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Wall effect on determination of laminar burning velocity in a constant volume bomb using a quasi-dimensional model

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In experiment, two optical and pressure-based methods are frequently used to evaluate laminar burning velocity of a combustible mixture. In the currently reported work, the pressure-based method was utilized to find the laminar burning velocity using the measurement of pressure variations during the combustion process in a spherical bomb and analyzing them through a multi-zone quasi-dimensional model. To check the results of the method, isooctane–air mixtures were used at equivalence ratios of 0.85 and 1.0 and initial pressures of 95 and 150 kPa with 343 K initial temperature. The time history of the bomb pressure during the combustion event, initial pressure and temperature, fuel type, and equivalence ratio were applied as input to a Fortran program written by the author based on the multi-zone combustion model; and, flame radius-time, flame speed, and laminar burning velocity at different pressures and temperatures were evaluated assuming spherical flame growth. The obtained results were compared with those of some other researchers and a reasonable agreement was observed. The wall effect on the laminar burning velocity at the end of the combustion process was clearly highlighted and a reliable range of burning velocity was distinguished. The results showed that the evaluated laminar burning velocity was not reliable at the late part of the combustion process due to possible local contact of flame front and the bomb wall, the wall effect on the reacting species, flow to small crevices, and the boundary layer effect.

1. Introduction

Laminar burning velocity is defined as the velocity relative to and normal to the flame front surface with which unburned gas moves into the front and is transformed to products under laminar flow conditions [1]. Flame speed is defined as the temporal derivative of the flame radius evolution [2]. The flame front speed is relative to the burned gases behind it. Different methods have been used to determine the laminar burning velocity based on experimental data [3]. To develop engine combustion simulation codes, having a reliable laminar burning velocity correlation is crucial [4–7]. Many experimental works have been performed using constant volume combustion bombs with adjustable initial conditions [8–16]. Two common methods used in previous works are optical and pressure-based methods [17]. Experiments and analysis show that during combustion in a constant volume bomb, the pressure change in terms of relative flame radius (r_f/R) at the initial part of flame development is negligible. Illustrated in Fig. 1 is the typical bomb pressure versus the relative flame radius explored in the current study. As seen, up to $r_f/R = 0.35$, pressure change ($P - P_{in}$) is <0.05 bar.

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Nomenclature

A	area of flame front [cm^2]
F	fuel air ratio
M	molar mass [$kg\ kmol^{-1}$]
m	mass [kg]
n	number of moles [kmol]
P	pressure [bar]
R	bomb radius [mm]
$\tilde{R}$	general ideal gas constant [$kJ\ kmol^{-1}\ K^{-1}$]
r	flame radius [mm]
S	burning velocity [$cm\ s^{-1}$]
T	temperature [K]
t	time [sec]
u	specific internal energy [$kJ\ kg^{-1}$]
V	volume [cm^3]
x	species mole fraction
Greek symbols	
α	O_2 moles for one mole fuel in a stoichiometric mixture
ϕ	equivalence ratio
γ	specific heat ratio
ρ	density [$kg\ m^{-3}$]
ψ	N_2/O_2 ratio in the atmospheric air
Subscripts	
b	burning
b_i	ith burned
f	flame; fuel
in	initial
L	laminar
l	number of oxygen in fuel molecule
m	number of carbon in fuel molecule
n	number of hydrogen in fuel molecule
p	products
s	stoichiometric

In the optical method in a bomb, temporal change of flame radius is essential and, generally, a high-speed filming technique through transparent windows usually focused on the space limited inside the bomb preferably centered to the spark location is utilized [9–14]. This technique provides reliable results at the early stage of flame growth in which pressure and temperature of the unburned mixture do not change significantly; by contrast, a reliable result could not be obtained using the pressure-based method. If in the optical method the space under view extends to the bomb diameter scale, then the obtained results will not have a good accuracy over the main and late stages of the combustion period due to significant change of pressure with flame radius. However, to cover engine-working conditions, performing some tests initially with high temperature and pressure would create a very high peak pressure leading to problems from the point of safety for a transparent bomb.

In the pressure-based method using a constant volume bomb [15,16,18–20], the rate of pressure rise (dp/dt) and variation of pressure with flame radius are very important. Although the method does not give proper information at an early stage of flame growth, it can provide significant information during the middle and late combustion periods due to sensible variation of pressure with time. Using the method, some works have been reported utilizing a few equations based on the recorded peak pressure [14,15,20]. When the flame front arrives at the bomb wall at the end of the combustion period (such as a spherical bomb with a central ignition and initial laminar conditions), reliability to peak pressure depends upon wall effect on the flame front [19]; however, if the geometry of the flame growth disagrees with the bomb geometry (such as a cylindrical bomb or a spherical bomb with eccentric ignition), the bomb pressure history and its peak pressure will be influenced due to heat transfer and reduction of active flame front area. Utilizing an analytical or quasi-dimensional method, which is free of peak pressure, will result in reliable information.

Another method used to evaluate the laminar burning velocity is the method of one-dimensional calculations based on chemical kinetics [21–23]. Considering 215 species in a chemical kinetic mechanism, Martz et al. [21] provided a large amount of data for laminar burning velocity of isooctane–air mixtures with equivalence ratio, initial temperature, and pressure in ranges of 0.1–1.0, 298–1000 K, and 1–250 bar, respectively. They introduced a set of correlation fitting to the data.

To investigate the transient combustion process in a chamber, two-zone and multi-zone quasi-dimensional thermodynamic models were used frequently [4–8]. A reversed multi-zone combustion model was considered as multiple sequentially burned zones to analyze pressure–time data recorded in a combustion bomb.