Applied Energy 189 (2017) 568–577

Contents lists available at ScienceDirect

Applied Energy

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

Cell formation effects on the burning speeds and flame front area of synthetic gas at high pressures and temperatures

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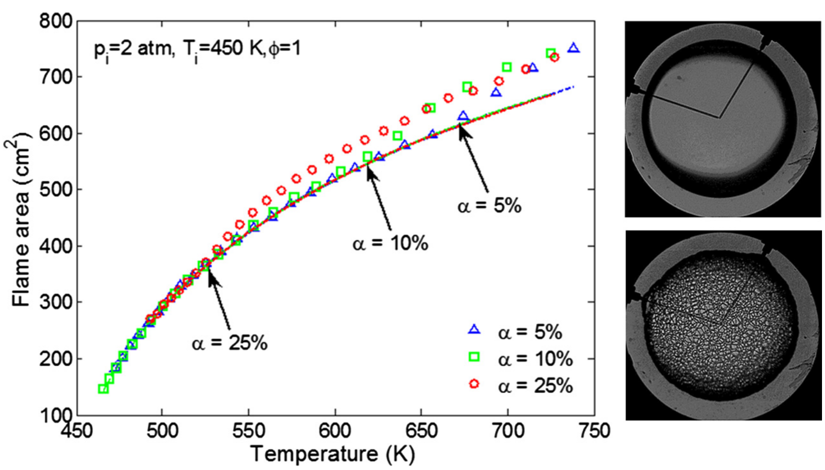
HIGHLIGHTS

- Effect of cell formation on burning speed and flame surface area is investigated.
- A new developed non-dimensional number called cellularity factor is introduced.
- Cellular burning speed and mass burning rate are calculated using differential based multi-shell model.
- Flame instability is studied using thermo-diffusive and hydrodynamics effects.
- Power law correlations are developed for cellular burning speeds and mass burning rates.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 July 2016
Received in revised form 16 December 2016
Accepted 17 December 2016

Keywords:
Cellular burning speed
Mass burning rate
Schlieren photography
Syngas
Cell formation
Cellularity factor
Instability analysis
Flame structure

ABSTRACT

Cellular burning speeds and mass burning rates of premixed syngas/oxidizer/diluent (H_2/CO/O_2/He) have been determined at high pressures and temperatures over a wide range of equivalence ratios which are at engine-relevant conditions. Working on high pressure combustion helps to reduce the pollution and increase the energy efficiency in combustion devices. The experimental facilities consisted of two spherical and cylindrical chambers. The spherical chamber, which can withstand high pressures up to 400 atm, was used to collect pressure rise data due to combustion, to calculate cellular burning speed and mass burning rate. For flame structure and instability analysis the cylindrical chamber was used to take pictures of propagating flame using a high speed CMOS camera and a schlieren photography system. A new differential based multi-shell model based on pressure rise data was used to determine the cellular burning speed and mass burning rate. In this paper, cellular burning speed and mass burning rate of H_2/CO/O_2/He mixture have been measured for a wide range of equivalence ratios from 0.6 to 2, temperatures from 400 to 750 K and pressures from 2 to 50 atm for three hydrogen concentrations of 5, 10 and 25% in the syngas. The power law correlations for cellular burning speed and mass burning rate were developed as a function of equivalence ratio, temperature and pressure. In this study a new developed parameter, called cellularity factor, which indicates the cell formation effect on flame surface area and burning speed has been introduced. The total flame surface area and cellularity factor for syngas at high pressures and temperatures have been calculated by combining the multi-shell model via the experimental pressure data with free flat flame simulation using detailed chemical mechanism. The results show that the

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http://dx.doi.org/10.1016/j.apenergy.2016.12.090

cellularity factor has a positive relation to pressure, equivalence ratio and hydrogen concentration while it has a negative dependency to temperature.

1. Introduction

A study to comprehensively measure and investigate the cellular burning speed, mass burning rate and cell formation effect of synthetic gas (syngas) at high pressures and temperatures is relevant and necessary to the scientific and combustion community [1–4]. Syngas, a mixture of H_2 and CO, has gained importance as an alternative fuel for stationary gas turbines and internal combustion engines. Power plants have been using syngas for more than a decade, citing increased energy efficiencies and less emissions than conventional coal fired plants. Syngas is also increasingly being used in petroleum refineries to help produce cleaner transportation fuels and improve overall efficiency of the plant [5]. Syngas can be derived from the gasification of coal or biomass, including municipal waste, agricultural residue, and herbaceous energy crops, therefore, reducing greenhouse gas (GHG) emissions. Syngas is also a primary input of Fischer-Tropsch (F-T) reactors to produce gas-to-liquid (GTL) fuels [6,7]. Research studies into understanding the cellularity effect on burning speed for syngas fuel, are extremely relevant particularly for use in engineering combustion modeling, for stationary turbine based power plants and for internal combustion engines in the transportation industry [8–11]. Mass burning rate is the rate at which a combustible mixture is consumed by flame front and is also a measure of the energy release during a combustion process. When the flame front is laminar and its area is simply obtainable a more commonly used term is laminar burning speed [7,12–18].

Syngas mixtures have been studied and researched at atmospheric and elevated conditions. Hassan et al. [19] measured the laminar burning speed of various hydrogen to carbon monoxide ratios, sub-atmospheric to elevated pressures (0.5–4 atm), atmospheric temperature and wide range of equivalence ratios (0.6–5.0) in a spherical combustion chamber. Natarjan et al. [20] 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 [21]. Vu et al. [22] 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. 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 0.8 and 1.0 using a dual-cylindrical setup. Askari et al. [24] measured the laminar burning speeds of syngas/air mixtures 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 concentration of 5%, 10% and 25%. Recently Askari et al. [25] investigated the effect of synthetic EGR addition on flame morphology and laminar burning speed of syngas/air mixture for a wide range of equivalence ratios, temperatures and pressures. A comprehensive literature search of burning speed measurements of all syngas composition exposed various gaps in the experimental data especially at elevated pressure and temperature conditions [21,26–29]. Some data exist but doesn't comprehensively capture the whole range of conditions between 2–50 atm and 400–750 K, with varying degree of stoichiometry and gas mixture compositions. Despite internal combustion engines being subjected to high pressures, few studies have been performed under comparable conditions. In a 2014 review of syngas research, Lee concluded that new measurements on the burning speed were needed at elevated pressures [30]. At high pressure conditions (higher than 2 atm) the syngas/air flame is cellular and calculating the laminar burning speed due to lack of exact flame surface area is impossible. So instead, the other parameters such as cellular burning speed and mas burning rate which are very useful in the modeling of combustion systems can be calculated.

In this paper, cellular burning speed and mass burning rate of syngas/oxygen flame which was diluted with helium [31], $H_2/CO/O_2/He$, were calculated for a wide range of equivalence ratios from lean to rich (0.6–2), temperatures from 400 to 750 K and pressures from 2 to 50 atm. The structure and effect of thermo-diffusive and hydrodynamic instabilities were studied at very high pressures at which the flame is always cellular. Power law correlations as a function of equivalence ratio, temperature and pressure for cellular burning speed and mass burning rate have been developed. The effect of cell formation on burning speed and total flame front area has been investigated in terms of a newly developed parameter, called cellularity factor. In addition to a complete experimental data, the theoretical laminar burning speeds via a steady one-dimensional laminar premixed free flame code from CANTER package [32] in conjunction with Davis et al. mechanism [33] were calculated and used to determine the effect of cellularity.

2. Experimental setup and procedures

The core component of the experimental setup includes a spherical combustion chamber that enables the measurement of the pressure rise from a combustion process at high pressures and temperatures. This chamber was mainly used to measure the pressure rise for calculating the burning speed and mass burning rate. The spherical chamber was designed to withstand pressures up to 400 atm and was located inside an oven which can be heated up to 500 K. The second component of the experimental setup is a cylindrical chamber with optically clear sides which enables visualization of flame propagation for the study of flame structure and instability analysis. The cylindrical chamber with optical side ports and all its supporting system were rigidly mounted on an optical bench. Using a focused LED light source and a series of mirrors the parallel light was guided through the optically clear Quartz windows and was reflected to a high speed CMOS camera capable of capturing images up to 40,000 frames per second. This schlieren photography method which works based on density gradient [34], is useful in visualizing flame propagation to investigate flame front structure for instability analysis. 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 [35]. Due to that reason the cylindrical chamber is just used for capturing flame propagation images which can be used in instability study. But for laminar burning speed measurement we just took advantage of our spherical chamber. A Kistler 601CA high-temperature pressure transducer in conjunction with a Kistler 5010B charge amplifier was used to record the dynamic pressure rise during flame propagation processes in both chambers. The filling manifold mainly constructed of 304 and 316 stainless steel Swagelok componentry and tubing is predisposed to accommodate inputs from 5