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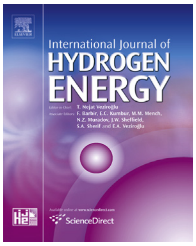

Turbulent flame speed for hydrogen-rich fuel gases at gas turbine relevant conditions

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ABSTRACT

In this paper, correlations of the global consumption-based turbulent flame speed (S_T) for hydrogen-rich fuel gases are presented. Interpretations on the derived S_T are supplemented by a fractal analysis of the flame front. The findings are based on an experimental investigation of lean-premixed, dump-stabilized axisymmetric flames at gas turbine conditions (preheated up to 623 K and pressurized up to 2.0 MPa). Depending on the turbulent Damköhler number (*Da*), distinct characteristics of a normalized turbulent flame speed, S_T/S_{L0}, are observed ($S_{L0}$is the unstretched laminar flame speed). While the dependence of S_T/S_{L0} on the turbulent Reynolds number (Re_T) is revealed for the flames with fast chemistry ($Da > 1$), flame stretch becomes dominant in determining S_T/S_{L0} for those with slow chemistry ($Da < 1$). The transition from flame front wrinkling to flame stretch as the dominant factor is also evidenced by the fractal characteristics of the flame front.

Introduction

Hydrogen is one of the potential energy carriers in the context of establishing a sustainable energy system. Concerning the thermochemical conversion of hydrogen energy, one of the options is to introduce hydrogen into state-of-the-art, lean-premixed gas turbine combustors, which are conventionally fired with natural gas. This pathway is generally linked to the concept of an integrated gasification combined cycle (IGCC), which is based on the combustion of fuel gases derived from the gasification of solid fuels (e.g., coal and biomass). The major constituents of these fuel gases are hydrogen and carbon monoxide (i.e., syngas), along with other diluents such as nitrogen and carbon dioxide. The H_2-to-CO ratios vary depending on the feedstock and the gasification process. If the ultimate goal remains "being carbon-neutral," a carbon capture and sequestration (CCS) technique must be integrated into the configuration of an IGCC plant prior to the combustion process. With such pre-combustion carbon capture, the hydrogen content in the fuel gas may approach 100 vol%. Since hydrogen is much more reactive than methane (the major constituent of natural gas), it becomes highly challenging to burn these so-called "H_2-rich" fuel gases (with the hydrogen content typically over 70 vol%) in lean-premixed gas turbine combustors. Accordingly, a greater understanding on the combustion characteristics of H_2-rich fuel gases is imperative to materialize the integrated IGCC-CCS concept.

One of the primary parameters that characterize turbulent premixed combustion is the turbulent flame speed (S_T). From

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the perspective of a volumetric fuel consumption rate, S_T can be implemented to determine the allocation of the flame contour within a combustion chamber. Among numerous experimental investigations on S_T, most of them focused either on various syngas mixtures [1–6] or on hydrogen-enriched hydrocarbon fuel blends [7,8]. Relatively few studies incorporated (diluted) hydrogen as a fuel gas [9–12]. For example, the S_T of spherically propagating, turbulent premixed hydrogen/air flames was studied by Kitagawa et al. [11]. The combination Re_T/Le^2 (Re_T and Le are the turbulent Reynolds number and the Lewis number, respectively) was proposed to be a practical parameter for describing both the hydrodynamic effect of turbulence (characterized by Re_T) and the thermo-diffusive effect (characterized by Le) on S_T. An "implosion" technique (in a spherical chamber) was implemented to retrieve the S_T of various fuel gases (including hydrogen) at elevated pressure by Bradley et al. [12]. The derived S_T was further correlated with the Karlovitz stretch factor and the "strain rate" Markstein number. Based on experiments performed on a Bunsen-type burner, Venkateswaren et al. [4] presented scaling laws of S_T for various syngas mixtures. The scaling was based on the laminar burning velocity of highly stretched flames, which is originally derived from the leading points model. It was concluded that the non-quasi-steady behavior of flame leading points must be accounted for to capture the pressure sensitivity of S_T. Similarly with a Bunsen burner, several model syngas mixtures relevant to coal gasification were studied by Kobayashi et al. [5]. The characteristic scale of hydrodynamic instability was found to serve as a lower limit to the smallest scale of flame wrinkles. Nonetheless, despite all the aforementioned work, the S_T data for (diluted) hydrogen/air flames ("H_2-rich" flames) at gas turbine relevant conditions (preheated, pressurized, and lean stoichiometries) are still scarce in the literature [13,14].

The characteristics of S_T may be best understood from a geometric perspective. Based on the "flamelet" concept [15] in turbulent premixed combustion, one effect of turbulence is to wrinkle a thin reaction front where the characteristics of a laminar flame are assumed to be kept [15,16]. Accordingly, the ratio of turbulent to laminar flame speeds (S_T/S_L) can be evaluated as an area ratio (A_T/A_L), where A_T and A_L are the instantaneous/wrinkled and the averaged/smoothed flame surface areas, respectively. The latter may also be comprehended as a "projected" surface at which the reactants are consumed at a rate represented by S_T. One of the approaches to derive A_T/A_L is the fractal analysis [17]. The idea is based on the observation that multiple scales of wrinkling are exhibited in turbulent premixed flames, and the geometric complexity can be characterized with a fractal description [18]. Originally a mathematical concept, the fractal analysis was first implemented by Mandelbrot [19] to describe the geometry of isosurfaces of scalars in homogeneous turbulence. It was later evolved [18,20] to model the geometric characteristics of a turbulent premixed flame front. Imagine the projection of a flame surface that is identified via two-dimensional laser diagnostics as a curve. The curve is considered "fractal" if a power law dependence exists between its measured length (L) and the measurement scale (ε), i.e., $L \sim \varepsilon^{1-D}$, where D is the fractal dimension. In practice, there are lower (the inner cutoff, ε_i) and upper (the outer cutoff, ε_o) limits of ε beyond which the power law dependence is no longer held [18]. ε_i represents the smallest scale of flame/turbulence interactions, and its normalized value (with respect to the laminar flame thickness) was shown to scale with the Karlovitz number (Ka) [21]. In contrast, ε_o is generally on the same order of magnitude as the integral length scale L_T [22,23], which scales with burner geometry or the dimensions of turbulence-generating grids.

In this work, the characteristics of turbulent, lean-premixed, non-swirled, dump-stabilized axisymmetric "H_2-rich" flames are experimentally investigated under preheated and pressurized conditions. Specifically, the correlations of the global consumption-based turbulent flame speed (S_T) and fractal parameters of the flame front are presented. Around 700 data points were collected for deriving the correlations of S_T, while one-fifth of the data include also information about the fractal feature. According to the regime diagram for premixed turbulent combustion [24], most of the data are allocated within the thin reaction zones regime. Fig. 1 presents four instantaneous, false-colored images acquired with planar laser-induced fluorescence of hydroxyl radicals (OH-PLIF) of the investigated H_2-rich flames. The inlet and the wall of the combustor are indicated by red bars. The respective boundary conditions (i.e., the Karlovitz number, Ka, and the turbulent Damköhler number, Da) for each flame image have been selected so that each is located in a different regime. No significant change in the morphology of the flame front is observed even when the corresponding Ka is approaching the regime of broken reaction zones. This is similar to the observation on syngas flames [1], and it also implies that independent of the large difference in Ka, a continuous contour of the reaction zone may still be derived successfully.

It should be emphasized that the objective of this work is not to argue over or determine the limits of the "flamelet" regime [15]. In an earlier investigation on natural gas/air flames [25], localized deviations from a laminar-like flamelet structure are already observed when $Ka > 5$. The validity of the flamelet hypothesis in the thin reaction zones regime (where $Ka > 1$) was also questioned in Ref. [26], where both turbulent methane/air and propane/air flames were studied. In contrast, lamella-like scalar-front structures are observed on lean-premixed hydrogen/air flames when $Ka > 15$ [27]. The persistence on the flamelet behavior is considered to be attributed to the much smaller flame residence time (compared to the unstretched laminar value) for the lean hydrogen/air flames. Furthermore, it was stated by Driscoll [16] that evidence of the premixed combustion occurring in distributed reaction zones is relatively scarce, and thin flamelets are still found to occur even when Ka greatly exceeds unity. Accordingly, the flamelet concept is considered as a reasonable basis for the present work. The S_T consists of two components, the surface wrinkling of the flame front (represented by the ratio S_T/S_{LK}) and the flamelet consumption speed (S_{LK}). The absolute values of S_T were first derived over a wide range of boundary conditions, and an improved fractal methodology [13] was implemented to analyze some of these flames, from which the information about the flame front wrinkling (S_T/S_{LK}) was retrieved. Any remaining