Fuel 230 (2018) 308–318

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Study of the spray characteristics of a diesel surrogate for diesel engines under sub/supercritical states injected into atmospheric environment

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ARTICLE INFO

Keywords:
n-Heptane
Sub/supercritical injection
Spray angle
Phase transition
Mach disk
Flash boiling

ABSTRACT

The spray characteristics of hydrocarbon fuel under superheated and supercritical conditions are quite different from the traditional liquid fuel injection. In this study, the macroscopic liquid phase and vapor phase spray geometry of n-heptane was investigated by Backlit Shadowgraph and Schlieren method to investigate the differences of spray pattern under various operation conditions such as fuel temperature, injection pressure and nozzle diameter. Furthermore, both the overall and near-field spray structures were analyzed to reveal the internal mechanism. During the experiments, the ambient environment was kept constant at atmospheric condition (25 °C, 0.1 MPa), the injection pressure was varied from 3 MPa to 5 MPa, always higher than the fuel critical pressure, and the fuel temperature was changed from 25 °C to 300 °C, spanning from liquid to supercritical state. Four different spray regimes have been identified based on the fuel temperature and spray geometry: liquid regime, flash boiling regime, near-critical regime and supercritical regime. Injection paths were analyzed on the basis of thermodynamic principle. The results showed that the fuel temperature has a minor effect on the macroscopic liquid phase and vapor phase characteristics below saturated-vapor temperature of 98 °C at the liquid regime. As the temperature is increased to about 200 °C, which is in the flash boiling regime, the local spray spreading angle of both the liquid and vapor phases increases, the downstream liquid phase of spray disappears gradually and high-intensity turbulence appears in the vapor phase image. At the near-critical regime where the fuel temperature is from 200 °C to the critical point (267 °C), the local spray angle of vapor phase begins to decrease and only a small area of liquid phase at the nozzle exit can be seen, while both the shock and flash boiling are visible. When the fuel temperature goes beyond the critical point locating in supercritical regime, the fuel spray is similar to a gas jet. The steady shock structure called Mach disk was observed and the fuel temperature has little influence on the Mach disk position and diameter in the supercritical regime. However, the fuel pressure and nozzle diameter significantly affect the Mach disk position and diameter.

1. Introduction

Recent years have witnessed the deterioration of the environment due to problems such as climate change and global warming, and the overuse of fossil fuels in internal combustion engines will accelerate these processes [1]. Furthermore, the particulate matter emission discharged by vehicles, especially diesel vehicles, causes haze which is extremely harmful to human health [2,3]. Thus researches that help reduce emissions are extremely important and the technology that can improve power performance and efficiency of modern diesel engines must be developed and implemented [4].

Fuel air mixing is one of the key factors that influences the in-cylinder combustion process. In recent years, substantial progress has been made to the fuel–air mixing process through the technology of high-pressure and ultra-high pressure injection systems. However, the bottleneck appears when the target pressure goes up to 300 MPa. Early studies [5,6] suggest that using high fuel temperature may be another valid solution which can increase the fuel air mixing rate and improve the combustion properties. The phenomenon named "flash boiling", which occurs in GDI engines at a certain degree of superheat, has been shown to have a great potential in promoting breakup and evaporation, leading to better fuel air mixing [7,8]. Recently, the situation called "supercritical condition," when the fuel temperature and pressure reach or are higher than the critical point of the fuel, may have great impact

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https://doi.org/10.1016/j.fuel.2018.05.050
Received 15 February 2018; Received in revised form 8 May 2018; Accepted 10 May 2018

Nomenclature

GDI	gasoline direct injection
SMD	Sauter mean diameter
DSLR	digital single lens reflex
CCD	charge coupled device
AR	analytical reagent
D	nozzle diameter (mm)
L	nozzle length (mm)
L/D	length-to-diameter ratio (−)
ISO	sensor sensitivity (−)
f-number	aperture (−)
x	distance to the nozzle exit (mm)
θ	local spray angle
X_m	locations of the Mach disks
D_m	diameters of the Mach disks

Subscript

r	right half spray
l	left half spray
i	total spray
m	Mach disks
inj	injection conditions
amb	ambient conditions

on fuel spray and combustion [9,10]. Compared to the traditional liquid fluid, a supercritical fluid mainly has properties of lower density, viscosity and tension, and higher diffusion [11], which are greatly beneficial to fuel air mixing. However, the fundamental research is still lacking. Thus, it is necessary to study the differences in spray characteristics of a liquid hydrocarbon fuel between traditional fuel injection and superheated fuel conditions.

Several researches have been reported on the injection characteristics of supercritical fluid. Newman et al. [12] conducted experiments on near-critical injection of liquid CO_2 and observed that the surface tension greatly reduced. Chen et al. [13] found that the injection temperature and ambient pressure were the main influencing factors of the supercritical jet penetration length. Oscbwald et al. [14–16] investigated the jet behavior such as the spread angle, core lengths of supercritical cryogenic nitrogen as a simulant for oxygen by several optical methods. Their study discovered that the thermodynamic state of the injected supercritical fluid plays the dominant role, rather than the injection velocity or momentum flux, in controlling the jet disintegration. Barata et al. [17] numerically investigated the cryogenic nitrogen jets under sub- and supercritical conditions using a variable density gas model. They compared the predicted initial jet growth rate with available experimental data by Chehroudi et al. [18,19] and showed good agreement for different supercritical density ratios. Doungthip et al. [20] experimentally and numerically studied the jet length and jet expansion angle of supercritical jet-A injection with varying fuel temperature and mass flow rate. They found that the jet length under supercritical fuel condition was shorter than in the subcritical state for the same mass flow rate and ambient pressure. Fan et al. [21] discovered that supercritical kerosene injection could improve the combustion efficiency in the supersonic combustion mode by approximately 10–15% over that of liquid kerosene. This is an amazing finding signifying that the engine performance could be significantly improved by injecting diesel or gasoline at supercritical conditions, if implemented.

However, the studies mentioned above almost all focused on small molecule cryogenic fluids or kerosene mainly for application to rocket engines. Recently, several studies related to vehicle internal combustion engines have been conducted. Boer et al. [22,23] experimentally studied supercritical gasoline combustion and emission of a single cylinder spark ignition engine. They indicated that the fuel under supercritical state will greatly reduce soot particle and CO emissions. Additionally, they reported that the direct injection of supercritical fuel results in high rates of heat release and high engine efficiency. Their work signifies that supercritical injection might increase the fuel flexibility of engines, which is a valuable consideration for the future. Anitescu et al. [24] investigated the macroscopic spray structure of dieseline, which is blends of diesel and gasoline with different volume fractions. Their injection results showed that a wider angle spray is generated as the fuel temperature increases, suggesting a better fuel–air mixing. Liu et al. [25] reported that the spray cone angle, penetration and Sauter Mean Diameter (SMD) of gasoline change with increasing the fuel temperature up to the supercritical condition. However, the intrinsic reasons leading to these results are still unclear. Lu et al. [26] numerically investigated the supercritical injection behavior and phase changes during the condensation process with a realistic equation of state model. They found that condensation occurs only if the temperature difference between the injection and ambient is large enough to promote strong heat transfer interactions. However, the fluids in their study are still gaseous. Wensin et al. [27] experimentally investigated the phase transition process of liquid fuels under supercritical environments simulating modern internal combustion engine operating conditions. They observed a transition to a supercritical state through a disappearance of the phase boundary. Some injection experiments were also conducted to study the phase behavior; however, in their work only the environment was under the supercritical state, but not the fuel.

Overall, some positive results have been reported on supercritical fuel injection in vehicle engines. However, comprehensive and deep understanding of the fuel spray behaviors under supercritical conditions, especially for diesel engines, is still necessary and fundamental experimental data are urgently needed. In this study experiments were carried out aiming to increase understanding of the spray behavior of diesel fuel under both the sub-critical states, including liquid condition (room temperature) and superheated conditions i.e. fuel temperature is higher than room temperature but lower than critical temperature, and the supercritical conditions. Since it has been shown by Anitescu et al. [28] and Lin et al. [29,30] that diesel is quite easy to coke under high temperatures leading to the blockage of nozzle, further studies are still needed to solve the coking problem. Considering the unavoidable difficulties related to the direct application of diesel in study of supercritical injection currently, n-heptane which is most commonly used as a surrogate of diesel [31], was adapted in this work.

In order to separate the influence of environmental factors, the current work is trying to investigate the spray characteristics of fuel under different fuel temperatures, injection pressures and injector nozzle diameters in an environment of ambient temperature and atmospheric pressure. In this way, the phase change process under different injection conditions, including the traditional liquid injection, subcritical and supercritical injection, can be revealed clearly. A fuel supply and injection system with two-stage heating system was designed to produce the conditions of all the experiment cases investigated in this study. Optical measurement techniques including Backlit Shadowgraph method using a DSLR (digital single lens reflex) color camera and Schlieren measurement using a high- speed camera were applied to record the macroscopic liquid phase and vapor phase spray structure respectively, to analyze the phase transition processes. In addition, magnified Schlieren images without a knife-edge were captured by a DSLR color camera to research the near-filed spray structure. During experiments, the injection background environment was kept at ambient temperature and atmospheric pressure, while the