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Full Length Article

Flame structure and laminar burning speed of gas to liquid fuel air mixtures at moderate pressures and high temperatures

Ziyu Wang*, Mohammed Alswat[1], Guangying Yu, Moaz Omar Allehaibi, Hameed Metghalchi

Mechanical and Industrial Engineering Department, Northeastern University, Boston, MA 02115, USA

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ABSTRACT

Gas to liquid (GTL) fuel, synthesized from natural gas through Fisher–Tropsch (F–T) process, has gained significant attention due to its cleaner combustion characteristics when compared to conventional fuels. Combustion properties such as flame structure and laminar burning speed of GTL/air mixture premixed flames have been investigated. The GTL fuel used in this research was provided by Air Force Research Laboratory (AFRL), designated by Syntroleum S-8, which was derived from natural gas via F–T process. A mixture of 32% iso-octane, 25% n-decane, and 43% n-dodecane by volume is considered as the surrogates of GTL fuel for filling process. Experiments were conducted using a cylindrical chamber to study the flame structure and a spherical chamber for laminar burning speeds measurement. The cylindrical chamber was set up in a Z-shape schlieren system coupled with a high-speed CMOS camera that was used to capture evolutionary behavior of flames at up to 40,000 frames per second. Pressure rise as a function of time during the flame propagation in the spherical vessel was the primary input of the multi-shell thermodynamic model used to calculate the laminar burning speed for the smooth flames. Power law correlations over a wide range of pressures (from 0.5 atm up to 4.3 atm), temperatures (from 490 K up to 620 K), and equivalence ratios (from 0.7 to 1.2) have been developed for laminar burning speeds of GTL/air flames. Experimental burning speed results have been compared with simulation values obtained by the solution of one dimensional steady premixed flame code from CANTERA using Ranzi's chemical kinetics mechanisms. Comparisons show very good agreement with the available experimental data in this study.

1. Introduction

Alternative fuels obtained from feedstocks such as natural gas, coal, and biomass are called synthetic paraffinic kerosene (SPK) fuels. Among SPK fuels, gas to liquid (GTL) fuel, synthesized from natural gas through Fisher–Tropsch (F–T) process, mainly consists of normal-alkanes, iso-alkanes and cyclic-alkanes, which are different from those of conventional jet fuels such as Jet A, Jet A-1, and JP-8. GTL fuel has played a significant role recently due to its clean combustion behavior because of less aromatic content and neglectable sulfur [1,2].

Over the years, the scope for deriving high value products from natural gas has attracted many companies all over the world, such as Syntroleum, Sasol, Shell, Chevron, ExxonMobil, and ConocoPhillips to invest in GTL technology development heavily on different scales [3]. Various groups have studied the economics and benefits of producing GTL fuel from natural gas recently [4,5]. GTL fuels may have different chemical compositions from different companies since they go through different F–T process; however, physical properties of the fuels are within the stipulated range for the aviation fuels. The GTL fuel from Syntroleum Corporation, S-8, is represented by a surrogate mixture in this work. The GTL fuel properties and its chemical composition are based on the reports from Air Force Research Laboratory (AFRL) [6,7]. The difference in fuel chemical properties will have an influence on the combustion and emission characteristics. The different aspects of the combustion performance and emissions of GTL fuel as an alternative fuel for automobile [8–16] and aviation [17–24] engines were investigated and compared with those of the traditional fuels.

Laminar burning speed which contains information regarding the mixture's diffusivity, reactivity, and exothermicity is one of the most important fundamental combustion characteristics. There are many studies on the laminar burning speed of aviation GTL fuel (S-8) in literature. Kumar and Sung [19,20] studied auto-ignition characteristic and laminar burning speed of GTL and conventional fuel/air mixtures. Atmospheric pressure laminar burning speeds of Jet-A/O_2/N_2 and S-8/O_2/N_2 mixtures were measured using a counterflow method at temperature of 400 K, 450 K, and 470 K. Singh et al. [25] investigated the

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* Corresponding author.
E-mail address: wang.ziyu2@husky.neu.edu (Z. Wang).

[1] Current address: Mechanical Engineering Department, University of Tabuk, Tabuk 71491, Saudi Arabia.

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Nomenclature

A_b	burned gas area
A_f	flame surface area
A_{eb}	electrodes area
A_{ph}	preheat zone area
A_{wb}	chamber wall area
a	fitted constant
b	fitted constant
c_p	constant-pressure heat capacity
c_v	constant-volume heat capacity
E	standard uncertainty
E_b	burned gas energy
E_i	initial energy
E_u	unburned gas energy
E_{eb}	electrodes boundary energy defect
E_{ph}	preheat zone energy defect
E_{wb}	wall boundary energy defect
e_b	burned gas specific energy
e_u	unburned gas specific energy
e_{bs}	isentropically compressed burned gas specific energy
e_{us}	isentropically compressed unburned gas specific energy
I	radiation intensity
j	number of narrow band
k_n	k-distribution absorption coefficient
M	number of directions
m	total mass
m_b	burned gas mass
m_u	unburned gas mass
$\dot{m}_b$	mass burning rate
N	number of Gaussian quadrature points
P	mixture pressure
P_0	reference pressure
p	pressure
p_i	initial pressure
Q_e	energy loss to electrodes
Q_r	energy loss to wall
Q_w	radiation energy loss
R	specific gas constant
r	flame radius
r_e	electrode radius
S_u	laminar burning speed
S_{uo}	reference laminar burning speed
T	temperature
T_b	burned gas temperature
T_i	initial temperature
T_u	unburned gas temperature
T_w	chamber wall temperature
T_{bs}	isentropically compressed burned gas temperature
T_{us}	isentropically compressed unburned gas temperature
T_{u0}	reference temperature
t	time
V	energy source volume
V_b	burned gas volume
V_c	chamber volume
V_e	electrodes volume
V_i	initial volume
V_u	unburned gas volume
V_{eb}	electrodes boundary displacement volume
V_{ph}	preheat zone displacement volume
V_{wb}	wall boundary displacement volume
v_b	burned gas specific volume
v_u	unburned gas specific volume
v_{bs}	isentropically compressed burned gas specific volume
v_{us}	isentropically compressed unburned gas specific volume
x_b	burned gas mass fraction
$\dot{x}_b$	rate of burned gas mass fraction
α_0	fitted constant
α_1	fitted constant
β_0	fitted constant
β_1	fitted constant
γ_b	burned gas heat capacity ratio
γ_u	unburned gas heat capacity ratio
δ_{eb}	electrodes boundary displacement thickness
δ_{ph}	preheat zone displacement thickness
δ_{wb}	wall boundary displacement thickness
κ	stretch rate
ν	wave number
ρ_b	burned gas density
ρ_u	unburned gas density
ϕ	equivalence ratio
ω_n	weight function

laminar burning speeds and Markstein lengths of n-decane, Jet-A, and S-8 and got similar laminar burning speed results at pressure of 1 atm, temperature of 400 K, and equivalence ratio from 0.7 to 1.4. Experimental and modeling measurement on laminar burning speed of GTL and 1-hexanol mixtures have been done by Kick et al. [26] at pressure of 1 atm, temperature of 473 K, and equivalence ratio from 0.9 to 1.4. Ji et al. [27] determined the laminar burning speed of jet fuel and its alternatives in the counterflow configuration at temperature of 403 K and atmospheric pressure. Hui et al. [28,29] have compared the fundamental combustion characteristics of conventional and alternative jet fuels at temperature of 400 K and 470 K. The laminar burning speed results of conventional and alternative jet fuels were similar; however, the ignition delay times of the latter were shorter than those of the former. Vukadinovic et al. [30] investigated the laminar burning speed and Markstein number of GTL and its blend at pressures of 1 atm, 2 atm, and 4 atm, temperatures of 373 K, 423 K, and 473 K in a cubic vessel using the optical laser method. Experimental and Detailed Kinetic Model study of GTL and its blend on ignition delay time and laminar burning speed at atmosphere pressure and temperature of 473 K have been done by Dagaut et al. [31,32] at various equivalence ratios. Askari et al. [33] studied the onset of auto-ignition for GTL fuel/air mixtures for different equivalence ratios of 0.8–1.2 and different initial pressures of 8.6, 10, and 12 atm at an initial temperature of 450 K in a constant volume vessel. Yu et al. [34] computationally calculated the ignition delay time and laminar burning speed of GTL fuel for different equivalence ratios of 0.7–1.4, different pressures of 1.0–25 atm, and different temperatures of 400–800 K.

Although there are many experimental and theoretical studies on laminar burning speed of GTL fuels, most of pressures in the literature are atmosphere pressure and the highest experimental temperature in the literature is 473 K. A comprehensive study on the behavior of laminar burning speed over a wide range of pressures, temperatures, and equivalence ratios has not been conducted yet. The GTL fuel used in this research was supplied by Air Force Research Laboratory (AFRL), designated by Syntroleum S-8, which was derived from natural gas via F–T process. A mixture of 32% iso-octane, 25% n-decane, and 43% n-dodecane [35] by volume is considered as the surrogates of GTL fuel for filling process. The initial GTL/air mixture composition is defined as:

$$\phi(0.32C_8H_{18} + 0.25C_{10}H_{22} + 0.43C_{12}H_{26}) + 15.83(O_2 + 3.76N_2)$$

where ϕ is fuel air equivalence ratio.

Properties of the S-8 fuel are presented in Table 1. The experiments have been done in moderate pressures and high temperatures in cylindrical and spherical chambers. Pressure rise has been measured using