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Exhaust gas recirculation effects on flame structure and laminar burning speeds of H_2/CO/air flames at high pressures and temperatures

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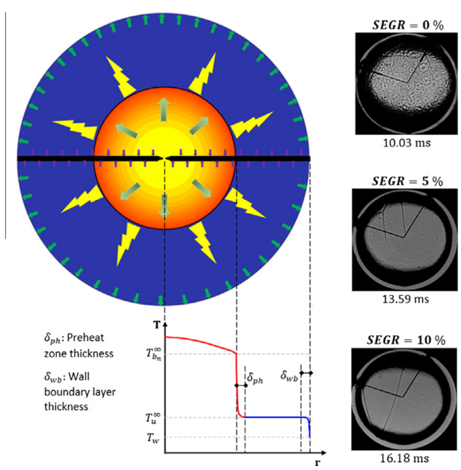
HIGHLIGHTS

- Effect of exhaust gas recirculation on flame morphology of syngas/air is investigated.
- Hydrodynamic and thermo-diffusive effects are evaluated on flame stability analysis.
- Burning speeds are calculated using a new differential based multi-shell model.
- Effect of exhaust gas recirculation on burning speed of syngas/air is investigated.
- Power law correlations are developed for easy use in numerical simulations.

GRAPHICAL ABSTRACT



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ABSTRACT

Experimental studies have been performed in conjunction with a novel differential based multi-shell model to investigate the flame structure and measure laminar burning speeds of H_2/CO/air/diluent premixed flames at high pressures and temperatures. This paper focuses on synthetic gas (syngas) as the fuel blend, which is a mixture of H_2 and CO, and investigates the effect of synthetic exhaust gas recirculation (SEGR) as the diluent on flame structure and laminar burning speed. SEGR is a mixture of 14% CO_2 and 86% N_2. In these experiments two different SEGR concentrations of 5% and 10% have been used. The experiments were performed in two constant volume spherical and cylindrical chambers. The cylindrical chamber was set up in a schlieren system equipped with a high speed CMOS camera, capable of taking pictures up to 40,000 frames per second, which was used to study the structure and stability of the flame. The laminar burning speed of the combustion process was calculated from the pressure rise measurement during flame propagation in spherical chamber. Power law correlations have been developed for laminar burning speeds of smooth H_2/CO/air/SEGR flames over a wide range of temperatures (298 K up to 450 K), pressures (from sub-atmospheric up to 5.5 atm), equivalence ratios (ϕ = 0.6–3) and three different hydrogen concentration of 5%, 10% and 25% in the fuel mixture. SEGR lowers the laminar burning speed and has significant effect on the flame stability compared to H_2/CO/air, especially for very lean and very rich mixtures. Experimental burning speeds of H_2/CO/air/SEGR mixtures have been compared with available measurements as well as computed values obtained by 1D free flame simulations using

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two chemical kinetics mechanisms. Very good agreements have been observed with the experimental data available in the scientific literature as well as computational burning speeds.

1. Introduction

Synthetic gas, also known as syngas, is fundamentally a mixture of hydrogen and carbon monoxide gases along with various other higher-order hydrocarbons. Syngas is considered an alternative fuel since it can be created through various sources such as biomass gasification, reactions that involve natural gas and coal, as well as the recycling of stationary turbine byproducts. With the advent of integrated gasification combined cycle (IGCC) technology, syngas can be created from coal with lower emissions. Thus, the development and research pertaining to syngas fuels are becoming more relevant amid growing concerns about pollutants and carbon emissions.

Syngas is considered as a strong candidate to replace many fuels currently in use, therefore, it is imperative to fully understand and characterize how syngas behaves in various conditions. The laminar burning speed adequately characterizes a fuel and provides a good indicator of how a fuel performs. It is widely used and contains information about a mixture's exothermicity, diffusivity, and reactivity. It is also important to study the laminar burning speed [1–12] in a high pressure environment as well as with different diluents, since those are normally gas turbine and internal combustion engines [13] relevant conditions. One typical form of diluent is the inert gas used in exhaust gas recirculation (EGR) technique commonly used in automobile engines [13], which is primarily a mixture of carbon dioxide, nitrogen, water and other products of combustion.

There is a wide assortment of literature on the laminar burning speed of syngas fuels with and without diluent. Hassan et al. [14] measured the laminar burning speed of various hydrogen to carbon monoxide ratios (3:97, 5:95, 10:90, 25:75, 50:50), sub-atmospheric to elevated pressures (0.5–4 atm), atmospheric temperature, and wide equivalence ratio (0.6–5.0) in a spherical combustion chamber. Sun et al. [15] used a dual-cylindrical chamber to extract laminar burning speed data at atmospheric temperature from many different H_2/CO ratios (1:99, 5:95, 25:75, 50:50), elevated pressures (up to 40 atm), and equivalence ratios (0.5–5.0). Sun et al. [15] also replaced nitrogen with helium as the diluent in order to increase the stability of flames, which allowed them to obtain data for much higher pressures. Natarjan et al. [16] used the burner and particle velocimetry technique to measure laminar burning speed for 5:95, 50:50, and 95:5 syngas percentages diluted with CO_2 and later extended measurements to higher pressures with helium substitution to reduce flame instability [17]. Prathap et al. [18] used the constant pressure method to measure the laminar burning speed of 50:50 H_2/CO mixtures diluted by N_2 and later CO_2 [19]. Vu et al. [20] compared the effects of CO_2, N_2, and He as diluents on the cellular instabilities in syngas flames in a cylindrical chamber at elevated pressures for a 50:50 hydrogen to carbon monoxide ratio, and found that helium suppresses instabilities. Burbano et al. [21] used the burner method to extend the data on the effects of CO_2 and N_2 dilution on laminar burning speed and stability over a wider equivalence ratio (0.6–4.3). Lapalme and Seers [22] investigated the effect of initial temperature (up to 450 K) and carbon dioxide and methane dilution on the laminar burning speeds of syngas flames, as well as provided a correlation based on their data. Han et al. [23] measured laminar burning speeds for various CO_2 diluent percentages (10–40%) at elevated temperatures and pressures for equivalence ratios of $\phi = 0.8$ and $\phi = 1.0$ using a dual-cylindrical setup. Wang et al. [24] reported laminar burning speed data for a wide range of equivalence ratio (0.6–5.6), hydrogen percentages (5–75%), and N_2 or CO_2 percentages (0–60%) using a heat flux burner as well as a Bunsen flame in conjunction with OH-PLIF method. Askari et al. [25] measured the laminar burning speeds of H_2/CO/air flames using a new differential based multi-shell model over a wide range of temperatures (298 K up to 617 K), pressures (from sub-atmospheric up to 5.5 atm), equivalence ratios (0.6–5) and three different hydrogen concentrations of 5%, 10% and 25% respectively. They concluded when the initial pressure increases, the tendency for the flame to destabilize takes place earlier due to a significant decrease of the flame thickness and enhancement of hydrodynamic instability. They measured the laminar burning speeds for smooth flames using the pressure rise method and developed power law correlations [25]. There is a wide range of scientific literature that is currently available on the laminar burning speed of syngas flames diluted with varying percentages of CO_2 or N_2, but no literature exists for syngas flames diluted exactly with both 14% CO_2 and 86% N_2 to simulate the exhaust gas recirculation in internal combustion engines.

The present study investigates the effect of synthetic exhaust gas recirculation, with the composition of 14% CO_2 and 86% N_2, on the stability and laminar burning speeds of H_2/CO/air flames. Since creating the real EGR, which is the engine post-combustion exhaust gases in our lab is impossible, a synthetic EGR with aforementioned composition which has the same specific heat as real EGR is used. The effect of SEGR addition (5% and 10%) to H_2/CO/air on flame morphology, flame stability and laminar burning speed has been studied in a wide range of temperatures, pressures and equivalence ratios for three hydrogen concentrations. In this paper laminar burning speeds of H_2/CO/air/SEGR mixtures and their correlations are reported over a wide range of temperatures (298 K up to 450 K), pressures (from sub-atmospheric up to 5.5 atm), equivalence ratios (0.6–3) and three different hydrogen concentration of 5%, 10% and 25% in the fuel mixture.

2. Experimental facilities

Experiments have been performed using a cylindrical chamber to study the morphology and stability of the flame and a spherical chamber for laminar burning speeds measurement. The cylindrical chamber is 13.5 cm in diameter and 13.5 cm in length. The cylindrical chamber is equipped with fused quartz windows that are sealed to the chamber with two high temperature elastomer O-rings. The cylindrical chamber is set up in a Z-shape schlieren system equipped with a high speed CMOS camera, capable of taking pictures up to 40,000 frames per second [26,27]. Two band heaters are installed in order to raise the initial temperature of the system up to 500 K. Both chambers are fitted with two extended automotive spark plugs, and K-type thermocouples to measure the temperature of the inside gas mixtures. The spark energy has been tuned to be sufficiently close to the minimum ignition energy to minimize the effect of spark discharge on flame expansion [28]. Fig. 1 shows the general configuration of the experimental set up.

The spherical chamber is made of stainless steel that can withstand pressures up to 400 atm. The spherical chamber is built using two hemispheres with a diameter of 15.24 cm. It is placed inside an oven to heat up the chamber up to the initial temperature of 500 K. The pressure rise inside the spherical chamber was measured using