MEASURING LAMINAR BURNING VELOCITIES

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Abstract

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The laminar burning velocity of a fuel is the rate of normal propagation of a 1D flame front relative to the movement of the unburned gas. This is a fundamental property of a fuel that affects many aspects of its combustion behaviour. Experimental values are required to validate kinetic simulations, and also to provide input for models of flashback, minimum ignition energy and turbulent combustion. Burning velocity affects burn duration and consequently power output in spark ignition engines. Burning velocities are affected by pressure, temperature, equivalence ratio, residuals, additives, and stretch rates.

The constant volume vessel has been used as it is considered both the most versatile and accurate method of measuring laminar burning velocities. An existing combustion vessel and oven were refurbished and new systems built for fuel injection, ignition, experiment control, data acquisition and high speed schlieren photography.

An existing multi-zone model was used to allow calculation of burning velocity from pressure and schlieren data, allowing the user to select data uncorrupted by heat transfer or cellularity. A twelve term correlation for burning velocity was validated using methane modelling data. The chosen data from all the experiments was then fitted to the correlation.

Methane, n-butane, n-heptane, iso-octane, toluene, ethylbenzene and ethanol were tested over a wide range of initial pressures (0.5, 1, 2 and 4 barA), temperatures (289–450 K) and equivalence ratios (0.7–1.4). For liquid fuels, tests with real residuals at mole fractions of up to 0.3 were also conducted. Stoichiometric mixture tests were performed at two initial temperatures (380 and 450 K) and the same four initial pressures. For mixtures of iso-octane and ethylbenzene, percentage volumes of 12.5, 25, 50 and 75% iso-octane were tested. It was found that the the percentage of iso-octane affected burning velocity non-linearly. For iso-octane/ethanol, a single 50:50% mixture was tested.

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Nomenclature

CMOS	complementary metal-oxide-semiconductor
DAQ	data acquisition
DISI	direct injection spark ignition
dp	decimal places
EGR	exhaust gas recirculation
FET	field-effect transistor
FFT	fast Fourier transform
fps	frames per second
GP	Gaussian process
GUI	graphical user interface
HCCI	homogeneous charge compression ignition
HT	high tension
IC	integrated circuit
LED	light emitting diode
LDV	laser Doppler velocimetry
mfb	mass fraction burned
NAND	NOT AND
ODE	ordinary differential equation
PIV	particle image velocimetry
ppm	parts per million
psi	pounds per square inch
PTFE	poly(tetrafluoroethene)
RC	resistor-capacitor
SR	sampling rate
TC	thermocouple
TIFF	tagged image file format
TTL	transistor-transistor logic

atm	atmospheres

α	flame stretch rate
α	thermal diffusivity
γ	ratio of the specific heats $c_{\mathrm{p}}/c_{\mathrm{v}}$

δ_ℓ	laminar flame thickness
ϵ	angular ray deflection
θ	half cone angle
λ	thermal conductivity
λ	wavelength of light
ν	kinematic viscosity
ρ	density
σ	ratio of unburned to burned gas densities
ϕ	equivalence ratio

A	flame surface area
B	luminance
c	speed of light in a material
c_0	speed of light in free space
C	contrast
C_p	molar heat capacity at constant pressure
d	diameter
D	mass diffusivity
E	illuminance
E	volume expansion ratio
E_a	activation energy
f	focal length
h	enthalpy
h	step size
I	current
k	Gladstone-Dale coefficient
k	Ostwald coefficient
Ka	Karlovitz number
L	inductance
L	Markstein length
L	optical path length
Le	Lewis Number
m	gradient
m	magnification
m	total mass
M	molar mass
Ma	Markstein number
n	reaction order
n	refractive index
n_0	refractive index of surrounding medium
N	f/# number
p	pressure
p_vp	vapour pressure

P	perimeter
Pe	Péclet number
Pr	Prandtl number
r_b	burned gas radius
r_i	radius prior to combustion ($t = 0$)
r_u	cold flame front radius
R	resistance
R	vessel radius
R_0	molar gas constant
s	entropy
S	sensitivity
S_f	stretched laminar flame speed
S_g	gas velocity ahead of the flame front
S_n	stretched laminar burning velocity (unburned gas)
S_nr	stretched laminar burning velocity (burned gas)
S_s	unstretched laminar flame speed
S_u	unstretched laminar burning velocity
Sc	Schmidt number
t	time
T	temperature
v	specific volume
V	voltage
V	volume
W	electrical work
x	mass fraction burned
x_r	molar fraction of residuals
y_r	mass fraction of residuals

Subscripts

b	burned
c	critical
c	due to curvature and associated with S_n
cr	due to curvature and associated with S_nr
e	end
f	fuel
mix	mixture
r	residuals
s	shell
s	due to strain rate and associated with S_n
sr	due to strain rate and associated with S_nr
t	total
u	unburned

Contents

Chapter 1

Introduction

Despite recent advances in other technologies, much of the world's automotive fleet still relies on combustion of gasoline for propulsion. In recent years improvements in diesel technology have led to an increase in the number of this type of engine in cars, particularly in Europe. However, new gasoline technologies such as spray-guided DISI and HCCI aim to give the part-load economy benefits of diesel with the power of gasoline.

For these reasons research into the properties of gasoline and its constituent chemicals is as relevant as ever. The combustion of medium chain length hydrocarbons, oxygenates and other petrochemicals is still not very well understood, particularly the kinetics of reactions which may involve hundreds of reactants, forming a vast number of intermediate species.

One of the most important parameters for any fuel is the laminar burning velocity. This is defined as the speed at which a flat laminar flame would propagate in a still gas. In reality, the exothermic reaction causes the burned gas behind the flame front to be hotter than the unburned gas in front of it. The burned gas expands, pushing the flame front forward at a speed considerably faster than the true burning velocity. Hence the burning velocity is defined as the measured flame speed minus the gas velocity, as is shown in Figure 2.1. The ability to assume the form of a self-sustained reaction wave propagating at this defined speed is the most distinctive feature of premixed combustion (Sivashinsky, 2002).

This property forms an important input parameter for models of turbulent combustion and ignition limits. It is also important in engine simulations, as predictions of burning velocity are related to burn duration (Lindström et al., 2005), which directly affects power output (Bonatesta and Shayler, 2008) and efficiency (Farrell et al., 2003). Despite its importance in combustion modelling, the modelling of the burning velocity itself is difficult, requiring valid kinetic and thermodynamic properties of the involved reactions and species (Heghes et al., 2005). Even for computations using complex chemistry, comparison with experimental results is required to validate the mechanisms used.

Burning velocity varies with unburned gas temperature and pressure, equivalence ratio and the specific fuel, oxidant and inert gases present. For flames that are not flat, curvature will have an effect. For curved flames that are not stationary in space, the velocity will also have an impact. The area of the flame is important, so a smooth flame must be ensured so that the surface area can be calculated.

Many measurements of burning velocities have been made in the last century, but until relatively recently experimentalists were not aware of the effects of stretch and cellularity, which can have a large effect on their results. This has led to a large disagreement in data between recent studies and historical sources. Of the more recent studies, most of the work has concentrated on hydrogen and methane. Liquid fuels in particular have not been studied extensively, especially at high pressures and temperatures (Bradley, 2008; Beeckman et al., 2009).

Several of the methods for measuring burning velocities require a combustion model to transform the measurements made into burning velocity data. These vary between analytical and numerical models, with one, two or more zones. The model selected needs to be validated against existing methods, and to account for temperature-dependant gas properties.

Most commercial liquid fuels are blends of many different components, constructed as a compromise between fuel properties, legislation and matching refinery output.

Laminar burning velocity is an important parameter of any automotive fuel, along with octane number, calorific value, lubricity, vapour pressure, ignitability and so on. Previous studies (Gülder, 1984; Hirasawa et al., 2002) have shown that the relationship between mixture proportions and burning velocity is non-linear, i.e. the burning velocity of a 50:50 mixture (normally by liquid volume) of two fuels is unlikely to be equal to the mean of the burning velocities of the individual components at the same conditions. Studies of mixtures aim to quantify these non-linearities so that manufacturers have a way of predicting the likely burning velocity of any arbitrary mixture, without having to measure each combination individually.

Use of exhaust gas recirculation (EGR) in gasoline engines to reduce $\mathrm{NO_x}$ emissions and throttling losses has led to interest in the effect of real residuals on burning velocities, to ensure that the quality of combustion is not adversely affected. So far only a few fuels have been tested in this way, and only with synthetic residuals, made from mixtures of inert components.

Combustion in an engine is highly complicated, and subject to many factors that cannot be controlled independently. Hence it is not suitable for fundamental studies which aim to isolate the operating variables (Fiock et al., 1940). Hence a range of methods of measuring burning velocities outside of an engine are presented (see Section 2.2). These ensure a laminar flame and allow for control of temperature, pressure and in, some cases, stretch rate.

The current study aims to provide accurate data for a variety of fuels at elevated temperatures and pressures to compare with previous studies, but it also aims to break new ground with studies of the effects of residuals on burning velocities and also to look at binary mixtures of fuels.