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Effects of mixture composition and turbulence intensity on flame front structure and burning velocities of premixed turbulent hydrocarbon/air Bunsen flames

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ABSTRACT

The influences of the equivalence ratio, turbulence intensity, and different thermo-diffusive characteristics on the flame brush characteristics, instantaneous flame front structures, and burning velocities of premixed turbulent methane/–, ethane/–, and propane/air Bunsen flames were investigated systematically. Particle image velocimetry and Mie scattering techniques were utilized to measure the turbulence statistics and to visualize flame front corrugations, respectively. All experiments were performed under a constant bulk flow velocity of 21.0 m/s. The equivalence ratio range was from 0.7 to 1.35 for methane/air flames, 0.7–1.45 for ethane/air flames, and 0.8–1.35 for propane/air flames. Two perforated plates were used to produce different turbulence levels. A series of comprehensive parameters including the characteristic flame height, mean flame brush thickness, mean volume of the turbulent flame region, mean fuel consumption rate, two-dimensional flame front curvature, local flame front angle, two-dimensional flame surface density, wrinkled flame surface area, turbulent burning velocity, mean flamelet consumption velocity, and mean turbulent flame stretch factor were obtained. The mean turbulent flame stretch factor displayed a dependence on the equivalence ratio and turbulence intensity. Results show that the mean turbulent flame stretch factors for lean/stoichiometric and rich mixtures were not equal when the unstrained premixed laminar burning velocity, non-dimensional bulk flow velocity, non-dimensional turbulence intensity, and non-dimensional longitudinal integral length scale were kept constant.

1. Introduction

For the improvement of certain class of combustion devices such as the lean premixed gas-turbines for power generation and the homogeneous charge spark-ignition engines for transportation, we need a better understanding of premixed turbulent combustion [1]. Despite the continuing progress in the field of premixed turbulent combustion, there still exist many unresolved problems regarding the underlying physics of the associated processes. The knowledge of flame brush characteristics, instantaneous flame front structures, and burning velocities, which are the manifestations of turbulence–flame interactions, is necessary in order to understand the mechanism behind the premixed turbulent combustion. This kind of information is not only desired for a better design of the related combustion devices but also for the numerical model testing.

The premixed turbulent flame geometries are classified into the “Envelope” category (Bunsen-type flames), “Oblique” category (V-shaped flames), “Unattached” category (counterflow and swirl-stabilized flames), and propagating flame kernels [2–4]. Abdel-Gayed and Bradley [5] examined a large number of burning velocity data sets for premixed turbulent flames on different burners, extracted from different sources. They also developed a two-eddy theory of burning, and they compared it with experimentally measured values. They suggested that the ratio of the turbulent to the laminar burning velocity might be correlated with the ratio of the root-mean-square (r.m.s.) of velocity fluctuations to the unstrained premixed laminar burning velocity and with the cold gas turbulent Reynolds number. Later, Abdel-Gayed et al. [6] modified the two-eddy theory of burning proposed in [5] to estimate the effect of flame straining on the burning velocity, and they reported burning velocity values obtained in an explosion bomb. They showed that the turbulent burning velocity increases with increasing r.m.s. of velocity fluctuations, whereas by further increasing the latter property, the rate of increase of the burning velocity with the r.m.s. of velocity fluctuations decreases. This observation is called the “bending” phenomenon [7]. Similar trends were previously reported in the literature, see, for example, Sokolik et al. [8], Karpov and Severin [9], Bradley [10], Duclos et al. [11], Aldredge et al. [12], Peters [13], Shy et al. [14], Kido et al. [15], Kobayashi et al.

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[16], Filatyev et al. [3], and Fairweather et al. [17]. This phenomenon may be attributed to the flamelets merging along with the gas expansion [3]. Abdel-Gayed et al. [6] presented the ratio of the turbulent to the laminar burning velocity in terms of the parameters previously reported in [5] plus a Lewis number for the deficient reactant and the dimensionless activation energy. Experimental measurements showed that the burning velocity of premixed turbulent flames increases with decreasing Lewis number for the deficient reactant, see, for example, Karpov and Severin [9], Kido et al. [15,18], and Nakahara et al. [19]. Abdel-Gayed et al. [20] presented the ratio of the turbulent to the laminar burning velocity in terms of the ratio of the effective r.m.s. of velocity fluctuations to the unstrained premixed laminar burning velocity and the Karlovitz flame stretch factor. Bradley [10] showed that the ratio of the turbulent burning velocity to the effective r.m.s. of velocity fluctuations has a power law relation to the product of the Karlovitz flame stretch factor and the Lewis number by investigating the experimental values reported in [20]. Gülder [21] proposed conceptual models for the prediction of burning velocity for three different combustion regimes. Each model was tested by comparing it to the measured data of various experimental rigs. It should be emphasized that all of these models are in terms of the turbulence statistics, namely the r.m.s. of velocity fluctuations and turbulent length scale. In their comprehensive review papers, Lipatnikov and Chomiak [22,23] reviewed the available empirical correlations to represent the turbulent burning velocity in the literature, and they discussed the effects of various parameters such as the turbulence intensity, turbulent length scale, unstrained premixed laminar burning velocity, molecular heat diffusivity, pressure, and Lewis number for the deficient reactant on the burning velocity of premixed turbulent flames.

Many attempts have been made over several decades in order to correlate the measured turbulent burning velocity data in terms of different parameters such as the turbulent length scale, turbulent Reynolds number, laminar flame thickness, volumetric expansion ratio, and the effects of non-unity Lewis number [4]. As noted in Bilger et al. [4], the correlations available in the literature are limited, and they are sensitive to flow configuration. It is proposed in [4,7] that the turbulent burning velocity data of one flame category should only be used for a geometry-specific correlation, and they should not be utilized for other flame categories. Filatyev et al. [3] stated that the turbulence intensity and turbulent length scale cannot be solely used for constructing a correlation to represent the turbulent burning velocity for Bunsen-type flames. This necessitated additional parameters for the turbulent burning velocity correlation, namely the bulk flow velocity, burner width, and turbulent Markstein number. Tamadonfar and Gülder [24] showed that the turbulent burning velocity decreases with increasing bulk flow velocity when other turbulence statistics are kept constant. They stated that this observation may be attributed to the formation of local extinctions due to an increase of flame front stretching caused by the large velocity gradients in shear layers. In their comprehensive study, Daniele et al. [25] evaluated the thermo-diffusive characteristics of flames stabilized on an axisymmetric burner by measuring the mean turbulent Markstein number using a fractal method. They showed that the mean turbulent Markstein number decreases with increasing equivalence ratio for lean syngas/air flames. In addition, the mean turbulent Markstein numbers for pure methane/air mixtures are equal to zero, and their absolute values increase for hydrogen-containing fuels with increasing H_2 content [25]. The physical mechanism associated with the thermo-diffusive effects is thoroughly explained by Lipatnikov and Chomiak [23]. In this mechanism, the flamelet consumption velocity increases (decreases) locally due to the local variations in enthalpy and mixture composition. Following Lipatnikov and Chomiak [23], if the mass diffusivity of the deficient reactant is larger than the thermal diffusivity of the mixture or the mass diffusivity of the excess reactant, the chemical energy provided to the flame front which is convex toward the reactants surpasses the heat losses due to the molecular conductivity, or the mixture composition for the lean mixture leads to the stoichiometric mixture due to the faster diffusion of the deficient reactant compared to the excess reactant. This process results in an increase of the local flamelet consumption velocity. On the other hand, the opposite phenomena occur for the flame front which is concave toward the reactants. This results in the faster propagation of the flame front which is convex toward the reactants and the slower propagation of the flame front which is concave toward the reactants. Thus, the flame wrinkling grows. To the best of the authors' knowledge, there has not been any systematic investigation conducted on evaluating the mean flamelet consumption velocity using the flame surface density method when other turbulence statistics are kept constant.

Table 1
Summary of geometrical properties and upstream position of the perforated plate from the burner exit for each of the perforated plate used in this study. Symbols: d = hole diameter of the perforated plate; M = mesh size of the perforated plate; β = blockage ratio of the perforated plate; h_e = upstream position of the perforated plate from the burner exit.

Perforated plate	d (mm)	M (mm)	β (%)	h_e (mm)
TG-I	1.0	1.3	53	100.1
TG-II	0.9	1.3	62	44.5

In this study, we explore the effects of the equivalence ratio, turbulence intensity, and different thermo-diffusive characteristics on the flame brush characteristics, instantaneous flame front structures, and burning velocities of premixed turbulent methane/–, ethane/–, and propane/air Bunsen flames. A series of broad parameters including the characteristic flame height, mean flame brush thickness, mean volume of the turbulent flame region, mean fuel consumption rate, two-dimensional flame front curvature, local flame front angle, two-dimensional flame surface density, wrinkled flame surface area, turbulent burning velocity, mean flamelet consumption velocity, and mean turbulent flame stretch factor were evaluated from the experimental data.

2. Experimental methodology

2.1. Bunsen-type burner

An axisymmetric Bunsen-type burner with a nozzle inner diameter, D, of 11.1 mm was utilized to produce premixed turbulent flames. The geometry of its components was documented in detail in [26]. The calibrated mass flow meters were used to control the flow rates of the filtered air and fuel. The accuracy for each of the flow meter was ±0.80% on its reading, and ±0.20% on its full scale. Three different hydrocarbons (methane, ethane, and propane) were utilized as the fuel in the experiments. The flame was anchored to the rim of the burner using an annular premixed ethylene/air pilot flame. Two perforated plates, that is, TG-I and TG-II, were used independently in order to generate different turbulence levels. Each of the perforated plate was mounted upstream of the burner exit. The holes of the perforated plates are arranged in a hexagonal array. This method of turbulence generation has been extensively utilized in the literature, see, for example, [24,27–37]. The hole diameter (d), mesh size (M), blockage ratio (β), and upstream position of the perforated plate from the burner exit (h_e) for each of the perforated plate are summarized in Table 1. The time-averaged image of a luminosity for a representative flame condition, Flame M12, is shown in Fig. 1.

2.2. Flow field characterization and test conditions

The two-dimensional particle image velocimetry was utilized to measure the instantaneous velocity vectors. The light source which