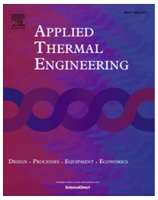
Applied Thermal Engineering 121 (2017) 511–519

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng



An investigation on a diesel jet's ignition characteristics under cold-start conditions

Fushui Liu [a], Zheng Zhang [a,b], Han Wu [a,*], Yikai Li [a], Yupo Ma [a], Xiangrong Li [a], Wei Du [a]

[a] School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
[b] School of Hydropower Engineering, Hebei University of Engineering, Handan 056038, China

HIGHLIGHTS

- Diesel jet ignition characteristics was investigated under cold start conditions.
- The lower ambient density and higher injection pressure could result in misfire.
- The chemical process is more dominate than physical process at low temperature.
- High injection pressure is against to ignition due to reduced local temperature.
- Fuel heating is one of potential ways improving diesel engine cold start ability.

ARTICLE INFO

Article history:
Received 27 December 2016
Revised 22 April 2017
Accepted 25 April 2017
Available online 27 April 2017

Keywords:
Ignition characteristics
Cold start
Spray combustion
Initial flame
Optical diagnostics
Diesel engine

ABSTRACT

The diesel engine is widely regarded as a critical power source for transportation vehicles, construction machinery vehicles, and military-equipment due to its advantages of significant horse power, higher fuel efficiency, greater reliability. However, diesel engines do suffer from ignition issues in extremely cold environments. Ignition characteristics during the start-up process directly impact both the start-ability and emission levels of the diesel engine. In this study, various optical diagnostics, such as Mie scattering, shadowgraphy method, and high-speed imaging, were applied to investigate the spray's vapor and liquid phases as well as the initial flame development, while an optical constant volume chamber was used to observe the in-cylinder condition. During the experiments, the ambient temperature, injection pressure, and fuel temperature was varied in a large range to simulate different stages of the cold-start or warm-up processes. The results show that the penetration of the spray's liquid and vapor phases, flame lift-off length, and ignition delay all observably increase with a decrease in the ambient density, ambient temperature, and fuel temperature. Furthermore, the chemical process is the dominant factor for ignition at a low ambient temperature. A low ambient temperature may lead to a misfire due to the separation between the spray's vapor phase and the expected initial flame location. Additionally, a low ambient density could lead to misfires due to the low heating capacity of the ambient gas. The study results also show that the injection pressure does not significantly influence the ignition delay or the flame lift-off length, but a higher pressure could result in a lower ignition success rate due to over-mixing of the air-fuel. Additionally, the fuel temperature significantly influences the ignition, which advances the initial ignition time 0.1 ms with every increase of 10 °C under an ambient temperature of 535 °C.

1. Introduction

The diesel engine is widely regarded as a critical power source for transportation vehicles, construction machinery vehicles, and military-equipment due to its advantages of significant horse power, higher fuel efficiency, greater reliability, and more [1]. A modern, 'clean' automotive diesel engine is 20–40% more efficient than its gasoline counterpart [2]. However, diesel engines do suffer from ignition issues in extremely cold environments [3,4].

Typically, when the environmental temperature is below −11 °C, diesel engines with a CR less than 18:1 cannot easily be started without external assistance [5,6]. It may take as long as several hours to warm up the engine block, lubricant system, and cooling system to render it operational. For standard vehicles, such as personal-use cars and trucks, the delay simply reduces trans-

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[*] Corresponding author.
E-mail address: hwu@bit.edu.cn (H. Wu).

http://dx.doi.org/10.1016/j.applthermaleng.2017.04.133
1359-4311/

portation efficiency in daily life for individual drivers. However, for special-purpose vehicles, such as fire trucks, ambulances, and military equipment, the delay can negatively influence human life, property, and national security.

In addition, the problems that occur during the cold start of a diesel engine include high unburned hydrocarbon (HC), PM, carbon monoxide (CO) emissions, and low thermal efficiency [7–9]. The extra emissions due to cold start can vary by more than one order of magnitude between 23 °C and −20 °C [10,11]. Furthermore, the fuel conversion efficiency can decrease from approximately 40% to 9% during the cold-start period [12,13].

However, in most of the temperate climate zone and all of the frigid climate zone, the temperature falls to far below the freezing point in winter. In China, there are more than 13 provinces where the average temperature in January is lower than −10 °C and some areas where the temperature can drop as low as −40 °C.

Given these issues, previous studies have been conducted on the cold start of diesel engines. Wang et al. [14] stated that the fuel flow characteristics deteriorate at a low temperature. They found that a reduction in the fuel temperature, from 25 °C to −18 °C, caused a longer injection delay, shorter injection duration, and less injection fuel mass. Park et al. [15] found that the fuel quantity decreased by as much as 50% when the fuel temperature changed from 40 °C to −30 °C. Wang et al. [16] investigated the near-nozzle microscopic characteristics of diesel spray at 25 °C and −2 °C. They reported that the low temperature caused high viscosity and high surface tension, which could lead to poorer dispersion. Lee et al. [17] found that the droplet number and vapor fuel mass decreased, while Ref. [15,18,19] reported that the liquid-phase injection penetration increased and the spray angle decreased as the fuel temperature decreased due to low-saturation vapor pressure and high viscosity. These results indicate that a low temperature leads to not only an incorrect injection mass but also a poor air-fuel mixture, which suppresses the auto-ignition of the diesel jet.

The diesel jet's auto-ignition characteristics directly influence the cold-start ability, operational stability, and harmful emission levels. Broatch et al. [20] reported that the auto-ignition threshold temperature of the diesel jet is around 415 °C based on a zero-dimensional thermodynamic model. However, in fact, a cold-start ignition is a more complex process when considering the air-fuel mixture and chemical reactions. Hwang et al. [21] investigated the spray combustion characteristics in a constant volume chamber. A partial misfire was detected at the cold-start condition, while the entire spray plume ignited successfully at the hot-start condition. On a diesel engine with a glow plug assistance device, Chartier et al. [22] found that the initial flame starts at a position close to the glow plug and then spreads to the whole chamber. Perrin et al. [23] further reported that the flame propagation is closely related to the temperature and air-fuel stratification inside the chamber. On a standard diesel engine, without a glow plug, Han et al. [24] found that, in addition to ambient temperature, the injection timing is also an important factor that significantly influences the cold-start ability of diesel engines. The injection timing should be adjusted cycle-to-cycle during that start process if the user aims to warm up the whole engine faster. As known, the varied injection timings in the cylinder correspond to the different ambient temperatures, ambient pressures, and ambient densities. This means that the auto-ignition of the diesel jet under a cold-start condition is not just sensitive to the ambient temperature but also hyper-sensitive to the in-cylinder condition. In fact, for a practical engine, both the start stages and the control strategy influence the in-cylinder condition during the injection cycle-by-cycle.

Therefore, this work studied the ignition characteristics of the diesel jet under varied cylinder conditions in an optical constant volume system due to its advantage of being able to control the conditions. The ambient temperature, ambient density, injection pressure, and fuel temperature was varied within a large range to simulate engines operating at different injection timings, supercharge ratios, starting stages, and temperature environments. Furthermore, various optical measurement technologies, including Mie scattering, the shadowgraphy method, and high-speed imaging, were applied to investigate the diesel jet's atomization, fuel evaporation, and ignition process and to analysis the auto-ignition characteristics.

2. Experimental system

2.1. Constant volume chamber

The constant volume chamber system used in the experiment was made by Beijing BITEC Co., Ltd. The system was designed to operate at a maximum pressure and temperature of 6 MPa and 1000 K, respectively, to mimic the in-cylinder condition of a diesel engine. As seen in Fig. 1, four optical quartz windows with a diameter of 120 mm were embedded at each direction of the chamber for visibility. To prevent overheating, a set of window coolers was arranged around the quartz. A heating cartridge with a rated power of 10 kW was installed inside the chamber to obtain the high temperature. A high-accuracy pressure regulator was used to precisely control the charged gas pressure and density. The injection system consisted of an injector with a custom-made, single-hole tip mounted on the top center of the chamber and a common rail system with a capability of 160 MPa injection pressure. A coolant system was used to adjust the released fuel temperature of the injection system. All of the operating conditions, including injection pressure, ambient temperature, ambient density, and fuel temperature, can be controlled by a control unit. See further detailed information in Ref. [25].

2.2. Diagnostic technologies and data processing method

2.2.1. Diagnostic technologies

The shadowgraphy method was used to capture the air-fuel mixture, known as fuel evaporation and gas entrainment, by identifying the spatial density difference. The test system included a dysprosium lamp, shadowgraphy system, and a high-speed camera (the phantom V7.3 model). Using the recorded images, the structure, angle, and penetration of the fuel vapor distribution was observed after data processing.

The Mie scattering and high-speed imaging methods were coupled to capture the liquid phase of the fuel spray and the initial flame spots of the auto-ignition within the same image. During recording, the aperture of the camera was set to a wide size, because the initial flame was very weak; thus, the light source of the Mie scattering was adjusted to a low level to avoid overexposure.

During the experiments, the camera speed was set at 20,000 fps, the resolution was set at 512×256 pixels, the exposure time was set at 20 μs, and the aperture was set at F2.8.

2.2.2. Data processing method

The raw image of the air-fuel mixture captured by the shadowgraphy method did not properly show the desired information due to too much noise, which was caused by thermal flow turbulence. The standard background removal method, which consists of subtracting the initial image from the processed one, did not effectively eliminate all of the noise while picking up the structure. Thus, a different background removal method, consisting of subtracting between two adjacent images, was chosen to process the data and obtain high-quality images. Because the flow rate of the