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Full Length Article

Kerosene evaporation rate in high temperature air stationary and convective environment

Fang Wang*, Rui Liu, Min Li, Jie Yao, Jie Jin

Aero Engine Numerical Simulation Research Center, School of Energy and Power Engineering, Beihang University, Beijing 100191, China
Collaborative Innovation Center of Advanced Aero-Engine, Beijing 100191, China

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ABSTRACT

The liquid fuel evaporation rate, especially for aviation kerosene, is important in both aero-engine combustion chamber design process and spray combustion numerical simulation modeling, while the evaporation rate in high temperature stationary and convective environment is lack of both experimental data validation and theoretical analysis studies. In this paper, firstly the common kerosene and aviation kerosene evaporation characteristic was measured by experiments. The liquid fuel's single droplet was suspended in high temperature stationary or convective air environment. The evaporation characteristic was delineated by more than 70 sets of effective experimental data. Under the experimental condition in this paper, the higher the convective velocity is, the greater the droplet evaporation rate value becomes. Also there is difference between the common kerosene and aviation kerosene in evaporation rate value in the convective environment. Generally, the common kerosene has higher evaporation rate value than the aviation kerosene's in the same condition. Secondly, the Ranz-Marshall droplet evaporation model which is widely used and rooted from the stagnant film analysis method has been compared with the experimental results. There is certain deviation between the Ranz-Marshall model prediction results and experimental data. Then a two-dimensional analysis evaporation model (TDAEM) was tested by both stationary and convective experimental data. The TDAEM model's prediction results agree well with the experimental data which is from both this paper and other references.

1. Introduction

Liquid fuel is and will be the main energy source of most aero-engines, automobile engines, some rockets and supersonic combustion chambers. Basically, the liquid fuel needs to be atomized into droplets which evaporate in hot gas phase mixture [1,2]. So experimental and theoretical study of droplet's evaporation rate in high temperature stationary and convective flow is of great significance for both combustion chamber design process and spray combustion numerical simulation modeling [3,4]. As an important fuel source, aviation kerosene evaporation characteristics need more study.

Although kerosene droplet is a mixture of complex chemical composition, its evaporation characteristic still meets "d^2" law [5–7]. But some other oil droplets' evaporation characteristics do not meet "d^2" law [8] and show more complex evaporation characteristics [9]. As an important energy source and a widely used fuel, aviation kerosene droplet evaporation characteristics are lack of experimental studies and reliable verifications. Yu et al. [10] found that the liquid propellant LP1846 droplet's averaged evaporation rate in convection environment is about 10% bigger than that in stationary environment at the same environmental temperature with temperature range from 950 K to 1000 K by suspended droplet method. Wu et al. [11] used perforated disk in low-speed air duct to provide turbulence environment in order to research the hydrocarbon fuel evaporation rate in turbulence condition, and a single droplet turbulence evaporation rate model was also studied. Ma et al. [12] found by experiments that the higher the convective velocity was, the higher the evaporation rate value was. Stengele et al. [13] measured the evaporation rate of n-pentane and n-nonane droplets in high temperature (greater than 650 K) by free fall method. So the kerosene droplet evaporation characteristics in convective environment need experimental studies.

The earliest evaporation model is "d^2" law proposed by Godsave [6] and Spalding [7]. On the basis of "d^2" model, Law [14,15] proposed "rapid mixing model". Subsequently, Sirignano [16] modified it into "infinite conductivity model". Prakash and Sirigano [17,18] later supplemented "conduction-limit model" and put forward "Prakash-Sirigano axisymmetric model". Its simplified model which is called "Tong-Sirigano axisymmetric model" was also proposed later [19]. Bellan and

* Corresponding author.
E-mail address: fwang@buaa.edu.cn (F. Wang).

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Nomenclature

B	transport number (–)
c_p	constant pressure specific heat (J/(kg·K))
C_v	evaporation rate (m^2/s)
d	droplet diameter (m)
d_0	initial droplet diameter (m)
D	diffusion coefficient (m^2/s)
F_b	buoyancy (N)
g	gravitational acceleration (m/s^2)
K_e	evaporation constant (m^2/s)
Nu	Nusselt number (–)
Pe	Peclet number (–)
Pr	Prandtl number (–)
q_e	evaporation heat (J/kg)
r	radial position (m)
Ra	Rayleigh number (–)
Re	Reynolds number (–)
t	time (s)
T	temperature (K)
ΔT	temperature difference (K)
V	volume (m^3)
v	speed (m/s)
Y	mass fraction

Greek symbols

ρ	density (kg/m^3)
θ	transport number (–)
β	expansion coefficient (1/K)
λ	thermal conductivity (W/(m·K))

Subscripts

l	liquid
r	radial
w	wall
θ	circumferential
∞	far field

Harstad [20] proposed "non-equilibrium model" according to Langmuir-Knudsen's law. It is concluded that the droplet temperature in the model is not homogeneous and there exists a temperature gradient in space. In recent years, many researchers enriched and improved the classical evaporation models. The variation of droplet surface concentration with evaporation time was considered by Sazhin et al. [21]. Dombrovsky et al. [22] considered the heat transfer by radiation between droplets and environment. Kristyadi et al. [23] studied the droplet temperature at different positions in evaporation process along with time, and compared several models of energy equation. There are also some reports on the mixture fuel evaporation theory [24,25]. Godsave [26] and Spalding [27] et al. pioneered the theoretical study of droplet evaporation rate in convection environment and the spherically symmetric stagnant film approximate calculation method was proposed. Using the stagnant film analysis method, the two dimensional droplet evaporation problem in convective environment can be changed into a one dimensional problem. Other later researchers proposed boundary layer theory and two-dimensional analysis theory to deal with the droplet evaporation characteristics in high temperature convection condition [28]. Abramzon et al. [29] carried out theoretical study of convective vaporization of a fuel droplet with thermal radiation absorption and proposed a new model.

The mass exchange model between discrete phase (droplet) and continuous phase (gas) is fundamentally from the single droplet evaporation characteristic. There is almost the same discrete phase evaporation model as the single droplet evaporation model from stagnant film analysis, such as the Ranz-Marshall model. The Ranz-Marshall droplet evaporation model is widely used for spray numerical simulation especially after its integration with FLUENT. Wang et al. [34] used Langmuir-Knudsen droplet evaporation model to conduct numerical simulation of single n-decane droplet evaporation process, as well as thermal auto-ignition in high-speed droplet-laden mixing layers. Luo et al. [4] adopted infinite thermal conductivity model with no temperature gradient inside droplets in direct numerical simulation on supersonic turbulent spray jet. Petranovic et al. [30] used the Abramzon-Sirignano model as the two phase mass transfer model to calculate the evaporation process of spray and two phase combustion. It is difficult to estimate the accuracy of two-phase model by spray combustion simulation results. It's better to specially compare the two-phase model with the detailed experimental data. In actual combustor, droplets evaporate in high temperature environment. But most droplet evaporation models only behave well in low ambient temperature. Further validations in high temperature conditions are needed [3]. Further validation in high speed convection, such as supersonic spray combustion in Ref. [34], should be developed. At present, the comparison of experimental data and the model predictions in high temperature are not enough. The droplet evaporation model which can be applied in high temperature both stationary and convective environment is needed.

As for aviation kerosene, there are fewer theoretical work and experimental data for its evaporation characteristics and much fewer for its droplet evaporation rate in high temperature convective environment. In this paper, firstly, the single droplet evaporation rate of common kerosene and aviation kerosene will be measured in both stationary and convection environment under different temperature and velocity; secondly, the evaporation characteristics of common kerosene and aviation kerosene will be compared; then the widely used stagnant film evaporation model prediction result will be contrasted with experimental data. Finally, a new evaporation model will be proposed in the foundation of two-dimensional analysis, which can be applied in both stationary and convection environment and will be validated by experimental data. In order to get more accurate

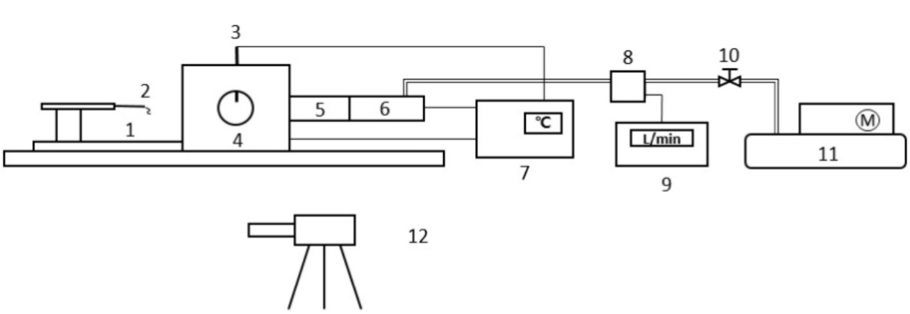

Fig. 1. Schematic of the experimental system. 1-slide way, 2-nichrome wire, 3-thermocouple, 4-electric heating furnace, 5-rectifier tube, 6-electric preheating tube, 7-temperature controller, 8-mass flow rate control valve, 9-mass flow meter displayer, 10-throttle, 11-air compressor, 12-high-speed camera.