Fuel 220 (2018) 763–768

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Evaporation and combustion characteristics of hydrocarbon fuel droplet in sub- and super-critical environments

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ARTICLE INFO

Keywords:
Hydrocarbon fuel droplet
Sub- and super-critical environments
Evaporation
Combustion

ABSTRACT

An experimental study on evaporation and combustion phenomena of single suspended hydrocarbon droplets was conducted in sub- and super-critical pressure environments under normal gravity. Droplet temperature and photographs were obtained by utilizing embedded thermocouple and high-speed video camera respectively. Experimental results show equilibrium vaporization stage exists during droplet combustion in sub-critical pressure environments, which accords with quasi-steady assumption. However, the equilibrium vaporization stage disappears during droplet combustion in super-critical pressure environments, quasi-steady assumption is not applicable. Droplet combustion time decreases rapidly with the increase of ambient pressure at sub-critical conditions and phase equilibrium controls the droplet burning rate. In super-critical conditions, the interface between droplet and ambient gas becomes ambiguous, droplet combustion time does not decrease and approaches a stable value; phase change disappears and diffusion coefficient starts to affect the droplet burning rate. The trend change of combustion time variation at critical pressure indicates that the critical pressure point is an important basis for judging whether the droplet enters the super-critical combustion or not. The ratio of droplet evaporation time to droplet combustion time has little change in sub-critical pressure environments, but it decreases rapidly in super-critical pressure environments, this indicates droplet evaporation process completes earlier in super-critical pressure environments.

1. Introduction

Fuel droplets evaporation and combustion research is an important part of the application of liquid fuels, in the super-critical environments, the “evaporation” and combustion characteristics of fuel droplet are the most important research contents that have been paid much attention in the field of combustion. Combustion is the main source of power for human beings. The combustion chamber environments of the direct-injection internal combustion engines, liquid-propellant rocket engines and a new generation of gas turbines and other high-pressure combustion equipment have reached super-critical fuel injection conditions [1,2]. The liquid fuel at a sub-critical initial temperature is injected into the combustion chamber and atomized. The atomized fuel droplets undergo evaporation, mixing with air, ignition, and combustion in an environment higher than their critical pressure. Spray combustion is carried out as a whole by a large number of droplets, its basic control unit is the process of droplet evaporation and combustion. The evaporation and combustion of a single droplet in super-critical environments is the basis for mastering the mechanism of spray combustion in the high pressure combustion equipment. Therefore, the study of evaporation and combustion of a single droplet is an important part of the research on the application of liquid fuel.

In recent years, experiments on evaporation and combustion of droplets at low pressure (lower than critical pressure of fuel) and atmospheric pressure have been carried out [3–10]. Numerical investigations of evaporation and combustion of fuel droplets in super-critical environments have also been carried out [11–16]. In the experiments, Zhang Mengzheng et al [17] conducted a preliminary research on evaporation and combustion phenomena of kerosene and UDMH single fuel droplet in super-critical environments using heavy piston actuator experimental system. So far, the understanding of the phenomena of super-critical liquid droplet evaporation and combustion is mainly seen in a few researches. Faeth et al [18] studied the high-pressure combustion characteristics of n-decane under microgravity conditions and found that the droplet combustion time decreases with the increase of ambient pressure. The minimum lifetime is achieved near the critical pressure of the droplet. From the critical pressure to the maximum pressure experimented, the combustion time of the droplet

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https://doi.org/10.1016/j.fuel.2018.02.073
Received 24 November 2017; Received in revised form 21 January 2018; Accepted 9 February 2018

begins to increase slowly. However, the result may not be effectively extended to other fuels with different physical and chemical properties due to one kind of fuel being used for experiments only. Kadota and Hiroyasu [19] studied the combustion characteristics of n-heptane, n-decane, n-dodecane, n-hexadecane, iso-octane and light oil droplets in super-critical environments. The experiments were performed under normal gravity conditions, it was found that the combustion time of all fuels decreases rapidly with the increase of ambient pressure when the pressure is less than critical pressure, it continues to decrease, but the speed is obviously slowed down when the pressure is greater than critical pressure. The change trend of the droplet combustion time changes at or near critical pressure. This phenomenon is enough to show that the factors influencing the burning rate in super-critical conditions begin to change greatly, such as the transition from evaporation rate to gas phase diffusion coefficient, because as the combustion process goes on, the surface of the droplet will enter super-critical state. At this point, no evaporation exists, and the gas diffusion coefficient becomes the main factor affecting the burning rate. Sato et al [20] conducted a high-pressure combustion experiment of droplet under normal gravity and microgravity conditions. It was found that under the normal gravity and microgravity conditions, the droplet combustion time increases with the increase of ambient pressure in super-critical pressure zone, which is different from the results of Kadota et al [19]. Segawa et al [21] studied the combustion characteristics of octadecanol droplets in a high-pressure gaseous environment with an oxygen volume fraction of 8%. The droplet temperature curves and synchronized droplet images were obtained when the ambient pressure reached 1.4 times critical pressure. It was found that the droplet temperature can rise to critical temperature during the combustion process, at this moment the interface between the droplet and the ambient gas became wavy, some interfaces appeared ambiguous. In addition, when the droplet temperature is below the critical temperature, a bright spot can be seen near to the center of the droplet image due to the droplet optical transparency and convergency of backlight. However, after the drop temperature reached critical temperature, the spot began to disappear, indicating that the droplets were no longer liquid and could only be described as a lump of dense gas. Zhang Mengzheng et al [17] found that the spontaneous combustion single droplet presents multiple point ignition phenomena. Moreover, the liquid droplet interface is blurred during the evaporation phase of the gel fuel. The authors could not analyze the variation of temperature of single droplet evaporation and combustion process in super-critical due to the lack of important data of droplet temperature. Although a large number of literatures related to the numerical simulation and experimental study of droplet combustion, there are still some deficiencies in the understanding of droplet combustion in super-critical environments, different investigations produce inconsistent and even opposite conclusions. At the same time, the establishment and verification of numerical model also urgently need more experimental results to provide sufficient basis.

There are several ways to realize droplet ignition in droplet experiment: heating wire ignition [22–31], spark ignition [32], compression ignition [33], hot gas flow ignition [34], carbon contact heating ignition [35], electric ignition [36], arc discharge ignition [20], rapid immersion in high temperature ignition [37–44], free fall into high temperature ignition [45] and the like. In high-pressure environment, most researchers use heating wire ignition. The method is also used in this paper.

Diesel is a complex fuel consisting of long chain alkanes, which are mainly composed of 15–18 carbon atoms. The combustion chamber environment of the direct-injection internal combustion engine at the time of fuel injection has been achieved to the critical condition of most elemental components in diesel fuel. Therefore, the authors selected n-hexadecane and n-heptadecane to further carry out experimental study on droplet evaporation and combustion in super-critical environments. In this experiment, a K-type thermocouple with a diameter of 50 μm was embedded into the droplet on the basis of the thin quartz thread suspension method to obtain the liquid drop temperature data synchronized with the high-speed photographic image.

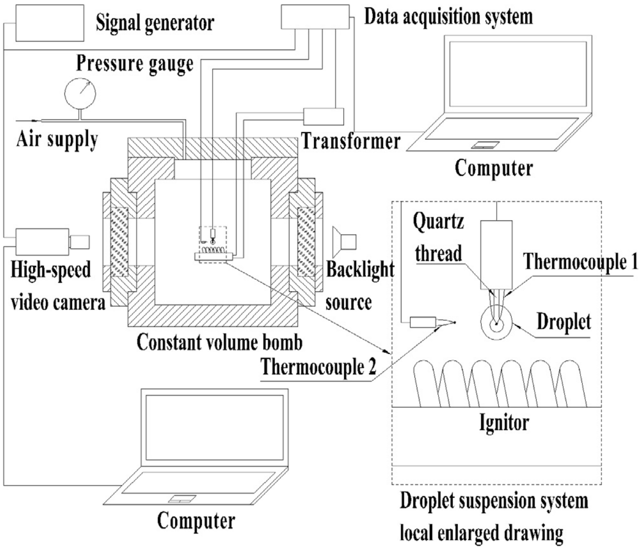

Fig. 1. Schematic diagram of experimental apparatus.

2. Experimental setup

The main part of the experimental apparatus, which consists of a constant volume bomb, a droplet suspension system, backlight source, high-speed video camera and data acquisition system, is shown schematically in Fig. 1. The both sides of the constant volume bomb are provided with quartz viewing windows with a diameter of 130 mm and a thickness of 80 mm. The diameter of the fine quartz thread used for hanging drops is 0.33 mm. In order to facilitate hanging, the tip of quartz thread is made into a ball with a diameter of 0.73 mm by hot working. The fuel droplet is suspended to a fine quartz baseball tip through a 10 μL micro syringe (with a minimum scale of 0.2 μL). The images of evaporation and combustion process of the fuel droplet was recorded with the NAC Memrecam GX-8 high-speed video camera at 1000 fps and Nikon MICRO NIKKOR 60 mm lens, the exposure time is 2.1 μs and tungsten halogen lamp was used as the backlight light source for the experiment.

The experimental fuel was n-hexadecane ($C_{16}H_{34}$, critical pressure P_{cr}: 1.4 MPa, critical temperature T_{cr}: 723 K) and n-heptadecane ($C_{17}H_{36}$, critical pressure P_{cr}: 1.34 MPa, critical temperature T_{cr}: 736 K), respectively. The droplet was suspended in a constant volume bomb, then filled with different back pressure (0.1 MPa–2.1 MPa) by compressed air bottle. The parameter P_r corresponds to the back-pressure P_a divided by critical pressure of the pure fuel tested P_{cr}, which is called as the reduced ambient pressure. The initial ambient temperature was room-temperature. The change of the droplet diameter is not observed in the process of charging the compressed air, because the boiling points of n-hexadecane and n-heptadecane are high, both of them are not volatile. The consistency of the droplet sizes under different back pressure is guaranteed. In this experiment, the droplet diameter and the ambient pressure are the factors that affect the uncertainty of droplet evaporation and combustion time. The uncertainty of diameter is mainly due to the error caused by the operator's ability to observe and judge. And it is found that the effect of pressure can be ignored. Its uncertainty is ± 3.28% by calculation, hence, the accuracy of experiments can be ensured. The nickel-chromium heating coil under the droplet is used as an igniter, the transformer provides the voltage to rapidly ignite the droplets, thus ensuring the consistency of the droplet size during ignition. To measure the temperature of the droplet, a fine K type thermocouple with a 50 μm diameter was used, as shown in Fig. 1,