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On the flame stability and laminar burning speeds of syngas/O_2/He premixed flame

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ABSTRACT

Fundamental properties such as flame structure and laminar burning speed of syngas/O_2/He premixed flames have been investigated. Synthetic gas, also known as syngas, is a mixture of hydrogen and carbon monoxide that has been used in the present study. Three different mole fractions of 5%, 10% and 25% of hydrogen in the syngas were used in this research. Experiments were done in a cylindrical and a spherical chambers. Flame structure studies were made in the cylindrical vessel. The cylindrical vessel was coupled with a Z-shape schlieren system, equipped with a high speed CMOS camera, which has the capability of capturing pictures up to 40,000 frames per second, in order to study flame structure and instability. Hydrodynamic and thermo-diffusive instabilities on the flame front during propagation of flames have been observed and studied. Helium's smaller molar heat capacity and higher thermal conductivity than nitrogen results in a more stable and smooth flames. The increase range of smooth flames can be used to validate chemical kinetics mechanisms at higher pressures and temperatures. Pressure rise data as a function of time during the combustion process was obtained through a pressure transducer in the spherical vessel was the primary input of the multi-shell model used to calculate the laminar burning speed for the smooth flames. Power law correlations over a wide range of pressures (from sub-atmospheric up to 7.3 atm), temperatures (298 K up to 650 K), and equivalence ratios (0.6–3.0) have been developed for laminar burning speeds of smooth H_2/CO/O_2/He flames. At equivalence ratios corresponding to maximum laminar burning speeds, the experimental laminar burning speeds show a positive relationship with pressure. Experimental laminar burning speeds of H_2/CO/O_2/He mixtures have been compared with numerical values calculated by free flat flame simulation using two chemical kinetics mechanisms and some discrepancies discovered for equivalence ratios greater than 2. The effect of helium as a diluent on flame morphology and laminar burning speeds of syngas are compared with two diluents, nitrogen as well as nitrogen that is further diluted with synthetic exhaust gas recirculation (SEGR).

1. Introduction

Synthetic gas, also known as syngas, is expected to play a significant role in future renewable and environmentally friendly energy demand. It is a combustible mixture containing varying levels of H_2 and CO, as well as some levels of CO_2, CH_4, N_2, H_2O and higher order hydrocarbons in some instances [1,2]. Syngas can be produced by various methods such as the gasification of coal or biomass, steam reforming of coke and recycling of organic waste emissions. It is considered to be an alternative fuel which is used to produce a wide range of synthetic solvents, fertilizers, and materials. This alternative fuel can be used during engine cold start to lower HC emissions as a reformer gas [3]. It also plays an important role in stationary power plants that use the integrated gasification combined cycle (IGCC) [4]. A large focus has been cast on syngas recently for its potential use in the gas turbine industry as a replacement of natural gas [5–7]. Furthermore, syngas and hydrocarbon-syngas mixtures could be a proposal of the reduction of pollution such as NO_x, SO_x and CO_2 and the extension of flame stability limit in different combustion systems [8]. Syngas is also a primary input of Fischer-Tropsch (F-T) reactors to produce gas-to-liquid (GTL) fuels [9,10]. Thus, it is necessary to determine the laminar burning speed [10–17] and flame structure of this fuel as it contains information regarding the mixture's diffusivity, reactivity, and exothermicity. It is also of great importance to study the

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laminar burning speed and flame structure in a high pressure and temperature conditions as well as with diverse diluents, since those are the relevant conditions found in internal combustion engines [18], power plants and gas turbines. The inert diluent gas helium as a replacement of nitrogen has been used in the present work. Substitution of nitrogen in air with helium can increase stability of the flame and extend the pressure and temperature range of data collection for which the flame is still smooth and laminar due to its smaller molar heat capacity and higher thermal conductivity than nitrogen.

There have been many studies on the laminar burning speed and flame structure of syngas with and without diluent. The laminar burning speed of syngas air mixture has been measured by Hassan et al. [19] at different hydrogen concentrations (3–50%), atmospheric temperature, elevated pressures (from sub-atmospheric up to 4 atm), and wide range of equivalence ratio using constant pressure spherical flames method. Sun et al. [5] employed a dual-chambered cylindrical apparatus to measure laminar burning speed of $H_2/CO/O_2/He$ mixtures at various hydrogen concentrations (1–50%), atmospheric temperature, high pressures (up to 40 atm), and a wide range of equivalence ratios. Natarajan et al. [1] measured laminar burning speed of lean syngas mixture using the Bunsen burner and stagnation flame methods at two different pressures (1 atm, 5 atm) and preheat temperatures (up to 700 K) with CO_2 dilution. Laminar burning speed have been determined by Natarajan et al. [7] later in a wide range of hydrogen percentage at reactant preheat temperatures and pressures (up to 600 K and 15 atm) relevant to gas turbine. An O_2/He mixture (1:9 by volume) has been used as the oxidizer in order to increase the flame stability. Prathap et al. [4] collect laminar burning speed data of syngas mixture with N_2 and later CO_2 diluent using the constant pressure spherical flames method [20]. Burke et al. [21] collected mass burning rates data of syngas flames at different equivalence ratios (0.85–2.5), elevated pressures (from 1 atm to 25 atm), and atmospheric temperature with various diluents (He, CO_2, Ar). Vu et al. [22] studied the different effects of three different diluents (He, CO_2, N_2) on the laminar burning speed and flame instabilities of 50:50 H_2/CO mixtures at atmospheric temperature and elevated pressures. Burbano et al. [23] investigated the effects of different diluents (CO_2, N_2) on laminar burning speed and flame stabilities of syngas at atmospheric pressure and temperature over a wide range of equivalence ratio. Lapalme and Seers [24] measured laminar burning speed of syngas flames with CO_2 and CH_4 dilution at initial temperature (up to 450 K). Han et al. [25] used a dual-cylindrical setup to determine laminar burning speeds for elevated pressures, temperatures and various CO_2 diluent percentages. Laminar burning speed data for various hydrogen percentages (5–75%) and equivalence ratios (0.6–5.6) of syngas with CO_2 and N_2 diluent (0–60%) have been collected by Wang et al. [26] using a Bunsen flame coupled with OH-PLIF method as well as a heat flux burner. Askari et al. [27] used a new differential based multi-shell model to study the laminar burning speed and flame instability of $H_2/CO/air$ flame of three different hydrogen concentrations (5%, 10%, and 25%) over a wide range of pressures (from 0.5 atm up to 5.5 atm), temperatures (from 298 K up to 617 K), and equivalence ratios (0.6–5.0). Askari et al. [28] studied the laminar burning speeds and flame stability of $H_2/CO/air$ with EGR addition (5% and 10%) later by the same model, over a wide range of pressures (from 0.5 atm up to 5.5 atm), temperatures (from 298 K up to 450 K), equivalence ratios (0.6–3.0) and three different hydrogen concentrations of 5%, 10%, and 25% in the fuel mixture.

The present work studies the effect of substitution of nitrogen in the air with helium with the same volumetric percentage, i.e.: 21% O_2 and 79% He, on the laminar burning speeds and stabilities of $H_2/CO/O_2/He$ flames. Laminar burning speeds of $H_2/CO/O_2/He$ mixtures and their power law correlations have been determined at three different hydrogen mole fractions of 5%, 10%, and 25% in the fuel mixture over a wide range of pressures (from 0.5 atm up to 7.3 atm), temperatures (from 298 K up to 650 K) and equivalence ratios (0.6–3). Smooth and cellular structures of $H_2/CO/O_2/He$ flames have been analyzed in terms of hydrodynamic and thermo-diffusive instabilities. The positive dependency of laminar burning speed on pressure for a specific range of equivalence ratios has been discussed using normalized sensitivity coefficients.

2. Experimental facilities

Experiments have been conducted in a spherical chamber for laminar burning speed measurements and in a cylindrical chamber, which is coupled with a schlieren photography system, for flame stability and structure analysis. The spherical vessel is made of stainless steel that can withstand pressures up to 400 atm. It is built from two 15.24 cm diameter hemispheres that are placed inside an oven in order to heat the vessel up to 500 K. Two extended spark plugs with a spark gap of 0.9 mm are installed in the spherical and cylindrical chambers to enable central point ignition alongside a K-type thermocouple which is used to measure the temperature of the interior chamber wall and gaseous mixture. The effect of spark discharge on flame expansion has been minimized by tuning the spark energy sufficiently close to the minimum ignition energy [18].

The cylindrical chamber has an inner diameter and length of 13.5 cm and is also made of stainless steel. The cylindrical vessel is capped on both ends with fused-silica windows that are sealed with high temperature elastomer O-rings. A Z-shape schlieren system coupled with a high speed CMOS camera is set up to capture pictures up to 40,000 frames per second [29,30]. Two band heaters attached on both ends of the cylindrical vessel are installed that can heat the vessel up to 500 K, a limitation set by the pressure transducer and the material properties of the O-ring. A Kistler high sensitivity pressure sensor [31] is used to measure the pressure rise inside both the spherical and the cylindrical chambers [21]. A data acquisition system is utilized to collect the pressure-time data as well as the flame propagation pictures. A schematic diagram of the experimental facilities is shown in Fig. 1.

Both spherical and cylindrical chambers were filled by the partial pressures method using a manifold supply system consisting of pipes, valves, high accuracy pressure transducers, constituent gas tanks, and a vacuum pump. After the chamber was filled with fuel, oxidizer, and diluent, the mixture was given 5 min to reach quiescence and a uniform temperature. An excel spreadsheet was used to find the initial conditions and a LabView program was used to initiate the combustion process as well as record data. A gas chromatograph (GC) was used to check the composition of premixed mixture inside the chamber in order to verify the accuracy of the system and partial pressure method. The experiments have been done using both chambers at each operational condition, and pressure rise data were collected using the spherical chamber. The same experiments were repeated in cylindrical chamber in order to study the stability and morphology of the flame and check its reproducibility. The flame appears to be relatively affected by cylindrical chamber geometry for large radii since the flame shape is naturally spherical. It may cause some unwanted errors in laminar burning speed calculation [32]. Due to that reason the cylindrical chamber is only used for capturing flame propagation images which can be used in instability study. But for laminar burning speed measurement we took advantage of our spherical chamber. Only flames that were completely spherical, smooth, and laminar have been used to calculate the laminar burning