Combustion and Flame 159 (2012) 3286–3299

Contents lists available at SciVerse ScienceDirect

Combustion and Flame

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

Effects of high pressure, high temperature and dilution on laminar burning velocities and Markstein lengths of iso-octane/air mixtures

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ARTICLE INFO

Article history:
Received 27 March 2012
Received in revised form 8 June 2012
Accepted 12 June 2012
Available online 1 August 2012

Keywords:
Iso-octane/air mixture
Nitrogen dilution
Oxygen enrichment
Laminar burning velocity
Markstein length

ABSTRACT

Spherically expanding flames are employed to measure flame velocities, from which are derived the corresponding laminar burning velocities at zero stretch rate. Iso-octane/air mixtures at initial temperatures between 323 and 473 K, and pressures between 1 and 10 bar, are studied over an extensive range of equivalence ratios, using a high-speed shadowgraph system. Effects of dilution are investigated with nitrogen and for several dilution percentages (from 5 to 25 vol% N_2). Over 270 experimental values have been obtained, providing an exhaustive data base for iso-octane/air combustion. Experimental results are in excellent agreement with recently published experimental data. An explicit correlation giving the laminar burning velocity from the initial pressure, the initial temperature, the dilution rate, and the equivalence ratio is finally proposed. Computed results using the two kinetic schemes and the Cantera code are compared to the present measurements. It is found that the mechanisms yield substantially higher values of laminar flame velocities than the present experimental results. Effects of oxygen enrichment are also investigated. A linear trend relating the percentage of oxygen in air and the unstretched laminar burning velocity is observed. Effects of high pressure, high temperature, and high dilution rate on Markstein lengths are also studied. As already done for the laminar burning velocity, an empirical correlation is proposed to describe the Markstein length for burned gases as a function of initial temperature and pressure, for equivalence ratios between 0.9 and 1.1, which has never been done before in the literature.

1. Introduction

Over the past decades, reducing the pollutant emissions and improving the fuel consumption of internal combustion engines have become hot topics. While much effort has been devoted to the development of electrically powered vehicles, internal combustion engines still remain the focus of a considerable amount of research.

Reducing CO_2 emissions requires simultaneous developments in different areas, which include vehicle dynamics and weight reduction, although most of the CO_2 reduction takes place through modifications in powertrain systems. The most important tool to reduce emissions with powertrain technologies is engine downsizing.

Gasoline engine downsizing is the process whereby the load operating point is shifted to a more efficient region through the reduction of engine capacity, while the full load performance is maintained via pressure charging. This has long been known as one of the most effective technologies for immediate implementation [1]. Further improvements in fuel economy have been shown to be possible through increased levels of engine downsizing [2]. However, many technical difficulties related to severe operating conditions (high pressure, high temperature, and high dilution rate) need to be overcome to achieve this high performance.

A thorough understanding of flame propagation under such conditions is essential for designing more efficient engines. Simulating downsized engines therefore requires the ability to accurately predict flame propagation at high pressure, high temperature, and high dilution rates. These simulations use turbulent burning models that require knowledge of the laminar burning velocity of the fuel-oxidizer mixture as a function of the unburned mixture temperature, pressure, and dilution rate. Indeed, laminar burning velocity is a widely used parameter describing the propagation of a one-dimensional, planar, adiabatic, premixed flame.

In the present study, iso-octane is used as a surrogate fuel for gasoline. This alkane molecule is a primary reference fuel and is widely used to understand combustion phenomena in spark ignition engines. However, experimental literature data still exhibit significant inconsistency in the iso-octane laminar burning velocities measured. A few studies have considered high-pressure flame propagation of iso-octane, such as the work by Metghalchi et al. [3], in which data for high pressure were extrapolated from low-pressure measurements, or the prior work by Gülder [4] and Jerzembeck et al. [5]. However, published data remain scarce and

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http://dx.doi.org/10.1016/j.combustflame.2012.06.008

are not always consistent with one another. The spread of the measured values often exceeds the reported experimental uncertainty. Thus, there is a need for well-characterized and highly accurate fundamental experimental data for iso-octane.

The present study aims at constituting an exhaustive database of laminar burning velocities of iso-octane. The main goal of this study is to provide empirical correlations allowing the prediction of laminar burning velocity, over a wide range of temperature, pressure, equivalence ratio, nitrogen dilution rate, and oxygen enrichment rate. An empirical correlation to describe the Markstein length for burned gases as a function of initial temperature and pressure is also proposed.

2. Experimental setup

Experiments were carried out in a spherical stainless steel combustion chamber with an inner volume of 4.2 L (inner diameter 200 mm). A heater wire resistance located on the outer surface of the sphere was used to heat the initial gases to a maximum temperature of 473 K. Initial pressure inside the combustion chamber was limited to 10 bar.

The device is equipped with a vacuum pomp to achieve a residual pressure lower than 0.003 bar before the chamber is filled with the different gases. Synthetic air (79.5 vol% N_2 and 20.5 vol% O_2) was used for the experiments. Iso-octane was injected through a Coriolis mass flow meter (Bronkhorst mini CORI-FLOW 30 g/h) and the volumes of air and diluents were introduced with thermal flow meters (Brooks 5850S, 2 NL/min for air, and 0.5 NL/min for nitrogen). The injected air/diluent was directed to the exit of the Coriolis flow meter to convey the injected liquid. The inlet valve of the fuel/oxidant mixture was heated to 473 K to ensure the vaporization of iso-octane (vaporization temperature of 372 K at atmospheric pressure). To obtain a perfectly homogeneous premixed mixture a fan was installed inside the chamber to mix the gases. The fan is stopped 5 s before ignition in order to avoid any perturbation during the flame propagation experiments. A piezoelectric pressure transducer and a type-K thermocouple were used to check respectively the pressure level and the initial temperature before ignition. The maximum deviation between the effective initial pressure inside the combustion chamber and the required initial pressure was about 1%. The temperature fluctuation of the prepared mixture was within 2 K for the target initial temperature.

Two tungsten electrodes (diameter 1.5 mm), with a 1-mm gap, linked to a conventional capacitive discharge ignition system, were used for spark production at the center of the chamber. A larger gap between the electrodes provides more efficient ignition under lean conditions, but the electrodes must be fairly close to create and maintain the electric arc. In all experiments, the minimum discharge energy required for spherical flame initiation was supplied to the spark gap, in order to minimize the ignition-dominated phase [6]. To determine the minimum discharge energy, the charge time of the ignition coil was increased until spherical flame initiation. The minimum discharge energy was then deduced from the temporal measurements of the voltage and the intensity at the secondary winding of the ignition coil. This process was repeated for each operating condition. Depending on the initial pressure and temperature, the equivalence ratio, and the dilution rate, the discharge energy required for spherical flame initiation was varied between 25 and 51 mJ.

Two opposite and transparent windows (diameter 82 mm) provide optical access into the chamber. A LED illuminator (HardSoft DLR IL104G) equipped with an objective (HSO-PL-360) was used to provide continuous and incoherent light with a wavelength of 528 nm. A parallel light was created using a pinhole (diameter 3 mm), placed at the focal point of the objective, and a plano-convex lens (diameter 70 mm, focal length 1000 mm). After passing through the lens and the combustion chamber, the beam is displayed on a screen. The visualization of the flame was obtained using a classical shadowgraph method. Instantaneous images were recorded using a high-speed video camera (Photron Fastcam) operating at 6000 images per second. The temporal evolution of the expanding spherical flame was then analyzed. Figure 1 presents a schematic overview of the system.

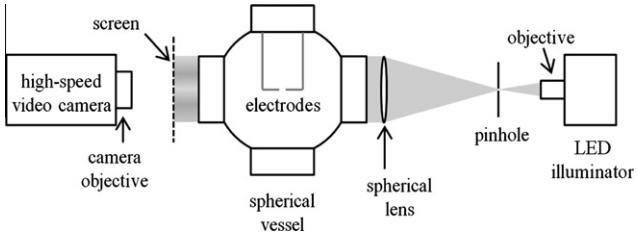

Fig. 1. Schematic overview of the system.

Measurements are limited to flames with diameters of 50 mm, corresponding to a volume of burned gases less than 1.6% of the chamber volume. Under this condition, the total chamber pressure can be considered constant during the initial stage of flame expansion. All the experimental values of laminar burning velocity reported in this paper are averages of three identical experiments. In the following, the mean value is presented.

3. Laminar burning velocity determination

After the spark, the flame front propagates spherically (Fig. 2). The instantaneous flame front radius was obtained from image postprocessing, after background subtraction. For each image, the luminous zone was fitted by a circle. The estimate of the circle radius and center is based on the minimization of the distance between the circle and luminous points. The temporal evolution of the flame front was obtained with the high-speed image recording. Only images corresponding to a flame front radius greater than 6.5 mm were used afterward in order to overcome ignition effects [7]. Then the laminar flame propagation velocity V_S^0 was deduced from the temporal evolution of the flame front radius r_f using a nonlinear methodology, which provides more accurate results [6,8]. This methodology is based on the nonlinear equation proposed by Kelley et al. [6],

$$\left(\frac{V_S}{V_S^0}\right)^2 \ln\left(\frac{V_S}{V_S^0}\right) = -\frac{L_b K}{V_S^0} \tag{1}$$

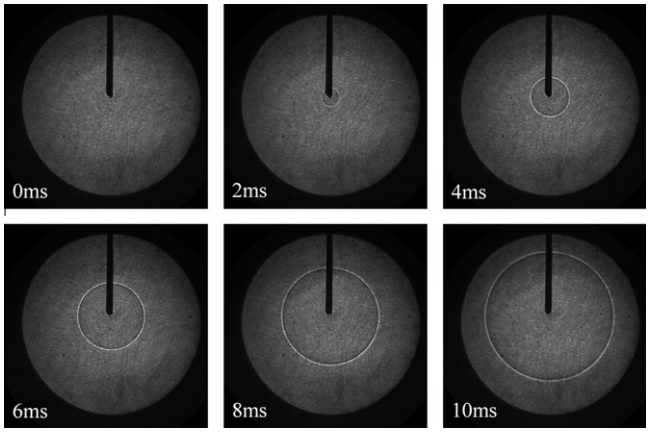

Fig. 2. Shadowgraph images of the propagating flame at different time delays after ignition (P_i = 1 bar, T_i = 423 K, ϕ = 1.0).