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Effect of ambient temperature on the puffing characteristics of single butanol-hexadecane droplet

Yu Zhang [a, b], Ronghua Huang [a, b, *], Yuhan Huang [a, b], Sheng Huang [a, b], Yinjie Ma [a, b], Shijie Xu [a, b], Pei Zhou [a, b]

[a] State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan, 430074, China
[b] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China

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ABSTRACT

Puffing characteristics of BUT50 (50% n-butanol and 50% n-hexadecane by mass) were investigated using the droplet suspension technology under 638, 688 and 738 K. Experimental results showed that BUT50 underwent transient heating, fluctuation evaporation and equilibrium evaporation phases under all ambient temperatures. In the fluctuation evaporation phase, the fluctuation frequency of 738 K was higher than that of 638 K. $(D_{max}/D_0)^2$ of 738 K was lower than that of 638 K. Easy bubble rupture led to high fluctuation frequency and low $(D_{max}/D_0)^2$ at 738 K. Three turning points were found in transient temperature growth rate at 638 and 738 K. Four characteristic droplet temperatures were analyzed, including droplet temperatures at the start (T_1) and end (T_2) of transient heating phase, at $(D_{max}/D_0)^2$ (T_3) and at the end of total lifetime (T_4). T_2 was slightly lower and T_3 was slightly higher than the boiling point of n-butanol. T_4 was lower than the boiling point of n-hexadecane. Furthermore, the transient heating duration (t_{TH}), fluctuation evaporation duration (t_{FE}) and total lifetime (t_{TL}) decreased with increasing ambient temperature. The reduction of t_{FE} played an important role in the decrease of t_{TL}. The percentages of t_{TH}/t_{TL} and t_{FE}/t_{TL} were stable with increasing ambient temperature.

1. Introduction

Many researches are carried out to improve dynamic, economic and emission performances of diesel engines, including combustion optimization [1,2], renewable fuels [3,4] and waste gas utilization [5,6]. Diesel is a kind of non-renewable fossil fuels. Its combustion is a major contributor of anthropogenic climate change and environmental pollution [1,7]. Therefore, it is necessary to find renewable and environmentally friendly fuels. n-Butanol has higher energy density and is more miscible with diesel than methanol and ethanol [8]. The oxygen content in n-butanol can improve fuel-oxygen mixture to reduce soot emissions [9]. n-Butanol also has the potential to reduce NO_X formation due to its high latent heat of vaporization [3,10]. Therefore, n-butanol is an attractive renewable fuel for diesel engines. Table 1 shows physical properties of n-butanol, n-hexadecane and diesel. n-Butanol can not be used as a neat fuel in diesel engines because of its lower heating value (3.31×10^7 J/kg), lower kinematic viscosity (2.22×10^{-6} m^2/s), lower cetane number (25) and higher auto-ignition temperature (658 K) than diesel (heating value: 4.25×10^7 J/kg, kinematic viscosity: 2.70×10^{-6} m^2/s, cetane number: 40-55, auto-ignition temperature: 501 K).

The addition of high n-butanol content into diesel can improve engine performance and emission characteristics [2,7,11,12]. The combination between high n-butanol content and exhaust gas recirculation (EGR) could simultaneously reduce NO_X and soot emissions [2]. ABE50 (the blend of 50% ABE and 50% diesel, ABE is the blend of 30% acetone, 60% butanol and 10% ethanol by volume) displayed combustion characteristics similar to neat diesel while achieving a shorter combustion duration and lower natural flame luminosity [11]. High volatility difference in butanol-diesel blends could lead to puffing and micro-explosion phenomena, which were the strongest around the equi-volumetric composition [7,12]. In summary, BUT50 (the blend of 50% n-butanol and 50% diesel) potentially increased thermal efficiency and decreased emissions when applied in diesel engines. As shown in Table 1, the physical properties of n-hexadecane are similar with those of diesel. Therefore, n-hexadecane is used as a representative for diesel to eliminate the influence of diesel's multicomponents [13]. In this

* Corresponding author. School of Energy and Power Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, 430074, China.
E-mail address: rhhuang@hust.edu.cn (R. Huang).

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Nomenclature

Variables

C	Circumference, [mm]
D	Droplet diameter, [mm]
k	Rate of bubble expansion, [mm^2/s]
n	Number of experimental samples, [–]
P	Images, [–]
S	Projected area, [mm^2]
t	Duration, [s/mm^2]
Δt	Interval time of temperature data, [s/mm^2]
T	Temperature, [K]
u	Uncertainty
x	Experimental value
X	Contribution ratio to lifetime reduction, [–]
Y	Normalized characteristic duration, [–]
λ	Temperature growth rate, [K▪mm^2/s]
τ	Moment, [s/mm^2]

Subscripts

0	Initial moment
amb	Ambient
A	A-type standard uncertainty
bac	Back
bot	Bottom
B	B-type standard uncertainty
c	Circumference equivalent
C	Combined standard uncertainty
fro	Front
FE	Fluctuation evaporation
HT	High temperature
LT	Low temperature
top	Top
tran	Transient
TH	Transient heating
TL	Total lifetime

Table 1
Physical properties of n-butanol, n-hexadecane and diesel [3,13,22,28,29].

Physical properties	n-Butanol	n-Hexadecane	Diesel
Molecular formula	C_4H_9OH	$C_{16}H_{34}$	C_{12}–C_{25}
Molecular weight	74.12	226.44	–
Lower heating value, [J/kg]	3.31×10^7	4.42×10^7	4.25×10^7
Latent heat of vaporization, [J/kg]	5.85×10^5	2.74×10^5	2.50×10^5
Kinematic viscosity at 313 K, [m^2/s]	2.22×10^{-6}	3.28×10^{-6}	2.70×10^{-6}
Oxygen content, [%]	21.6	–	–
Density at 293 K, [kg/m^3]	810	770	830
Boiling point at 1 bar, [K]	390	560	458–618
Auto-ignition temperature, [K]	658	483	501
Cetane number, [–]	25	100	40–55

work, BUT50 (the blend of 50% n-butanol and 50% n-hexadecane) is chosen as the test fuel.

It is meaningful to investigate evaporation and puffing characteristics because they are key factors influencing the engine performance. The droplet suspension technology is widely used to investigate the characteristics of single droplet. In this technology, a droplet is suspended on a suspension wire and transported into a hot and stagnant environment. The suspension wire mainly includes silica fiber [14,15], silicon carbide fiber [16–19] and thermocouple [10,13]. The main limitation of this technology is that the initial droplet size can only vary from 0.6 to 1.23 mm when the diameter of suspension wire varies from 0.1 to 0.2 mm [13–15,17,19]. The droplet is likely to fall down from the suspension wire if the droplet size is too big. On the other hand, the suspension wire has a significant impact on the droplet if the droplet size is too small. In spite of the limitation, this technology is widely applied in researches of single droplet, including evaporation [14,20–22], puffing [10,13,15], micro-explosion [23–25] and combustion [16–18,23,24,26,27]. The merit of this technology is the synchronous measurement of droplet temperature and images when a thermocouple is used as the suspension wire.

By the droplet suspension technology, some experiments were carried out to investigate the effect of ambient temperature on evaporation and puffing characteristics. Hashimoto et al. [22] researched evaporation characteristics of single droplet of palm methyl ester under ambient temperatures from 473 to 873 K. The results showed that the initial heating period and droplet lifetime decreased with increasing the ambient temperature. The average evaporation coefficient increased with the increase of ambient temperature because higher ambient temperature led to bigger Spalding transfer number. Similar results were also reported in Refs. [30,31]. Ma et al. [15] researched evaporation and puffing characteristics of single droplet of acetone–butanol–ethanol (ABE) and diesel blends under ambient temperatures from 423 to 823 K. The droplet lifetimes of ABE and diesel decreased with the increase of ambient temperature. The difference of droplet lifetimes between ABE and diesel became smaller at high temperature. Furthermore, the puffing phenomenon could be observed in the experiments of ABE-diesel blends. The puffing strength increased with increasing ambient temperature. Han et al. [13] researched evaporation and puffing characteristics of benzyl azides-hexadecane blends under ambient temperatures from 473 to 773 K. The lifetime decrease of benzyl azides-hexadecane blend was more than that of dodecane–hexadecane blend with increasing ambient temperature. This was because the inner reaction of benzyl azides enhanced the puffing phenomenon and improved the evaporation process. Furthermore, the reduction of fluctuation evaporation phase played a significant role in the decrease of droplet lifetime. Han et al. [10] also studied the evaporation and puffing of an ethanol-diesel-biodiesel droplet. The DE10 (the blend of 85% diesel, 10% ethanol and 5% biodiesel) droplet displayed a three-phase evaporation process, including transient heating, fluctuation evaporation and equilibrium evaporation phases. All the three phases decreased with the increase of ambient temperature. However, the percentages for each phase approximately remained identical when the ambient temperature changed from 623 to 723 K.

As review above, the researches of ambient temperature are focused on the effect of ambient temperature on evaporation coefficient, droplet lifetime and durations of the three phases. The novelty of this work is that new parameters are proposed to quantitatively analyze the puffing process. These parameters include temperature growth rate, similarity degree, deformation degree, rate of bubble expansion and four characteristic temperatures.