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Effect of burner diameter on the burning velocity of premixed turbulent flames stabilized on Bunsen-type burners

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ABSTRACT

Influence of burner diameter on the turbulent burning velocity of premixed turbulent methane/air flames was studied on two Bunsen-type burners with nozzle inner diameters of 11.1 and 22.2 mm. The equivalence ratio was varied from 0.6 to 1.0. The non-dimensional turbulence intensity, non-dimensional bulk flow velocity, and non-dimensional longitudinal integral length scale were kept constant for a given equivalence ratio for both burners. Particle image velocimetry and Rayleigh scattering techniques were used to measure the instantaneous velocity and temperature fields, respectively. The characteristic flame height decreased with increasing equivalence ratio from 0.6 to 1.0 for both burners, whereas it increased considerably by increasing the burner diameter. The transverse profiles of the leading edge and half-burning surface flame surface densities showed a tall and narrow region at each side of the burner exit, whereas they were distributed over a larger area farther downstream of the burner exit. The leading edge and half-burning surface wrinkling factors were found to be higher for the larger burner farther downstream of the burner, whereas they are about the same near the burner exit. The non-dimensional leading edge turbulent burning velocity increased with increasing non-dimensional turbulence intensity for both burners. However, the leading edge turbulent burning velocity was found to be higher with the larger size burner.

1. Introduction

The development of low-emission combustion systems such as gas turbines for power generation and engines for transportation requires a better understanding of premixed turbulent combustion [1]. The detailed understanding of flame brush characteristics and turbulent burning velocity are highly desirable for the design of premixed combustion systems and numerical model testing [2].

In their comprehensive study of the turbulent burning velocity, S_T, Abdel-Gayed et al. [3] examined a large number of experimental data sets from Bunsen, spherical, and V-Shaped flames, and proposed a general correlation for the non-dimensional turbulent burning velocity, S_T/S_L^0, where S_L^0 is the unstrained premixed laminar burning velocity. This dimensionless correlation was generated by utilizing the turbulent burning velocities from various burner geometries, and it was in terms of the ratio of the effective root-mean-square (r.m.s.) of velocity fluctuations to the unstrained premixed laminar burning velocity, u'_k/S_L^0, and the Karlovitz flame stretch factor, Ka'. Bradley et al. [4] then showed that the ratio of S_T to u'_k has a power law relation to the product of the Karlovitz flame stretch factor, Ka', and the Lewis number, Le, by investigating the experimental data presented in [3]. Gülder [5] proposed conceptual models for the estimation of S_T for three combustion regimes. These models were tested by comparing them to the measured data of various experimental rigs covering the range from flames stabilized in ducts to expanding flames. It should be emphasized that all these models are in terms of the turbulence statistics, namely the total turbulence intensity and turbulent length scale. Lipatnikov and Chomiak [2] reviewed the available empirical correlations for the prediction of S_T in the literature, and discussed the effects of various parameters such as total turbulence intensity, u', longitudinal integral length scale, Λ_L, unstrained premixed laminar burning velocity, S_L^0, molecular heat diffusivity, κ, and pressure, P, on S_T.

In his review paper, Driscoll [6] argued that approaches based on the assumption that the real premixed turbulent flames should have the behavior of an ideal geometry-independent flame do not help to advance the field of premixed turbulent combustion. If this assumption were to be justified, the non-dimensional turbulent burning velocities for different flame geometries would be similar when the magnitudes of non-dimensional turbulence intensity, u'/S_L^0, non-dimensional longitudinal integral length scale, Λ_L/δ_f,

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Nomenclature

Alphanumeric symbols

A_0 cross-sectional area of the burner (mm^2)
$A_{T,\langle c\rangle}$ mean turbulent flame surface area conditioned at a specific mean progress variable (mm^2)
c progress variable
d circular hole diameter of the turbulence generator (mm)
D burner diameter for round Bunsen burner (mm)
Da turbulent Damköhler number
f focal length of the lens (mm)
h axial distance from the burner exit (mm)
$H_{\langle c\rangle=0.5}$ characteristic flame height (mm)
I_R intensity of the flame image
I_a intensity of the air image
I_b intensity of the background image
I intensity ratio, see Eq. (2)
K ratio of the fuel–air mixture Rayleigh scattering cross section to the pure-air Rayleigh scattering cross section, see Eq. (2)
Ka' Karlovitz flame stretch factor
Ka turbulent Karlovitz number
Le Lewis number
M mesh size of the turbulence generator (mm)
Ma_T turbulent Markstein number
P pressure
r radial distance from the centerline of the burner (mm)
Re_{Λ_L} turbulent Reynolds number
S_L^0 unstrained premixed laminar burning velocity (m/s)
S_T turbulent burning velocity (m/s)
$S_{T,\langle c\rangle}$ turbulent burning velocity conditioned at a specific mean progress variable (m/s)
$S_{T,\langle c\rangle=0.05}$ leading edge turbulent burning velocity (m/s)
T_f flame temperature (K)
T_a air temperature (K)
T_{ad} adiabatic flame temperature (K)
$\langle u^2\rangle^{1/2}$ root-mean-square of velocity fluctuations in the axial direction (m/s)
u' total turbulence intensity (m/s)
u'_k effective root-mean-square of velocity fluctuations (m/s)
U_B bulk flow velocity (m/s)
$\langle v^2\rangle^{1/2}$ root-mean-square of velocity fluctuations in the radial direction (m/s)
$\langle w^2\rangle^{1/2}$ root-mean-square of velocity fluctuations in the azimuthal direction (m/s)
W burner width for slot Bunsen burner (mm)

Greek symbols

$\alpha_{\langle c\rangle=0.05}$ power coefficient, see Eq. (5)
β blockage ratio of the turbulence generator (mm)
χ_i mole fraction of the ith species
δ_f Zel'dovich thickness (mm)
η Kolmogorov length scale (mm)
ϕ equivalence ratio
κ molecular heat diffusivity (m^2/s)
Λ_L longitudinal integral length scale (mm)
ν unburned mixture kinematic viscosity (m^2/s)
Ω_c wrinkling factor
$\Omega_{c=0.05}$ leading edge wrinkling factor
$\Omega_{c=0.5}$ half-burning surface wrinkling factor
σ_m fuel–air mixture Rayleigh scattering cross section (cm^2/sr)
σ_a pure-air Rayleigh scattering cross section (cm^2/sr)
σ_i Rayleigh scattering cross section of the ith species (cm^2/sr)
Σ flame surface density (1/mm)
Σ_c flame surface density conditioned at a specific progress variable (1/mm)
$\Sigma_{c=0.05}$ leading edge flame surface density (1/mm)
$\Sigma_{c=0.5}$ half-burning surface flame surface density (1/mm)
$\Xi_{\langle c\rangle=0.05}$ dimensionless number, see Eq. (5)

Others

Δs interrogation box size (mm)
Δx velocity vector spacing in the axial direction (mm)
$f(\Delta x)$ longitudinal velocity correlation coefficient

and the turbulent Markstein number, Ma_T, are equal, where the Zel'dovich thickness, δ_f, is the ratio of the reactant mass diffusivity to the unstrained premixed laminar burning velocity [1]. However, the real turbulent flames of each flame geometry are believed to have different values of S_T from other flame types under constant $u'/S_L^0, \Lambda_L/\delta_f$, and Ma_T due to the expectations that the wrinkling processes and boundary conditions would be different [6,7]. Hence, it is suggested that any correlations that are developed for one flame geometry should be specific to that geometry and should not be applicable for other flame types. Based on this recommendation, Filatyev et al. [8] suggested to include the bulk flow velocity, U_B, and burner width, W, as additional parameters in the turbulent burning velocity correlation of Bunsen-type flames since these parameters are believed to affect the wrinkling process and the resulting value of S_T. As a result, they proposed the following independent variables that influence the turbulent burning velocity [8]:

$$\frac{S_T}{S_L^0} = f\left(\frac{u'}{S_L^0}, \frac{\Lambda_L}{\delta_f}, Ma_T, \frac{U_B}{S_L^0}, \frac{W}{\delta_f}\right). \tag{1}$$

It is worth noting that in the turbulent burning velocity correlation suggested by Filatyev et al. [8], $\left(S_T - S_L^0\right)/S_L^0$ was proportional to $(W/\delta_f)^{1/2}$, although the burner width was not varied in the aforementioned experiments. Thus, the dependency of S_T on W was not proven. To the best of the authors' knowledge, there has not been any systematic investigation carried out on the effect of burner width (diameter) of the slot (round) Bunsen-type burner flames on the turbulent burning velocity when other parameters that are included in Eq. (1) are kept constant. Hence, the objective of this study was to determine the influence of Bunsen-type burner diameter on the turbulent burning velocity, and to assess whether the burner size should be included in empirical (or semi-empirical) correlations for the turbulent burning velocity of Bunsen-type flames.

2. Experimental methodology

The premixed turbulent flames were generated using two axisymmetric Bunsen-type burners with nozzle inner diameters of 11.1 and 22.2 mm. The filtered air and methane grade 2.0 flow rates were controlled using calibrated mass flow meters. A premixed ethylene/air pilot flame at the periphery of nozzle exit was utilized to attach the main flame to the rim of the burner. For each burner, the turbulence was generated by a passive turbulence generator mounted upstream of the burner exit. The turbulence generator holes are arranged in a hexagonal array.