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A new stationary droplet evaporation model and its validation

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Abstract The liquid droplet evaporation character is important for not only combustion chamber design process but also high-accuracy spray combustion simulation. In this paper, the suspended droplets' evaporation character was measured in a quiescent high-temperature environment by micro high-speed camera system. The gasoline and kerosene experimental results are consistent with the reference data. Methanol, common kerosene and aviation kerosene droplet evaporation characteristics, as well as their evaporation rate changing with temperature, were obtained. The evaporation rate experimental data were compared with the prediction result of Ranz-Marshall boiling temperature model (RMB), Ranz-Marshall low-temperature model (RML), drift flux model (DFM), mass analogy model (MAM), and stagnant film model (SFM). The disparity between the experimental data and the model prediction results was mainly caused by the neglect of the natural convection effect, which was never introduced into the droplet evaporation concept. A new droplet evaporation model with consideration of natural convection buoyancy force effect was proposed in this paper. Under the experimental conditions in this paper, the calculation results of the new droplet evaporation model were agreed with the experimental data for kerosene, methanol and other fuels, with less than 20% relative deviations. The relative deviations between the new evaporation model predictions for kerosene and the experimental data from the references were within 10%.

1. Introduction

Liquid fuels are advantageous because of their high calorific value per volume, convenient transportation, and lower pollution emission than many gaseous and solid fuels. At present and in the near future, liquid fuels are and will be widely used in power machinery. However, the combustion of liquid fuels is a complex process, so that investigating it through experi-

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ment is difficult and expensive. The numerical simulation can be a powerful tool to study the detailed interaction relationship and flow structures in liquid fuel spray combustion. An accurate two-phase model set, particularly the droplet evaporation model, is crucial for spray combustion simulation in the engine combustor design process because it is highly significant to the flame structure, fuel burning rate and droplet spatial distribution.

During liquid fuel combustion, the droplets evaporate first, and then the gas phase mixture burns, with the spray burning rate positively correlating with the droplet evaporation rate. The liquid fuel is atomized before burning in engineering machinery to ensure the highest combustion efficiency possible in the combustor. The characteristics of single droplet evaporation are thus related to combustion chamber performance. In addition, the evaporation characteristics of liquid fuel droplet are the foundation in understanding many complicated combustion issues, such as combustion theory, combustor design, pollution and emission control, and fire safety. Therefore, the study of liquid fuel evaporation characteristics is theoretically and practically significant.

Droplet evaporation is a phenomenon associated with the processes of heat transfer, mass transfer, and gas flow. Many theoretical studies on the evaporation of a single droplet have been conducted. Godsave[1] and Spalding[2] proposed d^2 law, which is mainly applicable to the evaporation of a single-component droplet in a high-temperature quiescent environment. Law and Sirignano[3,4] presented the rapid mixing model based on classical d^2 law, where d is droplet diameter. This model suggests that the droplet temperature is spatially uniform but temporally varying. Sirignano[5] found that the internal circulation of a liquid droplet does not significantly reduce even if the vortex strength inside the droplet reaches a high level. Then Sirignano renamed the rapid mixing model as the infinite conduction model, which was more accurate in concept than the former. The finite heat conduction model was proposed by Prakash and Sirignano.[6,7] They presented that the internal circulation of a liquid droplet is unremarkable in static condition, and thermal diffusion dominates the heat transfer inside the droplet. Harstad[8] stated that the temperature inside a droplet is not uniform, and a temperature gradient in space exists; they also proposed a nonequilibrium model. Zhou[9] found that the intensive evaporation of a droplet in a forced convection environment does not have the characteristics of the boundary layer; consequently, he presented thick exchange layer theory. Zhou[9] proposed stagnant film theory to deal with the evaporation and combustion of droplets in a forced convection environment.

Rao and Lefebvre[10] examined kerosene droplet evaporation characteristics under different air conditions, and a new empirical formula for liquid fuel evaporation rate was developed from the experimental data. Stengele et al.[11] performed an evaporation experiment of free-falling N-pentane and N-nonane droplets; droplet evaporation law was obtained under the experimental conditions. The experimental results agreed well with the calculation results of the finite conductivity model. Wu et al.[12] conducted experiments on droplet evaporation in a turbulent environment and found two different evaporation regions. Ghassemi et al.[13] hung heptane and a 16 alkyl mixture droplet with quartz wire statically to investigate liquid droplet evaporation in a normal-gravity environment. Okamoto et al.[14] examined the evaporation and diffusion characteristics of kerosene and gasoline mixture through experiments. Irfan[15,16], Mishra[17], Hyemin[18], and other researchers conducted many evaporation experiments on single-component and mixed-liquid droplets, including kerosene, ethanol, and heptane. They determined the relationship between droplet evaporation rate and temperature, as well as the micro explosion phenomenon of kerosene droplet in the evaporation process. The evaporation of gasoline and ethanol was studied by Liu[19] and Hallett[20] et al. Khan[21] and Irfan[22] et al. also investigated kerosene evaporation through experiments. The single droplet evaporation process in microgravity was studied experimentally by Chauveau et al.[23], and the entire evaporation process was found to conform to d^2 law. Ma et al.[24] investigated droplet evaporation in a high-temperature gas flow environment. They found that temperature and flow velocity affect the stability of droplet evaporation. They also found that a critical temperature exists, at which the initial heating time of the droplet in the entire droplet evaporation time reaches the maximum.

In this paper, the evaporation phenomenon of liquid fuel droplets in a quiescent high-temperature environment through an electric heating suspended droplet experimental system is investigated firstly. Secondly, the prediction results of the existing popular evaporation models are compared with experimental data. Finally, thick exchange layer theory and a new droplet evaporation model are studied and applied to prediction of the droplet evaporation rate versus ambient temperature.

2. Experiment

2.1. Experimental device

The sketch map of experimental device used in this paper is shown in Fig. 1. It consists of five parts: the heating control system, temperature control system, experimental chamber, high-speed camera, and data acquisition system. The apparatus can provide a stable heating source, suspend droplet stably, and obtain images and digital signals synchronously.

2.2. Experimental method

The experimental devices were connected as shown in Fig. 1. The heating furnace was heated to the test temperature with the temperature controller. The high-speed camera (MONO,

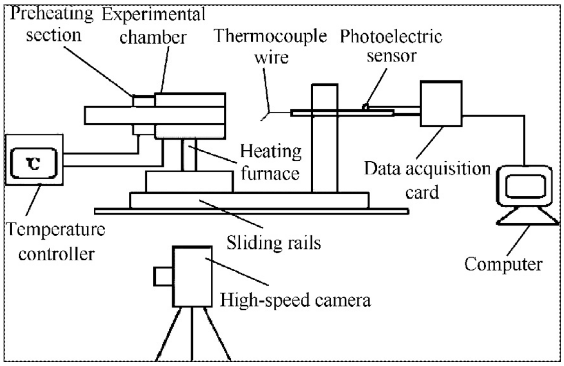

Fig. 1 Schematic of experimental system.

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