Applied Energy 195 (2017) 671–680

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Laminar flame characteristics of cyclopentanone at elevated temperatures

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HIGHLIGHTS

- Laminar flame characteristics of premixed cyclopentanone-air mixtures were investigated.
- Experimental data were obtained from Schlieren photography inside a Constant Volume Vessel.
- Laminar burning velocities of cyclopentanone are higher than gasoline but lower than ethanol.
- Empirical expressions were obtained for various equivalence ratios and initial temperatures.

ARTICLE INFO

Article history:
Received 12 December 2016
Received in revised form 3 March 2017
Accepted 8 March 2017
Available online 27 March 2017

Keywords:
Cyclopentanone
Laminar burning velocity
Markstein length
Constant-volume vessel

ABSTRACT

Cyclopentanone, a product of biomass pyrolysis of agricultural waste, has certain advantages as a biofuel candidate but so far little is known about its combustion characteristics. In this paper, the laminar flame characteristics of cyclopentanone, including stretched flame propagation speed, unstretched flame propagation speed, and laminar burning velocity, were measured and compared with gasoline and ethanol, using the outwardly propagating spherical flame method and the high-speed Schlieren photography technique. The experiments were conducted in a constant-volume vessel using various fuel-air equivalence ratios (ϕ = 0.8–1.6) at elevated initial temperatures (T_0 = 423, 448 and 473 K) and a fixed initial pressure (P_0 = 0.1 MPa). Linear and non-linear extrapolations were used to characterise the relationship between the stretch rate and the stretched flame propagation speed when Markstein length was near to or away from zero respectively. Empirical functions were obtained to calculate the laminar burning velocities of cyclopentanone for various fuel-air equivalence ratios and initial temperatures. The results show that Markstein length of cyclopentanone decreases when equivalence ratio is increased, and the turning point of equivalence ratio at which it changes from positive to negative is slightly below 1.4. The maximum laminar burning velocity of cyclopentanone appears at the equivalence ratio of approximately 1.2, regardless of the initial temperature. The laminar burning velocity of cyclopentanone has a smaller difference to that of ethanol and gasoline when equivalence ratio is leaner than stoichiometric, but when equivalence ratio increases from 1.0 to 1.4, it becomes increasingly lower than that of ethanol and higher than that of gasoline. The maximum laminar burning velocity of cyclopentanone is 0.82 m/s; for gasoline it is 0.72 m/s and for ethanol it is 0.86 m/s, at an initial temperature of 423 K and pressure of 0.1 MPa.

1. Introduction

Using biofuels is widely regarded as one the most desirable solutions to meet the dual challenges of environmental protection and energy security [1,2]. A promising generation of biofuels is characterized by a rich source of raw materials, fast renewable speed, potential to reduce greenhouse gas emissions, and promotion of agricultural economic development [3–5]. Currently, ethanol is one of the main renewable liquid fuels produced on a large scale in parallel with biodiesel. However, ethanol suffers from several limitations, such as low energy density and high energy consumption during its production. Recently, significant progress in manufacturing new biofuels has been made by using a new catalytic biomass-to-liquid process to convert both fructose and

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http://dx.doi.org/10.1016/j.apenergy.2017.03.031
0306-2619/

Nomenclature

ϕ	fuel-air equivalence ratio	ρ_b	density of burned gas, kg/m^3
S_n	stretched flame propagation speed, m/s	ρ_u	density of unburned gas, kg/m^3
S_l	unstretched flame propagation speed, m/s	α_T	temperature exponent
u_l	laminar burning velocity, m/s	T_0	initial temperature, K
α	stretch rate, 1/ms	P_0	initial pressure, MPa
r	instantaneous flame radius, mm	t	time, ms
L_b	Markstein length, mm		

glucose to the furan series family of molecules [6,7]. Among these molecules is cyclopentanone, a product of biomass pyrolysis of agricultural waste into furfural, which is then converted to cyclic ketone by aqueous hydrogenation [8–12].

Cyclopentanone is a colourless liquid with low toxicity, and has similar specific properties to gasoline and ethanol, shown in Table 1. It is oxygenated with an oxygen content of 19.05% and it has an H/C ratio of 1.6. Cyclopentanone has a volumetric density of 0.9487 g/cm^3, much higher than that of gasoline and ethanol. The heat of vaporization of cyclopentanone is higher than that of gasoline, which is an advantage in increasing air intake charge thus power density in internal combustion engines because the higher heat of vaporization lowers the intake charge temperature [13], especially in direct injection engines. The stoichiometric air-fuel ratio of cyclopentanone is lower than gasoline and similar to ethanol, which can lead to higher engine power-density. Cyclopentanone has an auto-ignition temperature of 445 °C, much higher than that of gasoline, indicating its excellent potential for resistance to engine knocking in spark-ignition engines, if used in gasoline blends for improving fuel economy.

The combustion characteristics of the intended fuel are key inputs required by an engine designer, and this is particularly pertinent for new biofuel candidates. Laminar flame characteristics are critical in determining the combustion flame development process [2,4,13]. Inherent in the chemical properties of a fuel, laminar burning velocity and Markstein length are the key parameters used in the study of laminar combustion [1,13]. Laminar burning velocity is used to verify the chemical reaction mechanism of the fuel, and it is also one of the required input parameters in the simulation of turbulent premixed flame propagation [18], as well as the simulation of the combustion process and emissions [19].

Techniques for the measurement of laminar burning velocity include using a Bunsen burner, the plane flame method, the stagnation surface method and using constant volume combustion vessels with high speed imaging. Due to the large errors associated with the Bunsen burner method, and the inconsistency in using the plane flame method, the stagnation surface and constant volume combustion methods are the ideal methods for laminar combustion measurement [20–23]. However, since the stagnation surface method cannot be used under high pressure conditions, this leaves using constant volume combustion bombs as the most widely used method to study the laminar combustion characteristics for a wide range of applications [24], as the measurement of the flame can be taken under various controlled initial conditions, including elevated temperatures. The authors' group has used this technique in the measurement of laminar burning velocity of different fuel blends [25–29], and the same technique has also been used in the study of hydrogen combustion characteristics by the first author [30,31]. The limitation of this method is that the stretched flame speed must be corrected and converted to the upstretched burning velocities, whereas the raw data obtained from the stagnation flame can be modelled readily [24].

Although the combustion characteristics of several furans as biofuel candidates, including 2,5-dymethylfuran and 2-methylfuran, have been reported [25–27,29], the existing literature on cyclopentanone is focused only on its production technology [32]. The laminar burning velocity of cyclopentanone is unknown, thus it is impossible for the engine community to predict the performance of the engine combustion using it as fuel [32]. In order to provide such data for the first time, this paper studies laminar combustion characteristics of cyclopentanone at different equivalence ratios (0.8–1.6) and temperatures (423–473 K), benchmarked to gasoline and ethanol. The experimental investigation, using a constant volume vessel and high-speed Schlieren imaging system, aims to measure and compare the laminar burning velocity and Markstein number of cyclopentanone with gasoline and ethanol under elevated temperature conditions. The elevated initial temperatures are used to ensure cyclopentanone is fully vaporised and also closer to engine charge temperature. By using a range of different temperatures, temperature exponential factors for the combustion velocity fitting correlations at varied conditions can be obtained. The experimental system and data processing techniques are described in the next section, followed by the results and discussion. The findings and conclusions of the work are given at the end of the paper.

Table 1
Properties of cyclopentanone [13–17].

Parameters	Cyclopentanone	Gasoline	Ethanol
H/C ratio	1.6	1.795	3
Density (kg/m^3)	948.7	744.5	789.0
Boiling point (K)	404	293–473	351
Auto-ignition point (K)	718	553	636
Gravimetric oxygen content (%)	19.05	0	34.78
Stoichiometric air/fuel ratio	10.6	14.6	9
LHV (MJ/kg)	34.8	44.0	26.9
Heat of vaporization (MJ/kg)	0.433	0.373	0.912
Lower limit of explosion	1.6%	1.2%	3.3%
Upper limit of explosion	10.8%	7.1%	19.0%

2. Experimental system and data processing

2.1. Experimental system

Fig. 1 shows a schematic of the experimental setup. It primarily consisted of the spherical constant-volume combustion vessel, fuelling system, gas exchange (intake and exhaust) system, ignition system, control and data acquisition system and high-speed Schlieren photography system.

The spherical constant-volume combustion vessel had an inner diameter of 350 mm, and the designed upper pressure and temperature limits were 4 MPa and 600 K, respectively. The air intake supplied from standard air bottles was introduced into the combustion vessel and heated by resistance heating coils installed in the vessel wall, and the vessel temperature could be precisely controlled by a proportional-integral-derivative (PID) controller. The combustion vessel was well wrapped by thermal insulation, reducing the heat