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Heating and vaporization characteristics of single RP-3 aviation kerosene droplet at elevated temperature and pressure

Jing Yin, Dong-Qing Zhu, Shu-Yan Chen, Zhi-Fu Zhou*, Bin Chen*
State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University,
Xi'an 710049, China
*Corresponding author: zfzhou@mail.xjtu.edu.cn
chenbin@mail.xjtu.edu.cn

Abstract

The performance of aero-engine is greatly relied on the vaporization process of fuel droplets generated by liquid spray. The vaporization of single droplet may well be representative of spray's diluted region. In this paper, a series of experiments were carried out to investigate the evaporation characteristics of RP-3 aviation kerosene droplet at elevated temperature (400 ~ 600 ^oC) and pressure (1 MPa) environment. An individual RP-3 kerosene droplet with an initial diameter of about 1mm was suspended at the junction of a thermocouple wire with 50 μm diameter to acquire the temperature evolution during the whole vaporization. A high speed camera was employed to record the droplet size simultaneously. Under low evaporation rate, the whole evaporation process of the test fuel was divided into two periods: transient heating and equilibrium evaporation. In the transient heating period, the droplet normalized square diameter first rises slowly to the maximum value and then falls back to the initial value. In the equilibrium evaporation period, the variation of the normalized square diameter of the droplet basically followed the d^2 law. However, the RP-3 kerosene droplet only underwent the equilibrium evaporation period under high evaporation rate without the first transient period. This is because the transient heating period is short relative to the whole droplet life due to the increase of evaporation rate under high temperature. The evaporation rate (K) of RP-3 kerosene droplet at different temperature environments was derived. It is observed that, K had a rapid increase firstly, reach the peak and then decrease monotonically. High ambient temperature indicates faster the rising rate of K value and the greater the peak evaporation rate, and consequently the more obvious the downward trend, and then it approached a steady value close to that of low temperature. The experimental data also revealed the temperature history of RP-3 kerosene droplet during the whole vaporization process. Droplet temperature (T_{drop}) always kept increasing under all temperature environments. The heating of droplets accelerates with increasing ambient temperature, which indicates faster increase of T_{drop}. And T_{drop} increased much slowly at the end of vaporization. The experimental results were important not only for providing physical evidence but also for providing a bank of data for numerical validations of RP-3 aviation kerosene droplet vaporization under high temperature and pressure.

Keywords

RP-3 kerosene, Droplet evaporation, Aero-engine, Evaporation rate, Mass and heat transfer

1. Introduction

As the heart of the aircraft, the aero-engine plays a decisive role in aircraft performance. To greatly improve the power density of the aeroengine and reduce emissions, it is necessary to ensure that the main combustion chamber has good combustion stability and efficiency. Droplet evaporation in the combustor of an aero-engine is a basic process of liquid combustion, which directly determines fuel spray atomization, air-fuel mixture formation and combustion quality. Accordingly, studies on the evaporation characteristics of an individual fuel droplet are indispensable to increase the fundamental understanding of the behavior of spray combustion and improve combustion efficiency and emission performance.

In the last several decades, many experimental approaches are employed for studying isolated droplet evaporation, of which the fiber-suspended droplet technique is the most widely applied. Using fiber-suspended droplet technique, many researchers experimentally investigated the single droplet evaporation characteristics of various fuels in atmospheric pressure and elevated temperature environment, including alkanes [1-3], kerosene [4, 5], fossil diesel [6, 7], biodiesel [8, 9] and so on. However, in the actual environment in combustion systems, fuel droplets will face high ambient temperature and high pressure when evaporating. Up to now, there are mainly two teams that have conducted experimental study of a single droplet in high-pressure and high-temperature environments: Korea Advanced Institute of Science and Technology [10, 11] and Nihon University [12, 13]. However, the suspension wires used in the above research at elevated pressures and temperatures are all quartz fiber. RP-3 aviation kerosene is a commercial jet fuel commonly employed in China [14]. However, the research on the evaporation characteristics of RP-3 kerosene is still blank in the current days. As a result, the present study aims to experimentally observe the evaporation behavior of RP-3 kerosene droplet at elevated temperature and pressure. The synchronized temporal variations of droplet size and temperature were obtained at ambient pressure of 1 MPa and environment temperature varying from 400-600 ^{o}C. The influences of ambient temperature on the RP-3 kerosene droplet evaporation characteristics at 1MPa is analyzed. The outcome would provide scientific evidence for investigating the evaporation characteristics of RP-3 kerosene droplet in realistic aero-engines.

2. Experimental apparatus and methods

The schematic diagram of the experimental apparatus for droplet evaporation at elevated pressures and temperatures is presented in Fig. 1. The setup adopts a double-layer structure, the outer structure is responsible for providing a high-pressure environment, and the inner structure is utilized to heat up the droplet. The outermost cylindrical pressure vessel (inner diameter 275mm; inner height: 350 mm) is made of stainless steel and can be resistant to high pressures up to 5 MPa. The temperature of the heating chamber is operated by a PID feedback temperature controller and can be attained in the heating chamber is up to 600 ^{o}C, and the temperature control accuracy is about ± 2 ^{o}C. Moreover, it is found that when the temperature of heating chamber reaches the maximum, the temperature of high-pressure chamber is kept below 50 ^{o}C. The droplet generation and transmission system can generate an individual droplet and hang it on the welding point of a thin thermocouple, and then transfer it stably and quickly to the specified environment. The suspension wire selected in this study is a K-type thermocouple with a diameter of 50 μm. It can not only be used to suspend liquid droplet, but also measure the inner temperature of the droplet. Backlighting imaging technique was employed to observe the droplet throughout the evaporation process. The entire evaporation process is photographed clearly through the high-speed camera (Photron brand Fastcam SA-Z) coupled with a micro-lens (Nikon AF Micro Nikkor 105mm f/2.8D). A light source was located on the opposite side of the camera to backlight the droplet. As the droplet starts to move into the high temperature chamber, the droplet temperature acquisition system and the camera were simultaneously triggered by Labview program. The temperature data (speed: 500 fps) and the backlit image (speed: 50-1000 fps) are transmitted into and stored in the computer. To extract the equivalent diameter of droplets in batch from the original images collected in the experiment, an image processing program based on the integral principle [15] is developed by MATLAB.

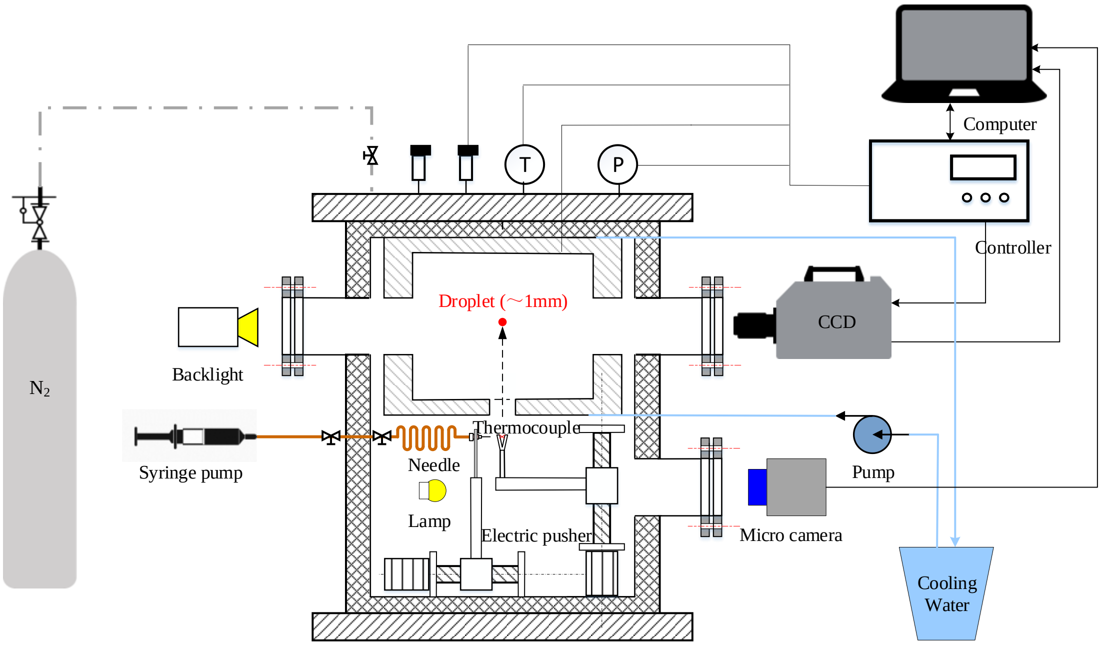

Fig. 1. Schematic diagram of the experimental equipment for single-droplet evaporation.

3. Results and discussion

Heating and evaporation experiments for RP-3 kerosene single droplet are conducted at different ambient temperature under ambient pressure of 1 MPa. The ambient temperature has varied from 400 to 600 °C in 50 °C increments. The droplet initial diameters were carefully controlled at 1.0 ± 0.1 mm in this work. Since it is too hard to obtain fuel droplets with precisely the same diameter in all experiments, the droplet diameter and evaporation time are normalized by the initial droplet diameter squared to minimize the influence of droplet initial diameter on the evaporation in the following analysis. Fig. 2 exhibits the variation of normalized squared diameter (d^2/d_0^2) of RP-3 kerosene droplet with the normalized time (t/d_0^2) at different ambient temperature at 1 MPa. As expected, at the same ambient pressure conditions, RP-3 kerosene droplet tend to evaporate faster in high ambient temperature. This is because the surface mass flow rate of droplet evaporation is jointly controlled by the mass-diffusion coefficient of fuel vapor in ambient gases and the saturated pressure of vapor at the droplet's surface. And both increase with ambient temperature, thereby significantly enhancing the droplet evaporation. It also can be seen that under the ambient pressure of 1 MPa, the variation trends of d^2/d_0^2 under different ambient temperatures have different characteristics. When the ambient temperature is lower than 500 °C, the evaporation characteristics of RP-3 kerosene single droplet presents a two-stage feature, namely, the transient heating period and the equilibrium evaporation period. During the transient heating period, d^2/d_0^2 first rises slowly to the maximum and then falls back to the initial value 1. While in the equilibrium evaporation period, d^2/d_0^2 approximately decreases proportionally with the normalized time. In the early evaporation process, since the thermal expansion caused by the increase of droplet temperature is greater than the droplet size reduction due to slow evaporation, the droplet size rises. The droplet surface temperature rises gradually over time, which increases mass transfer. When the surface evaporation rate is equal to the thermal expansion rate, the droplet size reaches its peak. Then, because of continuous heating, the evaporation rate of the droplet increases further. However, the RP-3 kerosene droplet only experiences the equilibrium evaporation period under 500-600 °C without the first transient period. This can be attributed to the fact that an increase in the ambient temperature accelerates the heating and evaporation of RP-3 kerosene droplet. Accordingly, the normalized time required for the droplet expansion rate and evaporation rate to reach equilibrium is shortened.

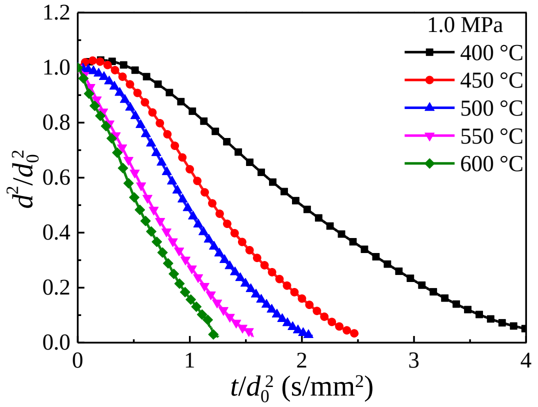

Fig. 2. Temporal variation of normalized squared droplet diameter (d^2/d_0^2) of RP-3 kerosene single droplet at different temperature under 1MPa

In order to analyze the evaporation characteristics of RP-3 kerosene droplet under varying working conditions more intuitively, the instantaneous evaporation coefficient of liquid drops was derived. The instantaneous evaporation coefficient (K) of droplet is defined as the slope of the curve fitting of d^2/d_0^2. Fig. 3 illustrates the variation of K for RP-3 kerosene single droplet with different temperature under 1 MPa. At this ambient pressure, the instantaneous evaporation coefficient curves of all RP-3 kerosene droplet exhibit decreased after increasing trend. When the ambient temperature is lower than 500 °C, the value of K is initially negative then gradually increases with the normalized time. After reaching the peak, it gradually tends to be stable and has a slight downward trend. The existence of transient heating period makes K negative in a short time. With evaporation, the increase of droplet surface temperature is beneficial to the evaporation, hence K is gradually dominated by the volume decline rate caused by droplet evaporation. Subsequently, with the fuel vapor mass fraction of the droplet surface increases, the difference in vapor mass fraction between the droplet surface and its ambient air is narrowed, which results in the reducing driving force of mass transfer. Under the ambient temperature of 500-600 °C, K of high temperature is positive throughout. And it is always greater than that at low temperature, which was resulted from the rate of evaporation depends on the effect of the fuel components' diffusivity coefficient and saturated vapor pressure. High ambient temperature corresponds to higher evaporation rate of droplets. As a result, the value of K decreases more quickly with the rapid accumulation of the vapor mass fraction of the droplet surface.

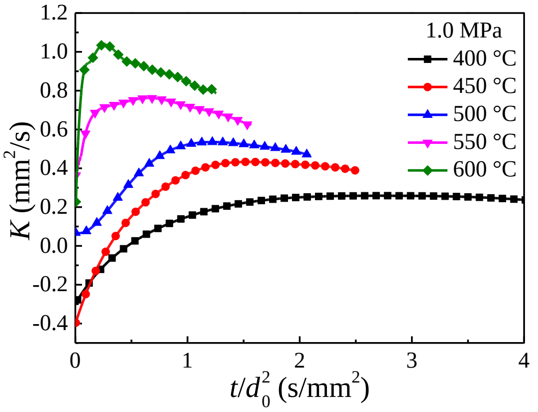

Fig. 3. Instantaneous evaporation rate coefficient of RP-3 kerosene single droplet at different temperature under 1 MPa

Fig. 4 shows the variation of the droplet temperature (T_{drop}) of RP-3 kerosene versus the normalized time (t/d_0^2) at different ambient temperature under ambient pressure of 1MPa. It can be seen that the droplet is always in the heating process throughout the evaporation process. The slopes of T_{drop} become gentle gradually over time. At elevated pressure environment, an increase in the ambient temperature generates a faster heating rate of the droplet inner temperature. This is because the studied ambient temperature range is well beyond the critical temperature of all components in RP-3 kerosene, and the heat transferred from the surrounding air is always sufficient to provide the latent heat of evaporation, which leads to the consistently increase of T_{drop}. The trend variation of T_{drop} depends on the variation of the heat penetrated into droplet interior. In the initial stage, a large difference of temperature exists between the droplet surface and its surrounding gas, indicating the large driving force of heat transfer. Meanwhile, due to the slow evaporation in the early evaporation process, more energy the droplet absorbed is remaining to heat the droplet thereby, resulting in the sharp increase of T_{drop}. As the droplet surface temperature increases, the heat absorption from ambient decreases and the evaporation rate increases. Most of the heat absorbed by droplet is used not for heating droplet but for evaporation, thereby weakening the heating rate of T_{drop}.

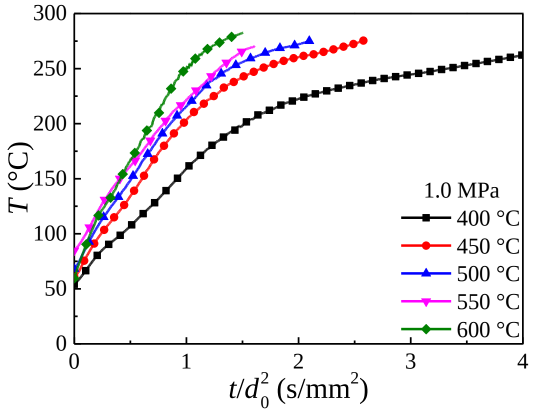

Fig. 4. Temperature evolution of RP-3 kerosene single droplet at different temperature under 1 MPa

4. Conclusion

The present investigation examined the effect of the ambient temperature on the evaporation process of RP-3 kerosene single droplet at 1 MPa. The major conclusions drawn from this paper are summarized below:

(1) The evaporation process of RP-3 kerosene single droplet at 400 °C and 450 °C consisted of two periods: transient heating period and equilibrium evaporation period. In the transient heating period, the droplet normalized square diameter first rises slowly to the maximum value and then falls back to the initial value. In the equilibrium evaporation period, the variation of the normalized square diameter of the droplet approximately conformed to the classical d^2 law.

(2) However, the RP-3 kerosene droplet only experienced the equilibrium evaporation period under high evaporation rate without the first transient period. This can be explained that raising ambient temperature promotes the droplet heating and evaporation, resulting in reducing the duration of transient heating period.

(3) The instantaneous evaporation rate (K) of RP-3 kerosene droplet experienced a process of increasing sharply at first and then decreasing. Moreover, the variation trend in K value becomes more pronounced with the increase of ambient temperature.

(4) Droplet temperature (T_{drop}) always kept increasing under all studied ambient temperatures. High ambient temperature results in promoting droplet heating, which indicates faster increase of T_{drop}. And the increase of T_{drop} has decelerated remarkably in the late evaporation process.

Acknowledgments

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