ТЕХНИЧЕСКИЕ НАУКИ / TECHNICAL SCIENCE

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INVESTIGATION OF DIESEL SPRAY CHARACTERISTICS IN LOW-TEMPERATURE AND LOW-PRESSURE CONDITIONS

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ИССЛЕДОВАНИЕ ХАРАКТЕРИСТИК РАСПЫЛЕНИЯ ДИЗЕЛЬНОГО ТОПЛИВА В УСЛОВИЯХ НИЗКОЙ ТЕМПЕРАТУРЫ И НИЗКОГО ДАВЛЕНИЯ

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Abstract. This study investigates the influence of altitude and injection pressure on diesel fuel spray characteristics, aiming to optimize diesel usage in high-altitude conditions. Experiments were conducted at three altitude levels (plains, 1670 m, and 2400 m) with corresponding atmospheric pressures and temperatures, alongside six injection pressures ranging from 50 MPa to 100 MPa. The investigation focused on key spray parameters: equivalence ratio, spray penetration velocity, turbulence kinetic energy, evaporation rate, spray penetration distance, and Sauter Mean Diameter (SMD). Findings indicate that increased injection pressure enhances spray penetration velocity, evaporation rate, and turbulence kinetic energy, while reducing SMD, irrespective of altitude. Conversely, higher altitudes were associated with increased spray penetration speed, larger SMD, decreased evaporation rate, increased turbulence, and a higher equivalence ratio. The study concludes that both altitude and injection pressure significantly impact diesel spray characteristics, providing essential theoretical support for the application and optimization of diesel fuels in varied altitude conditions.

Аннотация. Рассматривается влияние высоты над уровнем моря и давления впрыска на характеристики распыления дизельного топлива с целью его оптимизации для использования в высокогорных условиях. Эксперименты были проведены на трех различных высотах: на равнине, на высоте 1670 м и 2400 м, при соответствующих изменениях атмосферного давления и температуры, а также при различных давлениях впрыска, варьирующихся от 50 до 100 МПа. Основное внимание в исследовании было уделено ключевым параметрам распыления, таким как коэффициент эквивалентности, скорость проникновения аэрозоля, кинетическая энергия турбулентности, скорость испарения, дальность проникновения распыления и средний диаметр Саутера (SMD). Анализ полученных результатов показывает, что повышение давления впрыска способствует увеличению скорости проникновения аэрозоля, скорости испарения и кинетической энергии турбулентности, при этом происходит уменьшение SMD, независимо от высоты над уровнем моря. В свою очередь, увеличение высоты приводит к росту скорости проникновения аэрозоля и SMD, снижению скорости испарения, усилению турбулентности и повышению коэффициента эквивалентности. Таким образом, исследование подтверждает значительное влияние высоты и давления впрыска на характеристики распыления дизельного топлива, что предоставляет важную теоретическую основу для его применения и оптимизации в условиях различной высоты над уровнем моря.

Keywords: diesel fuel, high altitude, spray characteristics.

Ключевые слова: дизельное топливо, большая высота, характеристики распыления.

The operation of diesel engines within these elevated terrains is notably impacted by reduced atmospheric pressure, leading to lower oxygen availability. This phenomenon adversely affects diesel combustion processes, resulting in decreased engine power and fuel efficiency, alongside increased thermal loads and emissions of carbon dioxide and particulate matter. Meanwhile, the diminished oxygen levels at high altitudes lead to incomplete fuel combustion in diesel engines, directly contributing to reduced operational efficiency and elevated pollutant emissions. These effects pose significant environmental and health risks, particularly in China, where high-altitude territories are extensive. The challenges are multi-faceted, impacting transportation, industrial activities, and contributing to broader environmental degradation concerns.

Addressing these issues requires focused research and development towards optimizing diesel engine performance under low-oxygen conditions. Innovations in engine design, fuel technology, and emissions reduction are critical for mitigating the adverse effects of high-altitude operations.

H. Xie conducted an experimental study on the macroscopic spray characteristics of biodiesel and diesel in a constant volume chamber. The results demonstrated that ambient pressure and injection pressure significantly influenced the spray characteristics [1]. J. Fu explored the effect of injection pressure on the spray characteristics of biodiesel [2]. L. Jiang shows interest in the numerical simulation of biodiesel injection characteristics [3]. F. Xie explored the impact of injection pressure on fuel spray dynamics and fuel-air mixing properties [4]. D. Han investigated both macroscopic and microscopic injection characteristics of fatty acid esters in common rail injection systems, establishing a foundation for subsequent research [5]. Focusing on diesel/PODE hybrid fuel, C.Shi conducted experimental studies on both macroscopic and microscopic spray characteristics [6]. S.Guo conducted an experimental study on the correlation between structural parameters and injection characteristics of electronically controlled injectors for diesel engines [7]. B. Chen conducted research on the impact of varying fuel spray characteristics at high altitudes [8]. Y.Chen studied the AVL Fire's automotive cyclone exhaust [9]. F. Chen carried out a simulation study on the in-cylinder concentration field of a stratified lean combustion GDI engine [10]. Hwang J conducted a series of diesel spray combustion tests in a fixed-capacity combustion cartridge, at an injection pressure of 35 MPa and a fuel temperature range of 243 K to 313 K. The investigation focused on the effect of fuel temperature on spray and combustion characteristics[11].

However, the existing studies on diesel engine spray characteristics at high altitudes lack clear quantitative analysis, and the parameters set for the in-cylinder environment do not reflect the actual high-altitude thermal boundaries, thus failing to meet the demands for understanding spray characteristics in the unique plateau environment. Working at high altitudes, diesel engines exhibit issues such as reduced power, deteriorated atomization performance, and increased heat load. Therefore, an in-depth examination of diesel fuel spray characteristics at high altitudes is crucial for the widespread application of diesel engines.

Based on these, we conduct mechanistic studies on diesel spray characteristics across varying ambient backpressures, temperatures, and injection pressures. Utilizing software simulations to model diesel spray behavior under these diverse conditions, we then distill the governing principles of diesel spray dynamics, offering vital theoretical support and a reference framework for utilizing diesel fuel in high-altitude applications.

Unit Description for Simulation

In the AVL Fire software, the ToPology module constructs the simulation model of the fixed-volume bomb. A cylinder, measuring 100 mm in diameter and 180 mm in height, is designed with the specified data, setting the grid count to 320,000, as depicted in Figure 1. To avoid grid interference and data inaccuracy in the simulation, this study positions the model's upper surface center directly below the injector nozzle outlet. This placement centralizes the diesel fuel mist spray along the cylinder axis, enhancing data collection and analysis. This study employs a model with a single-hole nozzle, featuring a spray hole diameter of 0.00016 m, specifically designed for the diesel fuel injector.

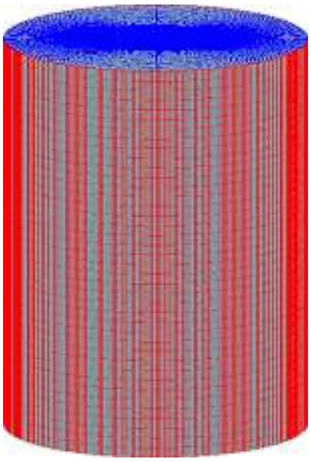

Figure 1. Tolerance bomb simulation model

1. The turbulence model used in the AVL Fire software is detailed below, (1) k-ε model：

k-ε model is classified as a double-equation model, falling under the category of semi-empirical equations based on the Boussinesq assumption. It boasts rapid computation speeds, high stability, and modest computational demands, making it widely utilized in current applications.Equation 1 and 2 are the fundamental equation as follows,

$$\rho\frac{dk}{dt}=\rho(P_k-\varepsilon)+\frac{\partial}{\partial x}[(\mu+\frac{\mu_l}{\sigma_k})\frac{\delta k}{\delta x_f}] \quad (1)$$

$$\rho\frac{d\varepsilon}{dt}=\rho(c_{\varepsilon_1}P_k+c_{\varepsilon_3}k\frac{\partial u_k}{\partial x_k}-c_{\varepsilon_2})\frac{\varepsilon}{k}+\frac{\partial}{\partial x_f}[(\mu+\frac{\mu_l}{\sigma_k})\frac{\delta \varepsilon}{\delta x_f}] \quad (2)$$

Where k represents the kinetic energy magnitude during turbulence, while ε signifies the turbulent energy dissipation rate. The turbulent pulsation length and time scale are intricately linked to k and ε. A higher k results in a larger time scale and turbulent pulsation length. Conversely, a larger ε reduces the time scale and turbulent pulsation length (2) k-zeta-f model.

k-zeta-f model belongs to one of the four-equation models and it is based on k-ε model. The four-equation model boasts improved accuracy and enhanced stability, yet its computation time is extended when compared to the k-ε model. It can be descriped as,

$$\rho\frac{dD_k}{dD_t}=\rho(P_k-\varepsilon)+\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\delta k}{\delta x_j}] \quad (3)$$

$$\rho\frac{dD_\varepsilon}{dD_t}=\rho\{(\frac{c_{\varepsilon_1}P_k-c_{\varepsilon_2}\varepsilon}{T})+\frac{\partial}{\partial x_J}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\delta\varepsilon}{\delta x_j}]\} \quad (4)$$

$$\rho\frac{dD_\varsigma}{dD_t}=\rho f-\rho\frac{\varsigma}{k}P_k+\frac{\partial}{\partial x_J}[(\mu+\frac{\mu_t}{\sigma_\varsigma})\frac{\delta\varsigma}{\delta x_j}] \quad (5)$$

$$f-L^2\frac{\partial^2 f}{\partial^2 x_j}=(c_1+c_2\frac{P_k}{\varsigma})\frac{\frac{2}{3}-\varsigma}{T} \quad (6)$$

Where

$$T=\max(\min(\frac{k}{\varepsilon},\frac{\alpha}{\sqrt{\sigma}C_\mu^\nu S\varsigma}),C_T\sqrt{\frac{\nu^3}{\varepsilon}}) \quad (7)$$

$$L=C_L\max(\min(\frac{k^{\frac{2}{3}}}{\varepsilon}),C_\eta\frac{\nu^{\frac{3}{4}}}{\varepsilon^{\frac{1}{4}}}) \quad (8)$$

Where k denotes the value of kinetic energy during turbulent flow; ε represents the rate of turbulent energy dissipation; ζ is a standardized value of velocity; L is the length during turbulence; *f* is the elliptic relaxation function; and T is the turbulence time.

2. Boundary and initial conditions:

In this study, calculations for the fixed-volume bomb simulation model are performed across three distinct altitude environments. Boundary conditions are established such that the set temperature boundaries match the surrounding and upper and lower wall surfaces of the model, with temperatures set at 850 K, 872 K, and 860 K.

Moreover, this study exclusively investigates the spray characteristics of diesel fuel at high altitudes. The fixed-capacity bomb model is filled with nitrogen to reduce the internal oxygen concentration to zero, aiming to eliminate interference from processes like combustion on the final results.

3. Required parameters:

This study simulates the spray characteristics of diesel fuel at high altitudes, focusing on examining the impacts of three sets of in-cylinder temperatures, six sets of injection pressures, and three sets of ambient back pressures on diesel fuel's spray characteristics. The working condition values utilized in this study are detailed in Table 1.

Table 1

SIMULATED WORKING CONDITIONS

Working conditions	*Environmental backpressure (MPa)*	*Environmental temperature (K)*	*Injection pressure (MPa)*	*Altitude (m)*
condition 1	4.85	872	50	plain
condition 2	4.85	872	60	plain
condition 3	4.85	872	70	plain
condition 4	4.85	872	80	plain
condition 5	4.85	872	90	plain

Working conditions	*Environmental backpressure (MPa)*	*Environmental temperature (K)*	*Injection pressure (MPa)*	*Altitude (m)*
condition 6	4.85	872	100	plain
condition 7	4.35	860	50	1670
condition 8	4.35	860	60	1670
condition 9	4.35	860	70	1670
condition 10	4.35	860	80	1670
condition 11	4.35	860	90	1670
condition 12	4.35	860	100	1670
condition 13	3.84	850	50	2400
condition 14	3.84	850	60	2400
condition 15	3.84	850	70	2400
condition 16	3.84	850	80	2400
condition 17	3.84	850	90	2400
condition 18	3.84	850	100	2400

4. Parameter Calculation:

The injection pressure and fuel injection quality correspond to each other, with their respective equations as follows:

$$q = \frac{0.658 d^2 \sqrt{p}}{\eta^2} \tag{9}$$

$$m^* = qp^* \tag{10}$$

Where m^* represents the diesel injection mass corresponding to varying injection pressures;d, the nozzle hole diameter, is set at 0.00016 m in this study; *p* signifies the injection pressure magnitude; *η,* the nozzle efficiency coefficient, is assigned a value of 1.2; ρ^*, the diesel fuel density, is established at 0.84 g/cm³.

All calculations are summarized in Table 2 below.

Table 2

DIESEL FUEL QUALITY ACROSS VARIOUS INJECTION PRESSURES

Injection pressure (MPa)	*Diesel quality (kg)*
50	5.53E-06
60	5.96E-06
70	6.40E-06
80	6.84E-06
90	7.37E-06
100	7.77E-06

Results and discussion

1. Effects of altitude on the development of spray patterns:

Figure 2 shows the comparison of the development of diesel spray patterns at different times under the condition of 50 MPa injection pressure and three different conditions of altitude [plains (4.85 MPa, 872 K), 1670m (4.35 MPa, 860 K), 2400 m (3.84 MPa, 850 K)]. From Figure 2, the development trend of spray at different altitudes is the same, all of them are conical droplet-like expansion, but careful observation can be found that the spray pattern is slightly different, with the increase of altitude, the oil beam is slightly elongated, which shows that the spray through the distance in the slow increase, this is due to the pressure inside the cylinder is reduced, the spray diffusion process when the resistance is reduced, which leads to the diffusion of This is due to the fact that when the pressure inside the cylinder decreases, the resistance during spray diffusion also decreases, leading to an increase in the spread.

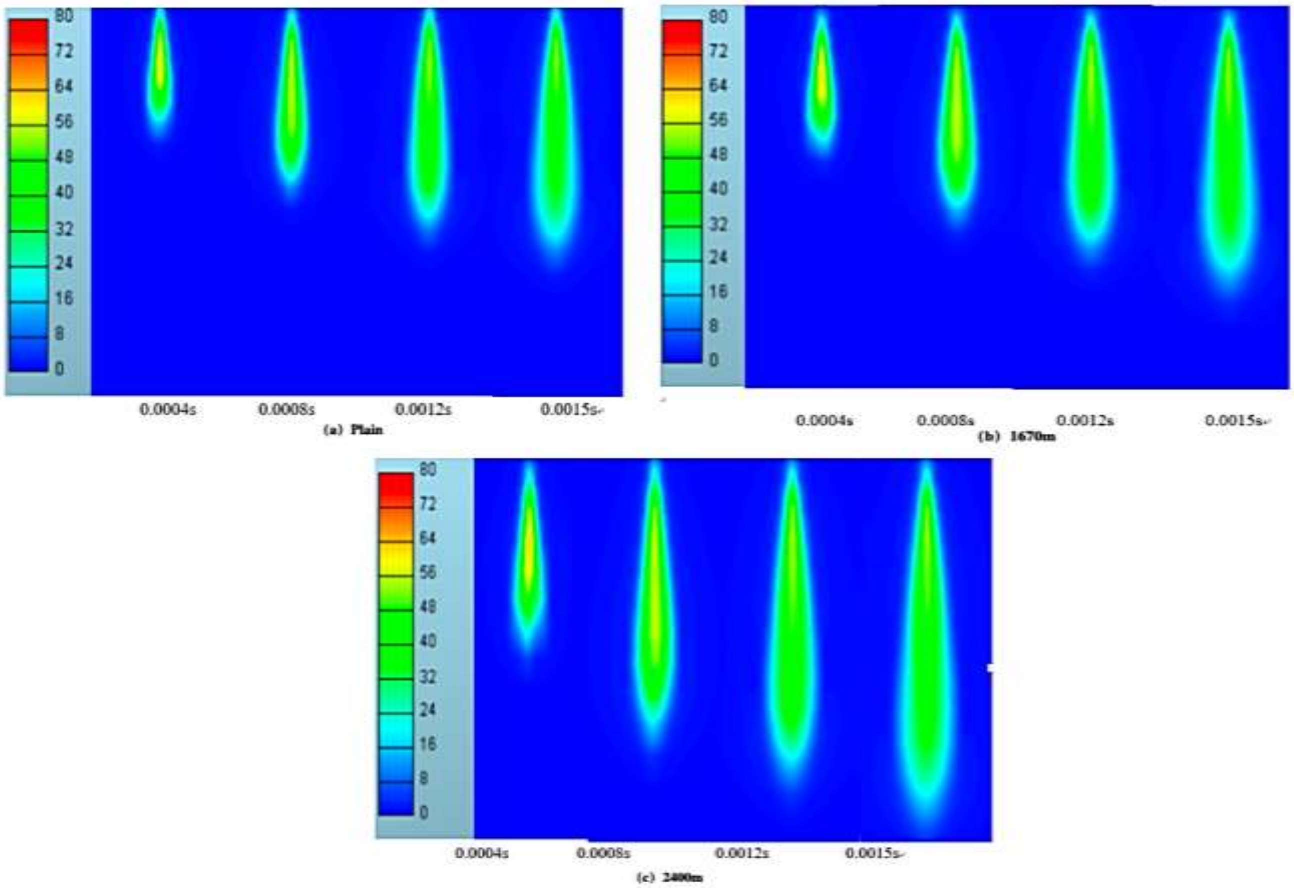

Figure 2. Development of spray patterns at different altitudes

2. Effect of altitude on spray rate:

Figure 3 illustrates the comparison of spray penetration velocity at various altitudes under a 50 MPa injection pressure, captured at 0.0015 seconds. The area of the blue zone is notably smaller than those observed at 1670 m and the plains. Observations indicate that at an altitude of 2400 m, the blue region's area is significantly smaller compared to those at 1670 m and the plains, suggesting an increase in spray penetration velocity with altitude. Consequently, spray penetration velocity is found to escalate with altitude. This escalation is attributed to decreased ambient density, reduced air intake volume, increased combustion-to-air equivalence ratio, and diminished interaction force between gas and liquid as altitude rises.

3. Effect of altitude on spray penetration distance:

Figure 4 displays the variation in spray penetration distance over time at various altitudes, under a control injection pressure of 90 MPa. Analysis of Figure 4 reveals that in the initial phase of oil spraying, spray penetration distance progresses nearly linearly with time and overlaps across different altitudes. In the later phase, however, variations in spray penetration distance at different altitudes become evident: as altitude increases, so does the spray penetration distance. This increase is attributed to the reduced ambient density and decreased resistance of the ambient gas at higher altitudes, which facilitates spray development in the axial direction, resulting in greater spray penetration distances.

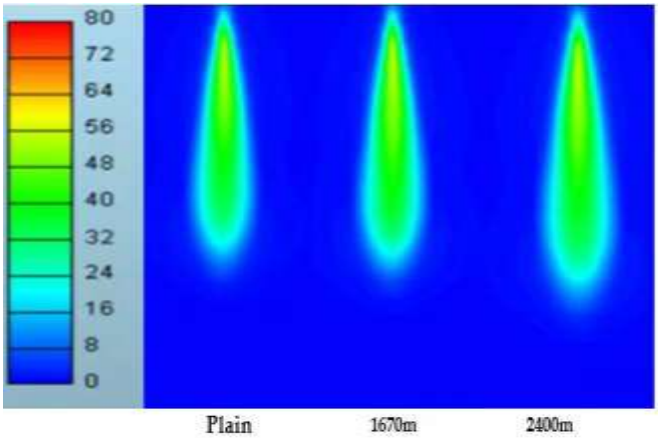

Figure 3. Spray rate at different altitudes

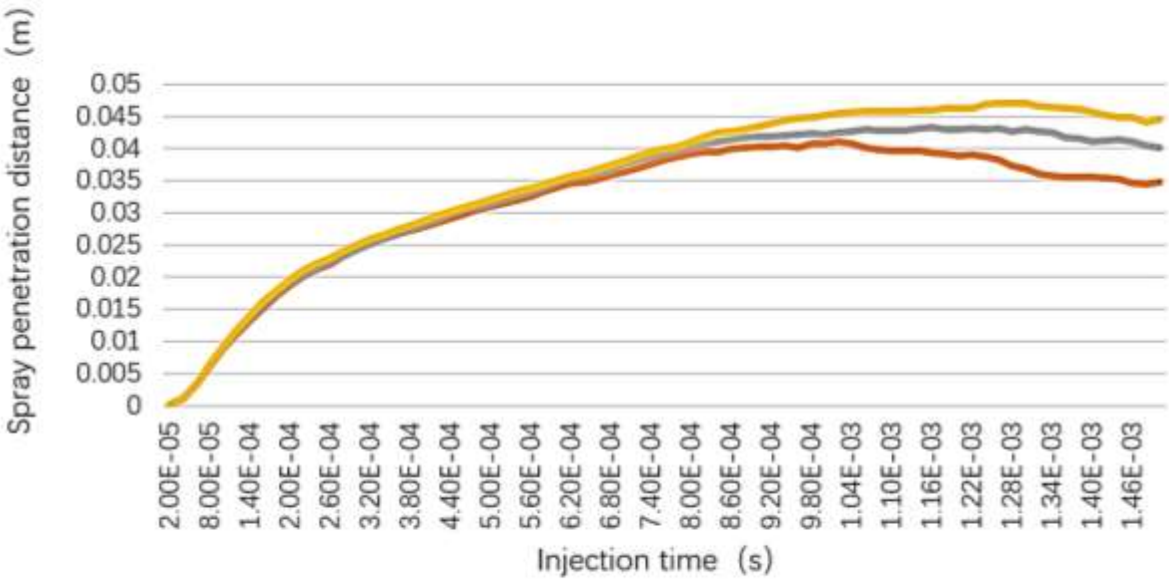

Figure 4 Spray penetration distance at different altitudes. Red line is plain; gray line is 1670 m above sea level; yellow line is 2400 m above sea level

4. Effect of altitude on the mean diameter of sot：

Figure 5 illustrates the comparison of the average Sauter Mean Diameter (SMD) at various altitudes under an injection pressure of 50 MPa. According to Figure 5, as altitude increases, the averageSMD also increases. This trend is attributed to decreasing ambient temperatures at higher altitudes, with temperatures recorded at 872 K on the plains, 860 K at 1670 m, and 850 K at 2400 m. Higher ambient temperatures lead to more complete disintegration of spray droplets, resulting in a smaller average SMD.

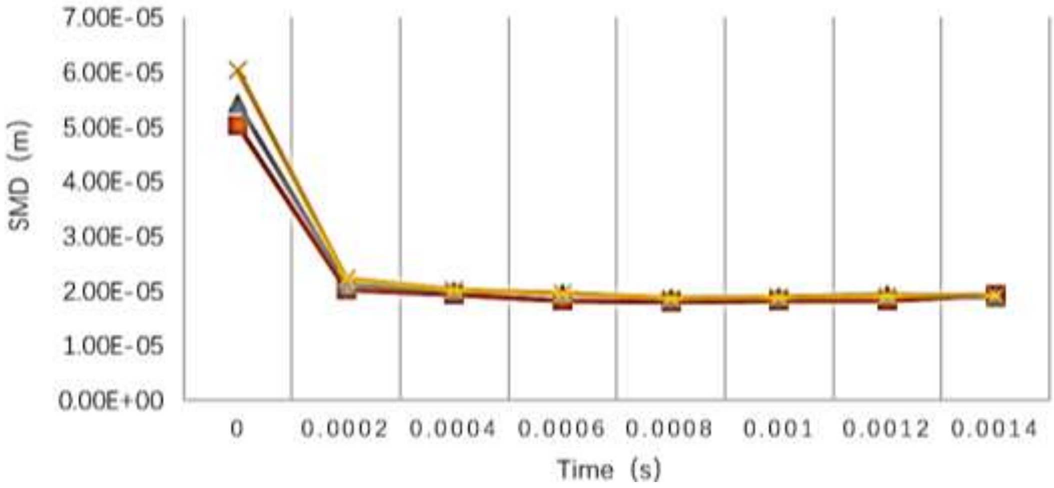

Figure 5. SMD at different altitudes. Red line is plain; gray line is 1670m above sea level; yellow line is 2400m above sea level

5. Effect of altitude on evaporation rates:

Figure 6 depicts the evaporation rate curve over time at various altitudes under an injection pressure of 100 MPa. As illustrated in Figure 6, the evaporation rate curve generally trends upward over time, while simultaneously decreasing with altitude. The evaporation rate is observed to decrease as altitude increases, primarily due to lower ambient temperatures at higher altitudes, resulting in less diesel mass evaporating and thus a lower evaporation rate.

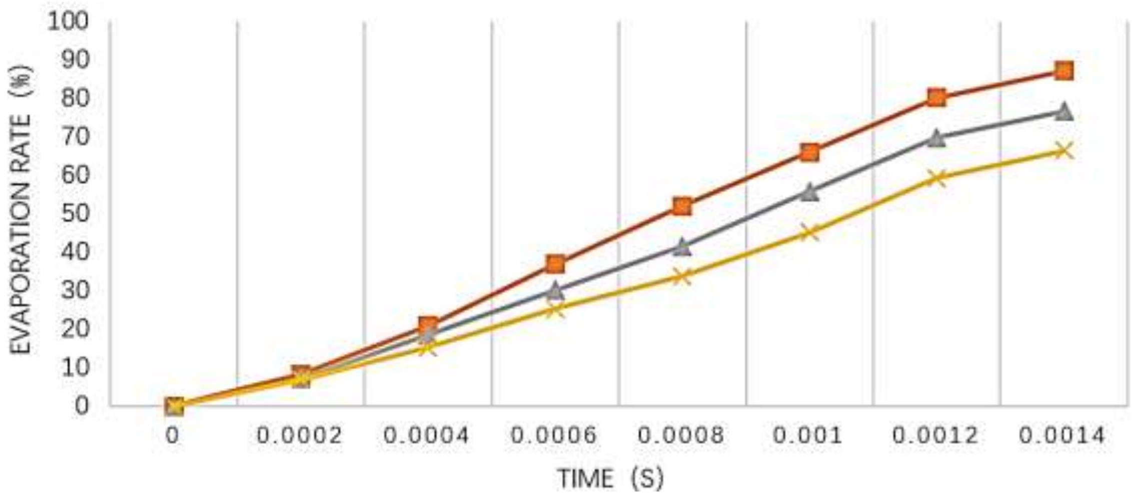

Figure 6. Evaporation rates at different altitudes. Red line is plain; gray line is 1670m above sea level; yellow line is 2400m above sea level

6. Effect of altitude on turbulent kinetic energy:

Figure 7 illustrates the comparison of the spray equivalence ratio at various altitudes under a spray pressure of 80 MPa and a spray duration of 0.0015 seconds. As depicted in Figure 7, the red area at the center of the oil beam notably expands with rising altitude. Thus, it is concluded that the equivalence ratio increases progressively with altitude. This phenomenon is attributed to higher medium density at lower altitudes, resulting in a greater mass of convolved air compared to higher altitudes, thereby yielding a lower equivalence ratio at lower altitudes compared to higher ones.

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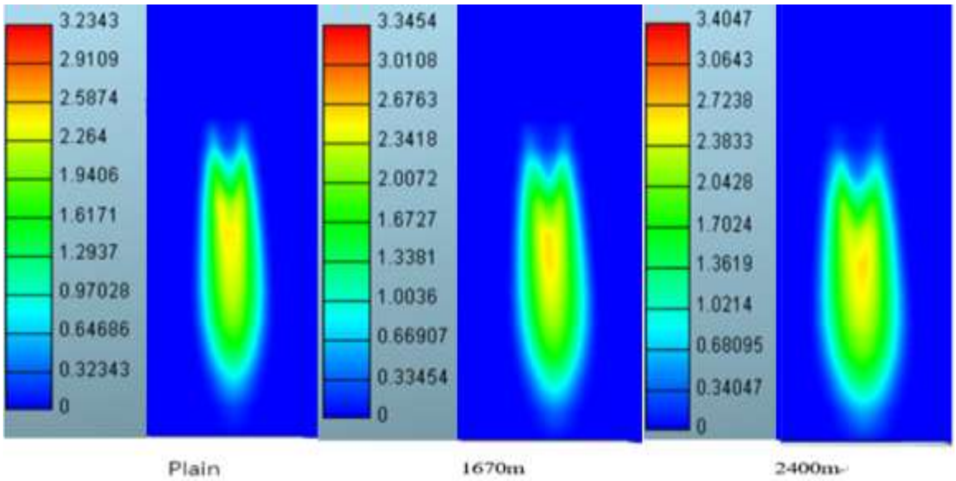

Figure 7. Equivalent ratios at different altitudes.

7. Effect of spray pressure on the development of spray patterns:

Figure 8 presents the comparison of diesel fuel spray shape development over time in plains at altitude, under various injection pressures: 50 MPa, 60 MPa, 70 MPa, 80 MPa, 90 MPa, and 100 MPa. The six plots in Figure 8 illustrate that, at a given altitude, the fuel spray maintains a consistent development pattern across different injection pressures, though variations in spray penetration distance are observed, increasing with higher injection pressures.

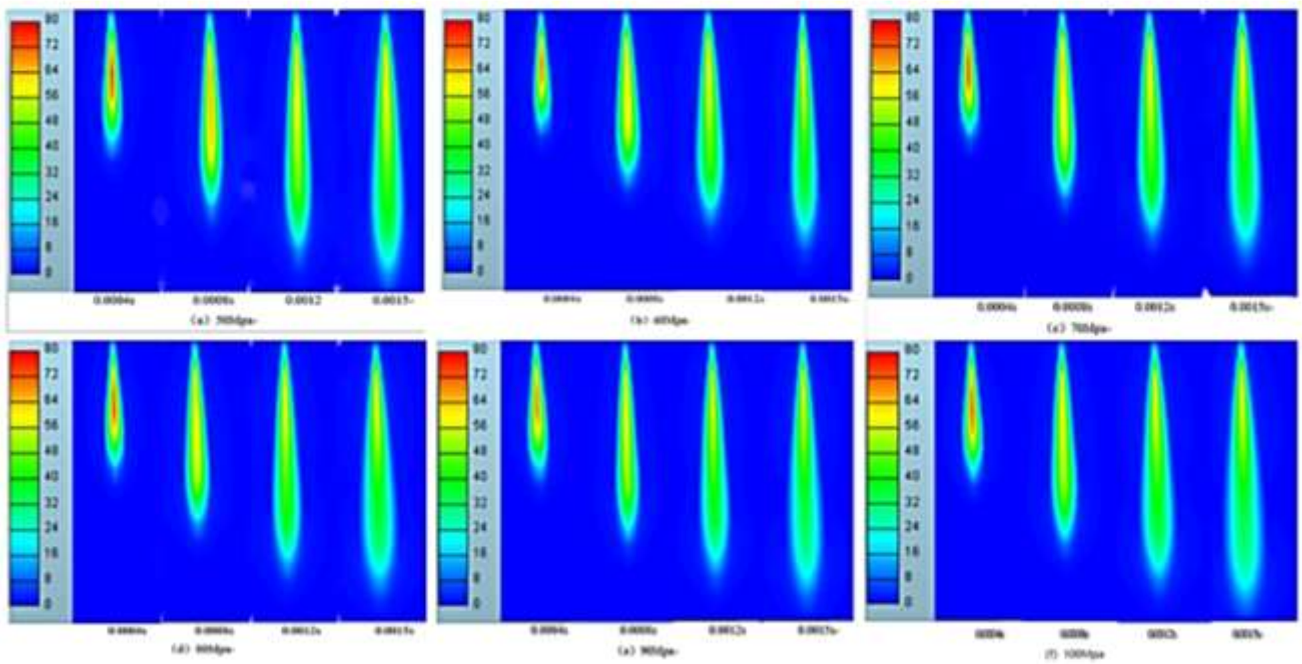

Figure 8. Spray pattern development at different injection pressures.

8. Effect of spray pressure on spray velocity:

Figure 9 illustrates the relationship between spray penetration velocity and injection pressure at 0.0015 seconds, under the condition of plains altitude. As observed in Figure 9, with the increase in injection pressure, the high-velocity region at the center of the spray (denoted by the red area) expands, indicating a corresponding increase in the penetration velocity of diesel fuel.

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This phenomenon occurs as the injection pressure rises, leading to a greater pressure difference across the nozzle orifice. Consequently, the diesel fuel receives more initial energy, which boosts its initial velocity.

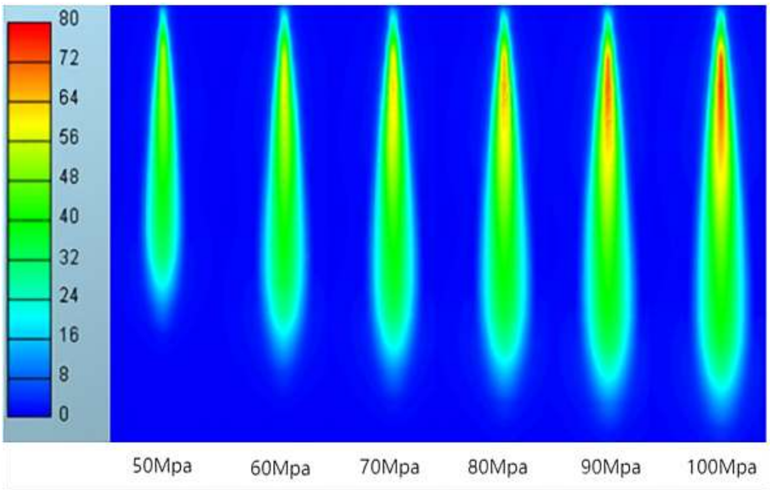

Figure 9. Spray rate at different injection pressures

9. Effect of spray pressure on spray penetration distance:

Figure 10 depicts the variation curve of spray penetration distance over time for diesel fuel at various injection pressures, under the plains' elevation condition. According to Figure 10, the influence of injection pressure on spray penetration distance appears minimal in the evaporative state.

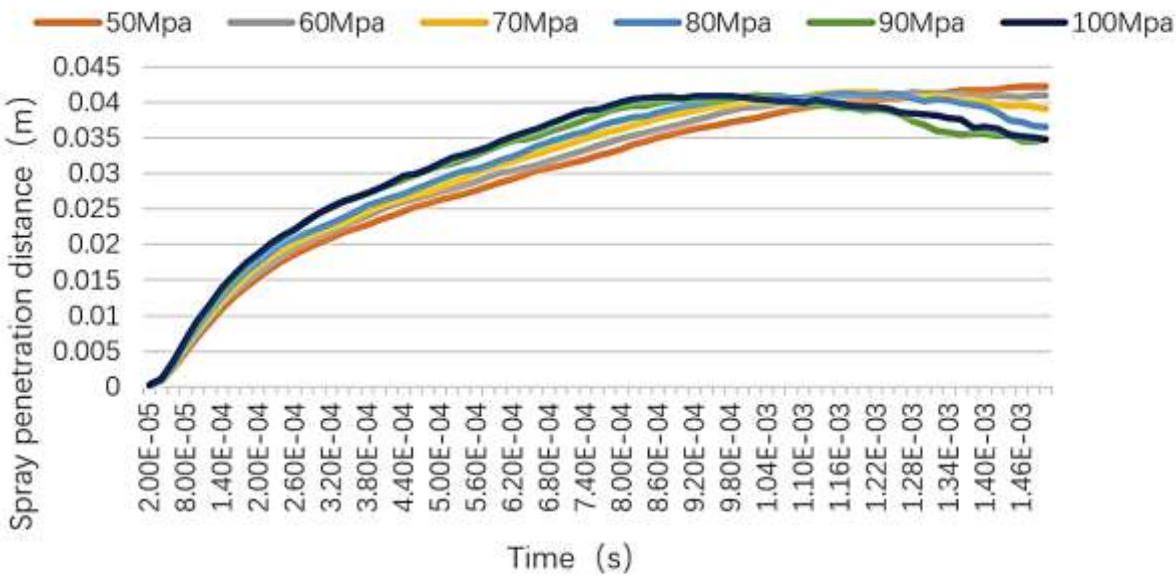

Figure 10 Spray penetration distance at different injection pressures.

10. Effect of Injection Pressure on the Mean Diameter of Sot:

Figure 11 displays the comparative curves of the SMD over time for diesel spray at various injection pressures at plains altitude. According to Figure 12, the SMD of the spray decreases as injection pressure increases. This reduction is attributed to the increasing pressure difference across the nozzle orifice as injection pressure rises, enhancing the initial momentum of oil droplets. This amplifies the coalescence-absorption effect between the spray and ambient gases, intensifying droplet fragmentation and evaporation, thus favoring the formation of smaller diameter oil droplets, resulting in a decreased average SMD.

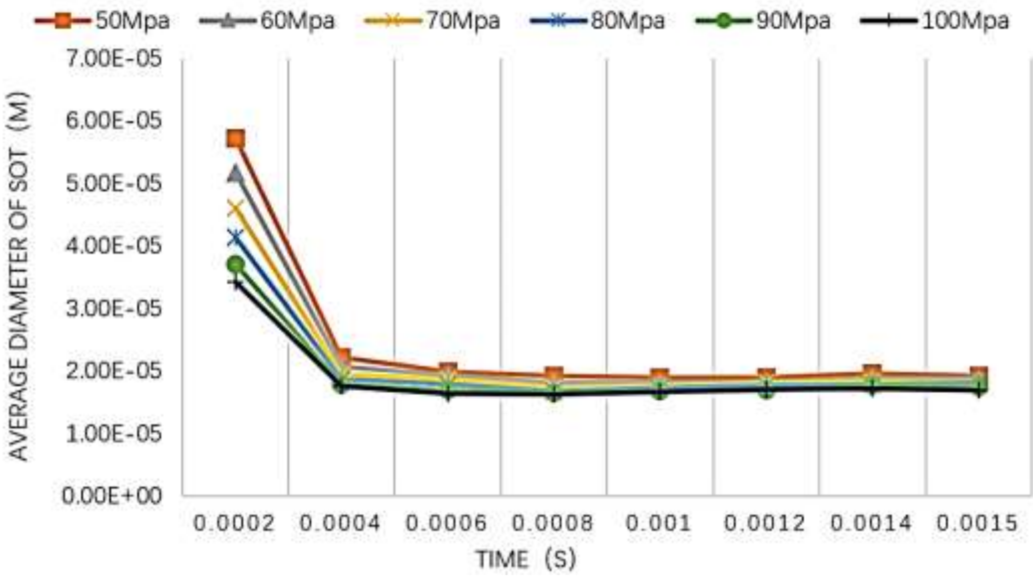

Figure 11. Mean diameter of Sauter at different injection pressures

11. Effect of Injection Pressure on Evaporation Rate:

Figure 12 illustrates the evaporation rate of diesel fuel over time under various injection pressures at plains altitude. As depicted in the figure, the evaporation rate of diesel fuel gradually increases with higher injection pressures. This increase is attributed to the growing pressure difference across the nozzle orifice with rising injection pressures, enhancing the initial momentum of the oil droplets. This amplifies the coalescence and entrainment effects between the spray and ambient gases, facilitating droplet fragmentation and accelerating the evaporation process. Consequently, the evaporation rate escalates with higher spray pressures.

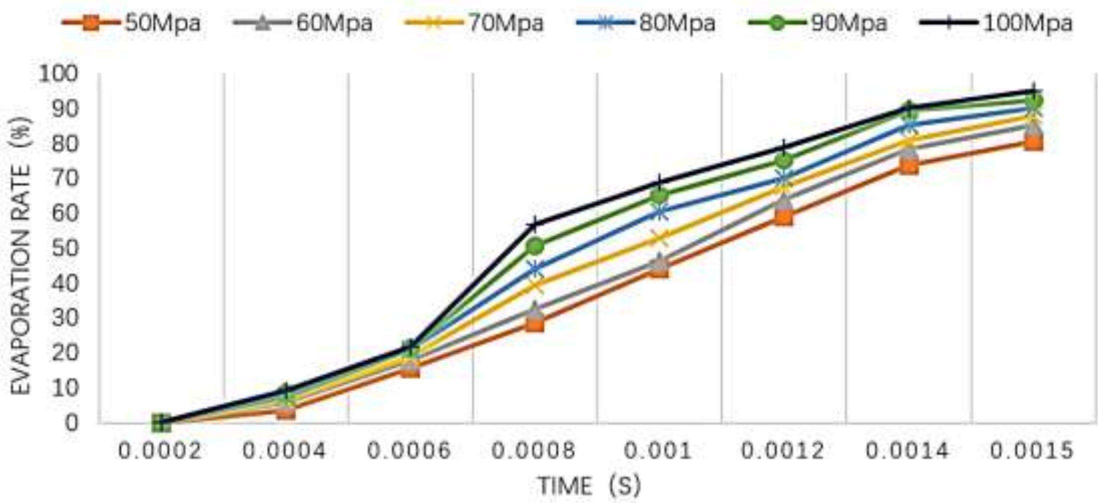

Figure 12. Evaporation rate of diesel fuel at different injection pressures.

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12. Effect of Injection Pressure on Turbulent Kinetic Energy:

Figure 13 illustrates the impact of varying injection pressures on the turbulent kinetic energy of the spray at plains altitude. As depicted in Figure 13, the turbulent kinetic energy of the spray gradually increases with higher injection pressures. This increase is attributed to the rising injection pressure, which enhances the pressure difference across the nozzle orifices, boosting the initial energy and, consequently, the initial velocity of the diesel fuel. Thus, higher injection pressures result in increased turbulent kinetic energy.

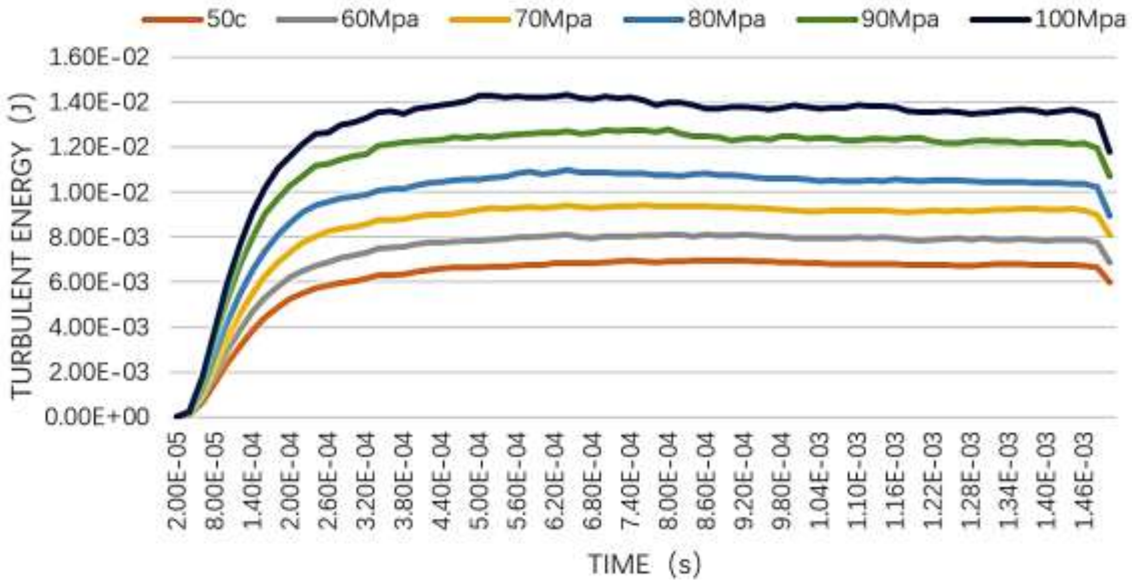

Figure 13 Turbulent kinetic energy at different injection pressures.

Conclusions

This study investigates "Diesel Fuel Spray Characteristics in Low-Temperature and Low-Pressure Environments" using CFD software AVL Fire. A constant volume bomb simulation model was established to perform diesel fuel spray calculations under various conditions, analyzing the effects of different injection pressures and altitudes on diesel fuel spray characteristics. The main findings are summarized as follows:

1. Effects of Altitude on Diesel Fuel Spray Characteristics: With rising altitude, diesel fuel spray penetration distance, spray penetration velocity, SMD, and turbulence kinetic energy increase, while evaporation rate and atomization effectiveness decrease. Additionally, the equivalence ratio elevates at higher altitudes.

2. Effects of Injection Pressure on Diesel Spray Characteristics: Diesel fuel spray velocity, evaporation rate, and turbulence kinetic energy augment with increasing injection pressure, while the SMD diminishes. In the evaporative state, injection pressure has a minimal impact on spray penetration distance. Higher injection pressures enhance atomization and promote more complete mixing of diesel fuel and air.

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