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Full Length Article

Experimental and numerical study on ethanol and dimethyl ether lifted flames in a hot vitiated co-flow

Zhijun Wu *, Qing Zhang, Tangtang Bao, Liguang Li, Jun Deng, Zongjie Hu

School of Automotive Studies, Tongji University, Shanghai 201804, China

HIGHLIGHTS

- Lifted flames of gaseous ethanol and dimethyl ether issuing into a hot co-flow.
- The opposite trend of the lift-off height and the fluctuation.
- The numerical study coupling RANS and EDC model based on experiment.
- The difference of the stabilization between simple fuel and the present fuel.
- The influence of chemical properties on the lift-off in two temperature range.

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ABSTRACT

Lifted flames of gaseous ethanol and dimethyl ether (DME) issuing into a hot co-flow are recorded with a high-speed camera. The flames of the two fuels at 433 K are studied in a co-flow temperature range from 966 K to 1149 K and at an ambient pressure of 1 atm. The experimental results show that the co-flow temperature has a substantial influence on the jet flame characteristics. It is concluded that the lift-off height is controlled by the ignition delay, whereas the fluctuation is mainly controlled by the sensitivity of the ignition delay to the co-flow temperature. A numerical study coupling the Reynolds averaged Navier-Stokes (RANS) equation with the eddy-dissipation-concept model (EDC) employing detailed reaction mechanisms is established and is consistent with the previous flame structure and lift-off height obtained by the experimental results. The radial profiles and axial distribution of important parameters reveal the acceleration of the mixing process caused by exothermic reactions and indicate the differences in the mixture fraction at the stabilization points between simple fuel (H_2 and CH_4) and the present fuels. The influences of the chemical reaction on the stabilization mechanism at low and high co-flow temperatures are also discussed.

1. Introduction

Over the last two decades, oxygenated fuels have received considerable attention due to the increasing global energy demand and the pressure from emission regulations. As alternative fuels, oxygenated fuels are commonly used as neat fuels or additives to conventional fossil fuels in engines and many other technical devices [1–4]. These fuels have been demonstrated to reduce the amount of CO, hydrocarbon, and soot due to their chemical structure or from applications in novel combustion processes, such as low temperature combustion [5–7].

Two oxygenates that have been considered as pollutant-reduction fuels and that can be obtained from biological sources are ethanol (CH_3-CH_2-OH) and DME (CH_3-O-CH_3). They are isomers and have some similar influences as additives from a chemistry perspective. Both of the fuels have advantages in main pollutant emission reduction, including CO, hydrocarbon and soot reduction. However, each of the fuels has some distinctive properties that are useful for different applications. Hence, research has been conducted regarding the contrast of the fundamental chemical reactions of the two fuels. A distinct negative temperature coefficient (NTC) region is only observable for DME [8] in low-temperature oxidation of the two fuels. Additionally, fuel-specific destruction pathways [9,10] lead to benzene formation in DME-propane combustion while to formaldehyde and acetaldehyde formation in ethanol-propane combustion. Furthermore, additional experiments [11–13] for applications of the two fuels have been per-

* Corresponding author at: School of Automotive Studies, Tongji Univeristy, 4800 Cao'an Road, Shanghai 201804, China.
E-mail address: zjwu@tongji.edu.cn (Z. Wu).

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formed in internal combustion engines. However, turbulent lifted flames, which connect the fundamental chemical kinetics to the more realistic applications, have yet to be investigated.

Many experiments [14–19] studying H_2/N_2 or CH_4/air lifted flames have been performed in Cabra burners. These experiments investigated flame temperature distribution, ignition delay, lift-off height, important species and some other important parameters of lifted flames. Different numerical simulations [20–24] were conducted based on the results of these experimental data. However, the interaction [25,26] between turbulence and chemical kinetics is complicated; thus, the exact conclusion of auto-ignition of the fuels and the stabilization of the flames is difficult to reach based on experimental data under different boundary conditions. Therefore, in the present study, the comparative experiments are designed to take advantage of the similar physical properties of ethanol and DME, thus eliminating the difference in the fluid dynamics, making it possible to decompose the interaction and focus on the influence of the chemical reactions on the lift-off phenomenon. Specifically, gaseous ethanol and DME are injected into a hot co-flow from a lean premixed hydrogen/air flat flame at atmospheric pressure. Structures, lift-off heights, fluctuations of lift-off heights, and widths of the flames are obtained under various boundary conditions in the experiment. The experiment is accompanied by simulations coupled with the Reynolds averaged Navier-Stokes (RANS) method and the eddy-dissipation-concept (EDC) model employing detailed chemical reaction mechanisms. These results clearly show the different auto-ignition characteristics between the fuels and the influence of the chemical reactions on the lift-off phenomenon and the stabilization of the lifted flames.

2. Experimental method

2.1. Vaporizer system for ethanol

Ethanol fuel is heated by a vaporizer system before injection, eliminating the influence of breakup, atomization and evaporation. The vaporizer system consists of a fuel tank, a heating chamber and a temperature control system. The liquid ethanol is pushed into the heating chamber from the fuel tank by an air compressor. Then, the liquid in the chamber is heated by an electric heater and evaporated. The gaseous ethanol flows through a pipe, which has an electric heating cable coiled around it. The voltage of the cable is controlled by the feedback temperature of the gaseous ethanol in the exhaust to maintain a steady temperature. The ethanol flow rate and pressure are adjusted by a flow meter with a flow control function and a pressure regulator. Table 1 shows the physical properties of ethanol and DME at 433 K [27].

2.2. Experimental setup

The co-flow temperature (T_c) is stably controlled by the Cabra burner [14,28]. The flow rate of hydrogen is adjusted to achieve the required temperature. Table 2 shows the important parameters of the experimental conditions. The underlined values correspond to the basic case. For example, a co-flow velocity of 3.34 m/s is measured at a co-flow temperature of 1185 K. All the data in the figures are under basic conditions if not indicated. The study domain is a cylindrical region, 200 mm in diameter and 350 mm in height (from the nozzle to the downstream distance), in which the temperature field is most stable.

The flow rate of air is measured by a vortex flowmeter. The flow rates of hydrogen and the fuels are measured by rotameters. The temperatures are measured by thermocouples of different types and the co-flow temperatures are corrected by Shaddix [29] method. Based on the accuracy of instruments, and on the average deviations of repeated measurement sets, the following maximum uncertainties can be ascribed for the measured data: 1% for the flow rate of air, 1.5% for the flow rates of hydrogen and the fuels, 0. 75% for the co-flow temperatures, 0.58% for the fuel temperatures.

Table 3 shows the corresponding compositions under the studied temperatures. Y indicates the mass fraction. As the co-flow temperature increases, the concentration of H_2O increases, and the oxygen and nitrogen contents decrease slightly.

2.3. Image post-processing and data evaluation

An automated image processing method is developed to process the massive amount of images obtained from the high-speed camera. In this paper, the flames are studied, and a statistical analysis of these phenomena is required. Data evaluation codes for flames are developed using MATLAB software. The red, green and blue (RGB) color information of the images is read and later converted to grayscale (G_s), which is given by the following equation:

$$G_s = 0.4R + 0.3G + 0.4B$$

The weight of the blue color is greater than that used in normal methods to emphasize the light blue in the flame-base. The grayscale threshold of the flame is 5. The definition principle we used in setting the threshold is a minimum value that can filter the background interference. Then, the grayscale images are converted to a binary image. The "bwareaopen" function is used to remove all of the connected components with less than 20 pixels from the binary image and to filter the small-scale noise. The lift-off heights and fluctuations and the flame widths are determined using this method. To ensure the precision of the selected threshold (5), a smaller grayscale threshold of 3 is used, and the filtration is performed manually. Only a slight difference is found between the grayscale thresholds of 5 and 3.

The following process is the reconstruction of the field distribution of the cylindrically symmetric flames. Deconvolution technique of Abel transform is employed as [30]:

Table 1
Physical properties of gaseous ethanol and DME at 433 K.

Properties	Ethanol	DME
Density (kg/m^3)	1.29	1.29
Viscosity (μPa s)	12.832	13.392
Specific heat at constant pressure (kJ/kg K)	2.0368	1.8384
Thermal conductivity (mW/m K)	29.80	33.51

Table 2
Important parameters for the experimental conditions.

Fuel temperature (K)	433
Velocity of central fuel (m/s)	21.9, 43.7
Co-flow temperatures (K)	966, 996, 1024, 1054, 1085, 1117, 1149
Velocity of co-flow (m/s)	3.34
Central tube diameter (mm)	4
Frame rate (FPS)	50

Table 3
Compositions of the co-flow at different co-flow temperatures.

	966 K	996 K	1024 K	1054 K	1085 K	1117 K	1149 K
Y_{H2O}	0.0562	0.0586	0.0612	0.0638	0.0664	0.0690	0.0715
Y_{O2}	0.182	0.179	0.177	0.175	0.173	0.170	0.167
Y_{N2}	0.762	0.762	0.762	0.761	0.761	0.761	0.761