 8.04%, the maximum velocity of atomized droplets decreases by 6.03%, and the spray quality of biodiesel deteriorates. In addition, when fuel temperature increases from 300 to 350 K, the maximum
concentration at the axial spray center undergoes a significant decline of 25.41%, the SMD of atomized biodiesel droplets decreases by 17.19%, the maximum STP and maximum velocity decrease by 8.13% and 7.6%, respectively.

Out of the varied range of spray parameters, injection pressure and fuel temperature have a greater impact on biodiesel spray characteristics than the nozzle length-diameter ratio. The increase in injection pressure has significant effects on the velocity distribution, STP, and SMD. A higher fuel temperature mainly affects the concentration distribution and the
SMD of atomized droplets. However, the increase in length-diameter ratio only impacts the concentration of the axial spray center, and it has little effect on other spray parameters. The result is derived from the simulation data in Table 5. When the length-diameter ratio is increased from 4 to 8, the maximum concentration of axial spray center is increased by 20.29%, while the extent of variation for the other spray parameters is relatively smaller, both below 9%. This result is also confirmed indirectly by some literatures. The literature results show that when the length-diameter ratio of the nozzle increases, the cavitation and turbulence inside the nozzle is weakened. In addition, the on-way resistance and the corresponding energy loss will be increased with the increasing of nozzle length, which will result in inferior spray quality and higher concentration of the spray center.

5 | CONCLUSIONS

In this study, the effects of fuel temperatures and hole length-diameter ratio on the spray characteristics of soybean biodiesel were investigated by numerical method under high injection pressure and ambient pressure. The analysis of spray characteristics was carried out in conjunction with the transient flow inside nozzle. To achieve this, three-dimensional calculation grids of spray nozzle and spray domain were setup by Gambit software, and the needle movement was achieved by the dynamic mesh technique. The spray calculation models were established using the FLUENT software, and the reliability of spray models was verified by experimental results. The conclusions of this study are summarized as follows:

1. The variation of STP and SMD is similar at different injection pressures, length-diameter ratios, and fuel temperatures. The STP shows a rapid growth trend at the initial spray stage and tends to slow down at the middle to late stages. The SMD gradually decreases with the development of injection time. The velocity and concentration of atomized droplets is highest at the axial spray center, and the velocity and concentration gradually decrease along radial direction extended from the spray center to the spray periphery.

2. The raising of injection pressure leads to faster initial velocity of fuel spray, which can promote the breakup of fuel droplets and improve spray quality. When the injection pressure is increased from 100 to 200 MPa, the STP of biodiesel increases by 27.17%, the SMD reduces by 14.81%, the maximum velocity of the spray cone zone increases by 33.96%, and the maximum concentration decreases by 7.1%.

3. When the nozzle diameter is constant and the nozzle length-diameter ratio is increased from 4 to 8, the STP of biodiesel decreases by 9.02%, the SMD increases by 8.04%, the maximum velocity of axial spray center decreases by 6.03%, and the highest concentration increases by 20.29%. Therefore, the increase in hole length-diameter ratio hinders the turbulence and cavitation flow inside nozzle, proving that it is not conducive for the optimal fuel atomization.

4. When fuel temperature is raised from 300 to 350 K, the STP of biodiesel decreases by 8.13%, the SMD increases by 8.04%, the maximum velocity of axial spray center decreases by 6.03%, and the highest concentration increases by 20.29%. Therefore, the increase in hole length-diameter ratio hinders the turbulence and cavitation flow inside nozzle, proving that it is not conducive for the optimal fuel atomization.

5. The variation of STP and SMD is similar at different injection pressures, length-diameter ratios, and fuel temperatures. The STP shows a rapid growth trend at the initial spray stage and tends to slow down at the middle to late stages. The SMD gradually decreases with the development of injection time. The velocity and concentration of atomized droplets is highest at the axial spray center, and the velocity and concentration gradually decrease along radial direction extended from the spray center to the spray periphery.
5. Compared to the hole length-diameter ratio, injection pressure, and fuel temperature have a greater impact on biodiesel spray characteristics. The increase in injection pressure has significant effects on the velocity distribution, STP, and SMD. The raising of fuel temperature mainly affects the concentration distribution and the SMD of atomized droplets. However, the increase in length-diameter ratio has an impact only on the concentration of the axial spray center, and it has little effect on other spray parameters.

ACKNOWLEDGMENTS

This research was funded by the National Key Research & Development Program of China (2017YFB0202302), the Key Research and Development Program of Shaanxi Province (2019ZDLGY15-07), the Youth Innovation Team of Shaanxi Universities (Energy Saving and New Energy Vehicles), and the Special Fund for Basic Scientific Research of Central Colleges, Chang'an University (No. 300102228403).

NOMENCLATURE

| STP  | spray tip penetration (cm) |
| SM  | Sauter mean diameter (μm) |
| SCA | spray cone angle (°) |
| TKE | turbulence kinetic energy(m²/s²) |
| L/D | length-diameter ratio |
| CFD | computational fluid dynamics |
| UDF | user-defined function |
| DPM | discrete droplet model |
| DRW | discrete random walk model |
| KH-RT | Kelvin-Helmholtz and Rayleigh-Taylor model |
| GCI | Grid convergence index |

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