IGNITION AND COMBUSTION CHARACTERISTICS OF WALL-IMPINGED KEROSENE (RP-3) FUEL SPRAY WITH VARYING INJECTION PARAMETERS

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The fuel quantity and injection pressure are two essential factors to optimize the injection strategy. In this paper, we focus on the investigation for the ignition and combustion characteristics of wall-impinged kerosene (RP-3) fuel spray at different injection quantities and pressures. Experiments are conducted in a constant volume combustion vessel to simulate the diesel engine condition, adopting a single-hole nozzle with 0.22 mm. The flame images are captured using a high-speed camera, and then the behaviors of ignition and combustion are processed and analyzed. The main emphasis is placed on the variation laws of the ignition position distance, the ignition delay time, the combustion duration, the flame area, spatially integrated natural luminosity and time integrated natural luminosity.

Keywords*: injection quantity, injection pressure, wall-impinged kerosene spray, ignition, combustion*

1. Introduction

The fuel combustion is a complicated process including fuel-air mixing and evaporation. It is not only the engine design that affects the engine performance but also the fuel that is used, which has a significant impact on the atomization, combustion and emission of fuels [1]. Kerosene has higher volatility, lower freezing temperature and zero aromatic content. All kinds of kerosene fuels are getting more and more researcher's attention. Even though many alternative fuels were presented and investigated in the past few years, no alternative fuel in the aviation engines has been found. Moreover, the single fuel concept (SFC) was presented to simplify the fuel supply since 1980s. JP-8 was selected as the fuel of military aircrafts, vehicles and equipment in the western countries [2-3]. In the meanwhile, the aviation piston engines fueled with kerosene are used in a large amount of general aviation aircrafts and military small aircrafts [4]. However, kerosene has different physical and chemical properties compared with diesel, leading to different combustion characteristics. Therefore, it's important to strengthen the combustion and economic performance in the engine fulled with kerosene.

In comparison with diesel, kerosene has shorter spray penetration due to higher volatility [5]. However, the fuel sprays are still likely to impinge on the piston head and give rise to "wall wetting" phenomenon in the high-pressure direct-injection engines fulled with kerosene due to the small bore and high injection pressure. This phenomenon could decrease the fuel-air temperature and increase the mixture concentration around the wall, causing longer combustion duration and higher HC, CO, and smoke level [6-7]. In order to decrease the impact of spray-wall impingement, it is extremely necessary to optimize the fuel injection strategy. The fuel quantity and injection pressure are two essential factors to improve the injection strategy and fuel combustion [8]. It has been confirmed that decreasing injection quantity and increasing injection pressure are effective ways to improve economic performance and reduce the emissions [9-10]. Thus, it is very necessary to research the ignition and combustion characteristics of wall-impinged kerosene sprays under different injection quantities and pressures.

A lot of researchers have researched the ignition and combustion characteristics of kerosene under different conditions. Pickett et al. investigated the differences between JP-8 and standard #2 diesel in a combustion vessel, and their results indicated that the ignition of kerosene has no much difference compared with diesel. The cool-flame and high-temperature ignition delays are higher for JP-8 [11]. Lee et al. investigated the combustion characteristics of fossil diesel and JP-8 fuel in a single-cylinder diesel engine, and determined that the ignition delay time of diesel is shorter, and the maximum heat release rate is lower compared with JP-8 [12-13]. Zhou et al. studied the combustion and emission characteristics of kerosene/diesel blending through numerical simulations. They reported that the addition of kerosene improves the engine performance and reduces the CO emission [14]. Tay et al. investigated the combustion and emission characteristics of kerosene and diesel fuels through numerical simulations. Results show that as the diesel is replaced by kerosene, it decreases carbon monoxide (CO), soot emissions and increases the engine efficiency [15]. Far et al. studied JP-8/air laminar burning speed in a spherical vessel. They found that increasing temperature or decreasing pressure can increase laminar burning speed [16]. Zhukov et al. studied the ignition delay times of Jet-A in a heated shock tube. They reported that the ignition delay times decrease with increased ambient pressure and equivalence ratio [17]. Chen et al. conducted a comparative study of diesel and RP-3 kerosene combustion in a compression ignition engine. They found that RP-3 improves the indicated thermal efficiency and reduces fuel consumption in comparison with diesel [18]. Zeng et al. researched the ignition delay of RP-3 kerosene through numerical simulations. They found that increasing temperature, pressure or decresing equivalence ratio can decrease the ignition delay times [19]. He et al. investigated the effects of pressure and equivalence ratio on soot information of RP-3 in a heated shock tube. They noted that the soot yield reduces significantly with decreased pressure or equivalence ratio [20].

As reviewed above, the scope of these researches lies in the ignition and combustion characteristics of JP kerosene series or a comparison between kerosene and diesel. However, these studies do not provide much attention to the investigation of RP-3 kerosene fuels, which are widely adopted in China but different from JP kerosene series. Moreover, the effects of the injection pressure and quantity on the ignition and combustion characteristics of an impinging kerosene (RP-3) spray have not been investigated, which is beneficial to improving injection strategy and engine efficiency. Consequently, the aim of this paper is to study the effects of injection quantity and pressure on ignition and combustion characteristics of wall-impinged kerosene (RP-3) spray. Experiments were performed in a constant-volume combustion vessel. A high-speed camera was used to obtain the flame images firstly. And then the flame images were processed by self-encode procedure in Matlab software. These images enabled variation laws for the ignition position distance, the ignition delay time (IDT), the combustion duration, the flame area (AF), spatially integrated natural luminosity (SINL) and time integrated natural luminosity (TINL) to be studied.

2. Experimental apparatus

The experiments were conducted in a high-pressure and high-temperature constant volume combustion system. As shown in Fig. 1, the facilities are constituted with a high-pressure and high-temperature experimental rig, common rail injection system, wall impingement equipment, and optical setup.

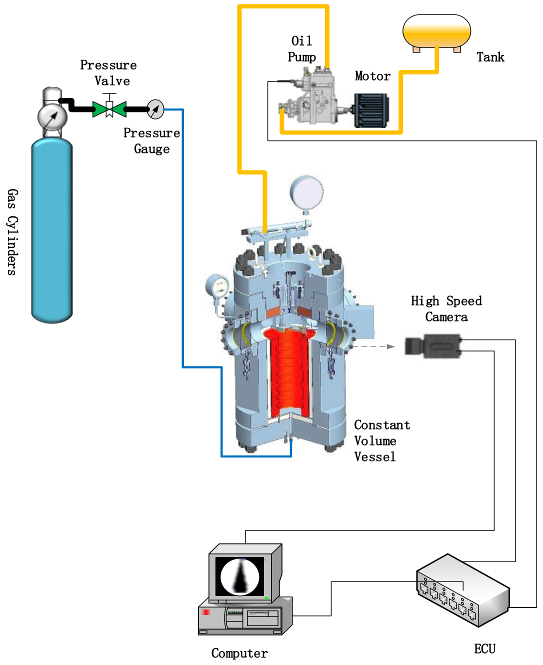

Fig. 1 General experimental layout

2.1 High-pressure and high-temperature experimental rig

The experimental rig contains the constant volume combustion vessel, gas intake and exhaust system, and temperature control system. The ambient temperature could be heated up to 1000 K and the ambient pressure can be regulated to 6 MPa in the combustion vessel. There are four large windows (100 mm in diameter) to make the interior of combustion chamber optically accessible, which are designed orthogonally encircling the cylindrical combustion vessel. The gas intake and exhaust system can feed air or nitrogen into the combustion vessel via controlling the inlet valves, and the accuracy of ambient pressure is ± 0.01 MPa. The temperature control system can control the gas temperature by regulating the power of electrical heater, and the accuracy of ambient temperature is ± 1 ℃.

2.2 Common rail injection system

The common rail injection system includes a high pressure oil pump, a common rail installed a pressure regulator, and an injector with a single-hole (0.22 mm in diameter) nozzle. The pump could provide up to 175 MPa injection pressure. The high pressure oil pump is used to establish the injection pressure in the common rail. The single-hole axis injector could avoid the spray-spray interaction and the interference of vessel walls. The unit controller of Kibox and corresponding control software electronically control all sections of the common rail injection system.

2.3 Wall impingement equipment

The wall impingement equipment is shown in Fig.2. It is classified as the four contents: the flange, impingement plate, coolant channel and thermocouple sensor. The size of the impingement plate is 80 mm × 80 mm. The spray can impinge on the impingement plate and spread around the plate. The coolant channel is designed inside the flat wall. The wall temperature can be controlled by regulating the flow and temperature of flowing coolant. The coolant in these experiments is a mixture of ethylene glycol and water. A thermocouple sensor is installed at 1.5 mm under the middle of the wall surface in order to acquire the surface temperature. The measurement range of the thermocouple sensor is from 0 to 1300 °C.

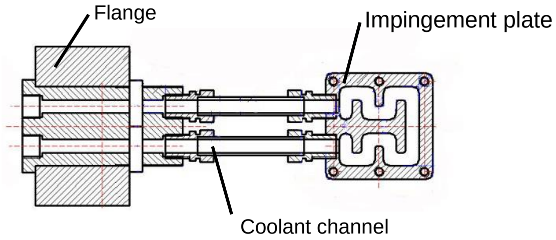

Fig. 2 Wall impingement equipment

2.4 Optical setup

In the experiments, a Phantom V7.3 high speed camera was situated in the axis of one window to acquire the flame images. Images of 512 × 256 pixel were captured for the flame. The imaging speed of the camera is 20 kfps. The time of two adjacent images is 0.05 ms. When the injector begins to inject the fuel, the control system activates the high speed camera to capture flame images.

3. Image processing method and experimental conditions

3.1 Image processing method

In these experiments, direct image method was used to obtain the flame images and visualize the flame development process. The image processing function in the MATLAB software was adopted to process the flame images. The processed step of original images mainly contains loading original image, gray processing and binaryzation. The resolution of the flame images is higher. The background of flame images is black and the flame appears light. Therefore, the information can be acquired from the clear contours of wall-impinged spray flame by binarizing the images [21]. The threshold used is 0.03.

The image processed is shown in Fig. 3. The horizontal distance (HD) of ignition position is obtained by the horizontal length from the injector center-line to the position where the initial flame luminosity appears. The vertical distance (VD) of ignition position is obtained by the vertical length from the nozzle hole to the position where the initial flame luminosity appears. The ignition delay time (IDT) is obtained by the period from the start of injection to the time when initial flame luminosity appears. The area of wall-impinged spray flame (AF) is calculated by summing the pixel values of flame images multiplied by the ratio of real area to pixels. Spatially integrated natural luminosity (SINL) is obtained by the total pixel value of bottom-view grayed images, which reflects the instantaneous natural luminosity intensity of the flame. To analyze the absolute luminosity of every combustion process, time integrated natural luminosity (TINL) is obtained by summing the SINL of the whole combustion event

[22-23].

a. Image of ignition position b. grayed image c. binarized image

Fig. 3 Processed image of wall-impinged spray flame

3.2 Experimental conditions

The detailed experimental conditions are shown in Table 1. The fuel adopted in the experiments was RP-3 kerosene. The properties of RP-3 kerosene are shown in Table 2 [18]. Injection laws for different injection parameters are shown in Fig. 4. The injection laws are obtained in a standard injection rate measure device (produced by EFS company). The ambient gas was air in the experiments. The experiments for every experimental condition were conducted five times to enhance the accuracy of the macro-parameters tested in this research.

Table 1. Experimental conditions

Test variable (units)	Range
Injection quantity (mg)	7.5,10,12.5,15,17.5,20,22.5,25
Injection pressures (MPa)	80,120,160
Nozzle diameter (mm)	0.22
Wall temperature (°C)	135
Ambient pressure (MPa)	4.5
Ambient temperature (°C)	540
Impingement distance (mm)	40

Table 2. Properties of RP-3 kerosene

Density (kg/L)@20°C	Kinematic viscosity (mm^2/s)@20°C	Cetane number	Lower heating value (MJ/kg)	Boiling point (°C)		
0.78	1.28	42.00	43.43	T10 =172.8	T50 = 104.9	T90 = 224.4

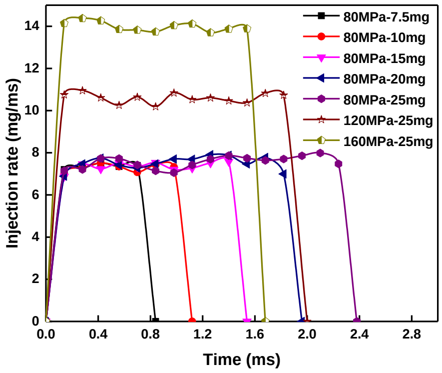

Fig. 4 Injection laws for different injection parameters

4. Results and discussion

4.1 Ignition characteristics

Fig.5 illustrates the horizontal distance (HD) and vertical distance (VD) of ignition position for different injection parameters. At low injection quantities and pressures, the ignition position is in the ambient air. At higher injection pressures, the ignition position is on the wall surface. The injection quantities that the ignition position reaches the wall surface are 12.5 mg (80 MPa injection pressure) and 10 mg (120 MPa injection pressure) respectively. At an injection pressure of 160 MPa, all of the ignition position are on the wall surface. As the injection quantities increase from 7.5 mg to 25 mg, the horizontal distances of ignition position increase from 1.5 to 6.33 mm (80 MPa injection pressure), 5.4 to 9.5 mm (120 MPa injection pressure) and 6.5 to 16.67 mm (160 MPa injection pressure) respectively.

This phenomenon could be attributed to the following two aspects. On one hand, the ambient temperature and heat energy in the vessel keep a fixed value. At a small injection quantity, the fuel spray could form high-quality mixing and higher air-fuel ratio due to a relatively better air entrainment [8]. It can absorb heat energy more rapidly in the local region. The liquid-phrase fuel is evaporated completely and generates limited combustible mixture before approaching the wall surface. Therefore, the ignition position is distributed in the ambient air at a small injection quantity. On the other hand, in comparison with smaller injection quantities after the end of injection, the spreading rate of fuel sprays is higher for larger injection quantities due to longer injection duration. In the meanwhile, higher injection pressures also lead to higher penetration rate and momentum [24]. The initial combustion region is pushed farther driven by the latter fuel. Even though the liquid-phrase fuel is evaporated completely before approaching the wall surface, the vapor-phrase fuel still moves downstream constantly and reaches the wall surface. The auto-ignition of the fuel-air mixture is affected by the wall surface with approaching the flat wall at low temperatures, causing farther ignition position. Therefore, the ignition position moves farther with increasing injection quantity and pressure.

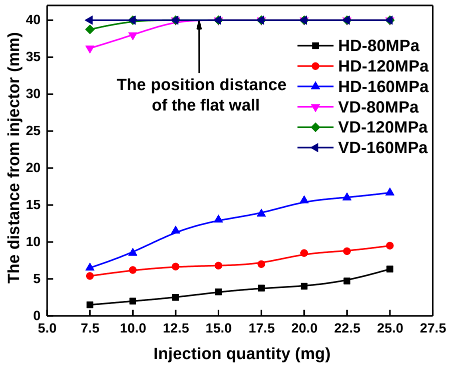

Fig. 5 Ignition position distances

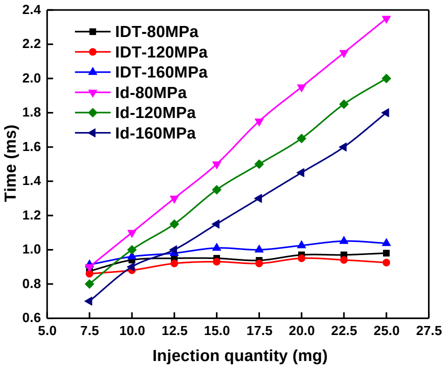

Fig. 6 IDT and Id for different injection parameters

Fig.6 illustrates the ignition delay times (IDT) and injection durations (Id) for different injection parameters. As the injection quantities increase from 7.5 mg to 25 mg, the ignition delay times vary from 0.88 to 0.98 ms (80 MPa), 0.86 to 0.93 ms (120 MPa) and 0.91 to 1.04 ms (160 MPa) respectively. The ignition delay times have no much difference at different injection quantities. However, all of the ignition delay times have the minimum value at an injection quantity of 7.5 mg. When the injection pressures increase from 80 MPa to 160 MPa, the ignition delay times decrease firstly and then increase.

This phenomenon could be attributed to the following factors. At an injection quantity of 7.5 mg, the ignition position is in the ambient air or approaches the injector center-line. Hence the ignition delay is less affected by the wall surface at low temperatures. At the small injection quantity, the fuel sprays have slightly higher evaporation rate due to relatively high-quality mixing [8]. It is easier to get enough thermal energy because of generating limited number of combustible mixture, decreasing the ignition delay. However, under the condition of a fixed injection pressure, the injection quantity displays little impact on the fuel-air mixing and evaporation process. The development process is similar in preparing specific combustible mixture. Therefore, the ignition delay time has no much difference with varying injection quantities. At higher injection pressures, more kinetic energy is used to enhance the atomization and evaporation of the fuel sprays. More droplets with smaller diameter are formed, decreasing the ignition delay time [25-26]. The ignition position moves farther away from the injector with increased injection pressures. As the air-fuel mixture is close to the flat wall at low temperatures, the mixture temperature is dropped and the ignition delay increases. Therefore, the ignition delay times decrease firstly and then increase with increased injection pressure.

At the small injection quantity with a high injection pressure, the ignition delay time is higher than the injection duration. At large injection quantities, the ignition delay time is lower than the injection duration. This phenomenon could be attributed to the following factors. At small injection quantities with high injection pressures, a more homogeneous mixture could be generated in a short time. This causes a low local temperature because of the large number of heat absorption at once [27]. Moreover, the existence of the flat wall at low temperatures increases the ignition delay time. Decreased injection quantity reduces the injection duration. Therefore, the ignition delay time is higher than the injection duration. With increasing injection quantity, the ignition delay time has no much difference whereas the injection duration increases at a constant rate. Therefore, the injection duration is higher than the ignition delay time at larger injection quantities.

4.2 Combustion Characteristics

Fig.7 illustrates the combustion durations with varying injection parameters. At an injection pressure of 80 MPa, the combustion duration increases from 2.1 to 7.1 ms for injection quantities of 7.5 mg to 25 mg. At an injection pressure of 120 MPa, the combustion duration increases from 1.1 to 4.2 ms for injection quantities of 10 mg to 25 mg. At an injection pressure of 160 MPa, the combustion duration increases from 1.35 to 2.7 ms for injection quantities of 15 mg to 25 mg.

This phenomenon could be attributed to following factors. Increasing injection quantity increases the injection duration. More fuel-air mixture could be generated in the combustion vessel. The injection duration is higher than the ignition delay time at larger injection quantities. Enough combustible mixture is generated for auto-igniting before the end of injection. Meanwhile, the fuel-air mixing and evaporation rate are less affected by the injection quantity. Therefore, the injection duration displays a significant impact on the combustion duration under the condition of a fixed injection pressure. It requires more time to cause fuel atomization, evaporation and combustion with increased injection quantity. As a result, the combustion duration is longer for larger injection quantity.

At higher injection pressures, the better atomization and evaporation have a significant impact on the combustion duration. Higher injection pressures lead to smaller vortical structures and larger spreading area [28]. More droplets with smaller diameter are generated, producing better entrainment, more mixture formation and efficient fuel vaporization. Additionally, the enhanced turbulence kinetic energy due to higher injection pressures improves fuel atomization, thereby hastening and intensifying the combustion [29]. Therefore, increasing injection pressure accelerates the combustion rate and reduces the combustion duration [30].

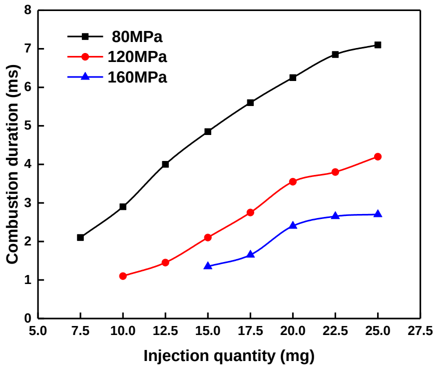

Fig. 7 Combustion durations with varying injection parameters

Fig.8 illustrates the variations of the flame area (AF) with varying injection parameters. An increase in the injection quantity doesn’t affect the variation rate of AF. The peak value of AF increases with increased injection quantity. The time reaching the peak value is longer for larger injection quantity. Increasing the injection pressure enhances the variation rate of AF. The peak value of the AF and the time reaching it decrease with increased injection pressure.

This phenomenon could be attributed to the following factors. The rapid increase of AF represents a rapid combustion of the air-fuel mixture, which reflects a rapid increase of the heat-release rate [31]. An increase in the injection quantity contributes to an increase in total amount of air-fuel mixture. More droplets can react with the ambient air, which enhances the combustion process. However, the injection quantity has no great effect on the atomization and evaporation rate of the fuel sprays. Therefore, increasing injection quantity does not affect the combustion rate significantly. Under similar combustion rate, the time of diffusion combustion is longer for higher injection quantity, which leads to higher flame area and longer time reaching the maximum value.

At higher injection pressures with a fixed injection quantity, the increment in the kinetic energy causes better air entrainment and forms finer droplets, resulting in rapid evaporation of the fuel sprays [32]. Meanwhile, high injection pressures can lead to strong swirl and turbulent disturbance between fuel sprays and ambient air. More ambient air is entrained into the core of fuel sprays. The injected fuel is distributed in a zone away from the flat wall because of strengthened spray-wall interaction [33]. These factors causes higher combustion rate and lower combustion duration, reducing the diffusion time of wall-impinged spray flame. Therefore, increasing injection pressure decreases the maximum value and the time reaching it.

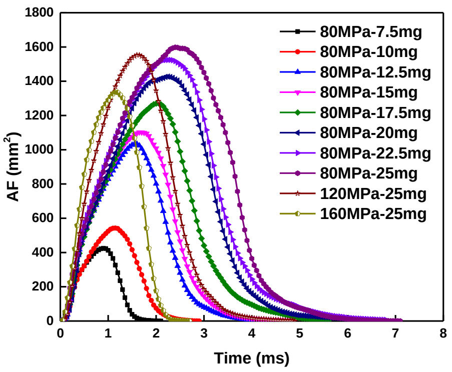

Fig. 8 Flame areas with varying injection parameters

Fig.9 illustrates the variation in the SINL with varying injection parameters. Increasing the injection quantity displays tiny difference on the variation rate of SINL. An increase in the injection quantity increases the maximum value of SINL and the time approaching it. Increasing the injection pressure accelerates the variation rate of SINL. The maximum value of SINL and the time approaching it decrease with increased injection pressure.

SINL reflects the formation and oxidation process of soot particle [34-35]. The variation law of SINL is similar to AF. Under the condition of a fixed injection pressure, the injection rate is analogous for different injection quantities, as shown in the Fig.4. At the larger injection quantity, more fuel sprays are injected into the combustion vessel and the diffusion distance is farther. As a result, it requires a longer time for fuel sprays to spread and react with ambient air in the combustion vessel. The impact of evaporation causes a wider diffusion area after wall impingement, which results in the increase of maximum value and time reaching it in SINL [36].

At higher injection pressures with a fixed injection quantity, the variation of the flame area take places more rapidly owing to smaller droplets, better atomization and higher dispersion [37]. It leads to the rapid increase of SINL because of increased combustion rate. Furthermore, increasing the injection pressure provides a higher velocity for fuel sprays to diffuse in the combustion vessel, resulting in the faster combustion and shorter combustion duration [38]. More complete combustion and shorter combustion duration normally mean higher combustion efficiency for higher injection pressures [39]. Therefore, increasing the injection pressure decreases the maximum value and the time reaching it.

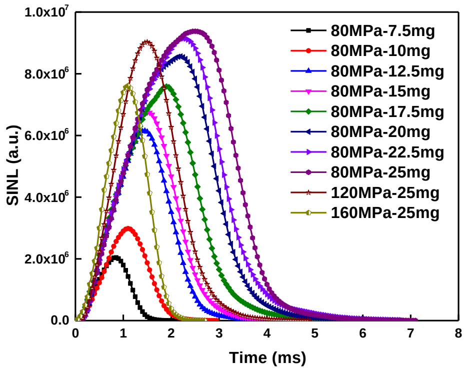

Fig. 9 SINL with varying injection parameters

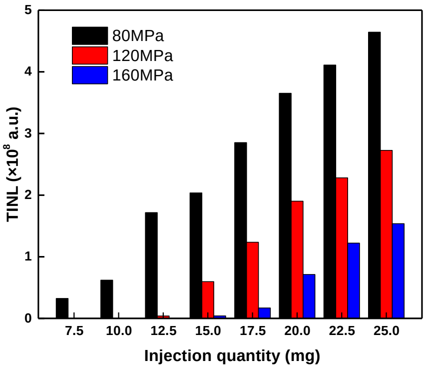

Fig. 10 TINL with varying injection parameters

Fig.10 illustrates the TINL with varying injection parameters. The TINL could reflect the soot level of the whole combustion event. The TINL increases with increased injection quantity and decreases with increased injection pressure.

This phenomenon could be explained by the following factors. An increase in injection quantity increases the injection duration and combustion duration. At larger injection quantities, more fuel sprays impinge on the wall. The local formation of an extravagant fuel-rich region contributes to the incomplete fuel combustion and increased soot emissions [40]. On the contrary, increasing injection pressure accelerates the diffusion rate. More fuel droplets with lower sauter mean diameter are generated, contributing to finer atomization and superior dispersion [41]. The turbulent motion of fuel-air mixture in the combustion vessel is also strengthened at high injection pressures. The fuel sprays mix more evenly with the air, which results in higher combustion rate and shorter combustion duration. The diffusion combustion is related to the soot emission, thus shorter duration of diffusion combustion results in lower soot level [42]. Therefore, soot formation increases with increased injection quantity while decreases with increased injection pressure.

5. Conclusion

1. At low injection quantities and pressures, the ignition position is in the ambient air. With increasing injection pressures, the ignition position reaches the flat wall rapidly, and it is pushed farther from the injector. For a fixed injection pressure, the ignition delay times of wall-impinged spray flame have no much difference with increased injection quantities. The ignition delay times decrease firstly and then increase with increased injection pressures. At the small injection quantity with a high injection pressure, the ignition delay time is higher than the injection duration. At large injection quantities, the injection duration is higher than the ignition delay time.
2. The combustion durations increase with increased injection quantities and decrease with increased injection pressures. The variation rate of AF and SINL has no much difference with increased injection quantity under the condition of a fixed injection pressure. Increasing the injection pressure could enhance the variation rate of AF and SINL. An increase in injection quantity increases the maximum value of AF and SINL and the time reaching it, whereas increasing injection pressure decreases the maximum value and the time approaching it. The TINL increases with increased injection quantity and decreases with increased injection pressure.
3. At small injection quantities, a low injection pressure is a suitable choice due to the existence of flat wall at low temperatures, which is beneficial for igniting in the ambient air and shortening the ignition delay. At larger injection quantities, higher injection pressures are more appropriate. Higher injection pressures can contribute to superior dispersion and better fuel atomization, which is conducive to shorten the duration of diffusion combustion, enhance combustion efficiency, and decrease soot emissions.

Nomenclature

HD -The horizontal distance of ignition position [mm]
VD -The vertical distance of ignition position [mm]
IDT -The ignition delay times [ms] AF - Flame area [mm^2]
SINL -Spatially integrated natural luminosity [-] TINL -Time integrated natural luminosity [-]

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