



An experimental and numerical study of the evaporation and pyrolysis characteristics of lubricating oil droplets in the natural gas engine conditions



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ABSTRACT

The auto-ignition of lubricating oil droplets in cylinder has been confirmed to be one of the major reasons of abnormal combustion in natural gas engines. A series of fundamental experiments were carried out to elucidate the lubricating oil evaporation and pyrolysis behaviors under different ambient temperatures. An enhanced multi-component evaporation and pyrolysis model for lubricating oil droplets was presented. This model takes into account all key processes during the droplet lifetime, including the finite heat conduction and mass diffusion in the liquid phase, multi-component diffusion in the gas phase, as well as the pyrolysis and polymerization of high molecular-weight hydrocarbons in high temperatures. By comparing with the measurements of the droplet behaviors of lubricating oil and heavy oil, the present model shows good predictions of the droplet behaviors. Furthermore, this model was used to discuss the detailed behaviors of lubricating oil droplets in natural gas engine conditions. It is found that the lubricating oil droplets have significantly different behaviors from those of diesel and gasoline. They show slight pyrolysis and polymerization behaviors due to the high molecular-weight components. The heating period is crucial for the lubricating oil droplets, and the highest ratio of the heating period to the total droplet lifetime is up to 80%. The smaller droplet takes shorter time to get the high concentration of oil vapor surrounding the droplet surface than the larger droplet.

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1. Introduction

Large natural gas engine is an internal combustion engine which runs on natural gas, and it is a new generation green power that can meet the International Marine Organization (IMO) Tier III harmful emission standard without using after treatment. The kernel tasks of large natural gas engines development are to increase the power density and ensure the stable combustion. However, the problem of abnormal combustion not only severely impedes the increase of the brake mean effective pressure of the engine, but also results in the destructive effects [1]. Recently, some technical reports [1–3] emphasized that one of the main causes of abnormal combustion in natural gas engines is the auto-ignition of lubricating oil droplets in the combustion chamber. Actually, the lubricating oil droplets are dragged by the charge motion in the natural gas engine cylinder and heated by the surrounding gas during the compression stroke. Once the lubricating oil droplets auto-ignite before

normal flame arrives at where oil droplets exist in cylinder, the abnormal combustion could happen. If the auto-ignition happens before the normal ignition time, an even severe abnormal combustion, auto-ignition, could occur. Therefore, understanding the mechanism of the auto-ignition of lubricating oil droplet is critical for the development of natural gas engines.

The auto-ignition frequency is mainly controlled by the ignition delay, including the physical and chemical ignition delay [4–6]. The physical ignition delay of lubricating oil droplets is mainly controlled by the evaporation process, because there is no break up occurrence for the lubricating oil droplets with low relative velocity to the ambient gas. Based on the previous works [4,5], the physical ignition delay accounts for the most time of the total ignition delay for the high molecular-weight hydrocarbons. As a result, the evaporation process makes the significant effects on the ignition delay of lubricating oil droplets, and sequentially determines the auto-ignition probability. Therefore, a fundamental experiment is needed to study the evaporation behavior of the lubricating oil droplets. Due to the experimental limitations, the numerical study is also required to get the insight into the

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Nomenclature

AR	aromaticity		
A, B, C	Antoine coefficients		
$D_{i,g}, D_{i,l}$	diffusion coefficients		
D_0	initial droplet diameter		
E_1, E_2, E_3	Arrhenius law constants		
h_b, h_e	coefficient in Eq. (16)		
h_{eV}	heat of evaporation		
h_i	specific enthalpy		
h_{py}	heat of pyrolysis		
h_{po}	heat of polymerization		
k_1, k_2, k_3	Arrhenius law constants		
m_i	mass		
\dot{m}	mass variation rate		
MW	molecular weight		
N, N_l	number of species		
Nu	Nusselt number		
\dot{Q}	heat flux		
R	distance from droplet center		
R_l	droplet diameter		
\dot{R}	droplet variation rate		
Sh	Sherwood number		
T	droplet temperature		
u	velocity		
t_1, t_2, t_3, t_4, t_5	moments of time		
v	diffusion velocity		
x	mole fraction		
y	mass fraction		
		<i>Greek symbols</i>	
		ρ	density
		λ	thermal conductivity
		γ	activity coefficient
		ε_i	normalized fraction
		σ	surface tension
		ω_i	acentric factor
		<i>Superscripts</i>	
		c	corrected
		s	surface
		r	residual
		<i>Subscripts</i>	
		i, j	species
		eV	evaporation
		g	gas
		l	liquid
		py	pyrolysis
		po	polymerization
		r	relative
		v	vapor
		0	initial value

evaporation characteristics for lubricating oil droplets in the natural gas engine conditions characterized by the high temperature and pressure.

The compositions of real lubricating oils are known to play a pivotal role in determining the auto-ignition frequency. Typical lubricating oils include base oils (about 90 vol.% or more) and various additives [7]. The base oils are essentially a complex mixture of hydrocarbon molecules (paraffins, naphthenes, and aromatics), and the carbon number is in the range of C_{16} to C_{50} [7,8]. In previous studies, most of work were conducted on the ignition of diesel and heavy oil droplets, there are few studies focused on the ignition delay of lubricating oil droplets, especially for the evaporation time. Kuti et al. [6] experimentally investigated the chemical ignition characteristics of lubricating oil droplets. In their work, hexadecane ($C_{16}H_{34}$), heptadecane ($C_{17}H_{36}$), and octadecane ($C_{18}H_{38}$) were selected as the surrogates of lubricating oils. Fundamental chemical kinetic modeling studies showed that alkanes larger than C_{14} exhibit nearly identical fuel/air gas-phase ignition delay times across a range of operating temperatures [9,10]. Based on the results in Ref. [11], the normal paraffins larger than C_{18} show similar cetane number. Hence, the three surrogates of $C_{16}H_{34}$, $C_{17}H_{36}$, and $C_{18}H_{38}$ can well predict the chemical ignition delay of lubricating oils. However, these surrogates have a big difference with lubricating oils in the physical properties, thus, they are unable to predict the physical ignition delay.

Most studies focused on the evaporation characteristics of diesel and gasoline surrogates [12,13], few studies have been concentrated on lubricating oil droplets. A few numerical simulations approximated the heptane (C_7H_{16}) or hexadecane ($C_{16}H_{34}$) as the physical surrogate of lubricating oils [14,15]. However, according to the previous work [16], the evaporation rate of different components has significant discrepancies. For instance, the droplet lifetime of C_7H_{16} is almost half of $C_{16}H_{34}$ under high temperatures. Based on the work of Wang et al. [17], the average carbon number

of lubricating oils is C_{27} – C_{28} , which has higher boiling point compared to C_7H_{16} and $C_{16}H_{34}$. Accordingly, C_7H_{16} or $C_{16}H_{34}$ cannot represent the physical properties and predict the evaporation behavior of lubricating oil droplets. Since the ignition time of oil droplets is mainly governed by the more volatile components [2], a multi-component evaporation model is needed to get a deeper knowledge of evaporation process for lubricating oil droplets in natural gas engine conditions.

Some previous works [18,19] noted that high molecular-weight hydrocarbons have a tendency to undergo thermal cracking, which is characterized by high molecular components decomposing into ones with low molecular-weight. This phenomenon takes place in the presence of high molecular-weight hydrocarbons ($MW_i \geq 350$) [19], which occupies a certain proportion in lubricating oils. Garaniya et al. [20] investigated the evaporation and pyrolysis characteristics of heavy oil droplets, which has larger molecular-weight components than lubricating oils. Kim et al. [21] experimentally studied the pyrolysis reaction for a mass of lubricating oils in a tubing bomb micro-reactor. Most of previous works about the pyrolysis of lubricating oils were concentrated on the pyrolysis reaction pathway, few studies focused on the oil vapor species and distribution around the droplet through evaporation and pyrolysis processes. However, the oil vapor species and distribution have the primary effects on the occurrence of abnormal combustion in natural gas engines. Hence, a multi-component evaporation and pyrolysis model is needed to describe each species behavior in a single lubricating oil droplet, as well as the oil droplet lifetime under natural gas engine conditions.

In this study, the evaporation and pyrolysis behaviors of the lubricating oil droplets in natural gas engine conditions were investigated. In the experiment, the lubricating oil droplets with different initial sizes were exposed into high ambient temperatures. The droplet size change history was recorded by using a high-speed camera with a long-distance microscope. In

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