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Laminar burning behaviour of biomass gasification-derived producer gas

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ABSTRACT

In the currently reported work, a mixture of H_2, CO and N_2 (21:24:55 vol%) has been considered as representative of the producer gas coming from gasification of lignocellulosic biomass. Laminar burning velocities have been determined, with simultaneous study of the effects of flame stretch rate and instabilities. Experimentally determined laminar burning velocities derived from schlieren flame images, over a range of equivalence ratios, have been compared with those determined using the CHEMKIN code. Good agreement obtained for 1 bar flames, but significant differences were observed for high pressure cellular flames. Markstein numbers were also derived from the experimental data and corresponding Lewis numbers were calculated. Hydrogen thermo-diffusive effects tended to destabilise lean flames, while the CO content resulted in laminar burning velocity peaking at very high equivalence ratios. The peak burning rate of producer gas proved faster than those of conventional fuels, such as isooctane and methane.
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1. Introduction

Recent European energy policies [1] strongly encourage the use of biomass in order to address three targets: diversification of energy supply, reduction of CO_2 emissions and contribution to rural development. One of the main advantages of gasification is the possibility of installing small, low-cost and efficient gasifier-engine plants. These enable use of the biomass close to source and so elimination of most of the biomass waste storage and transportation costs. In this manner, biomass gasification constitutes an attractive option and an alternative to direct combustion. A low-energy-content gas is generated in the gasification process through an oxygen deficient reaction; the so-called 'producer gas' is an H_2 and CO rich fuel, which also comprises N_2, CO_2 and small quantities of CH_4 and H_2O. Previous studies have shown that the autoignition delay time of producer gas is longer than that of isooctane at temperatures below 1100 K [2]; in fact the knock tendency of a spark ignition engine fuelled with producer gas is quite low, yielding good engine performance at very high compression ratios [3,4]. Although the calorific value of producer gas is ten times lower than that of natural gas, its stoichiometric fuel/air ratio is ten times higher (it needs less air to burn). Thus the energy density of the fuel–air mixture is similar for the two fuels [5] and the loss of power (cf. natural gas) is low, especially under lean conditions. With regard to pollutant emissions: the low adiabatic flame temperature of producer gas helps in limiting NO_x production, whilst its hydrogen content assists reduction in particulate and unburned hydrocarbon emissions [6,7]. These properties render this alternative fuel attractive for mechanical or electrical energy production in internal combustion

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Nomenclature

A	flame front area
D_{ij}	mass diffusivity
L_b	Markstein length
Le	Lewis non-dimensional number
Ma	Markstein number
p	pressure
r	flame radius
S_n	stretched laminar flame speed
S_s	unstretched laminar flame speed
t	time
T	temperature
u_l	laminar burning velocity

Greek symbols

α	stretch rate
α_t	thermal diffusivity
δ_l	laminar flame thickness
ϕ	equivalence ratio
ρ_b	burned gas density
ρ_u	unburned gas density

engines, or in external combustion systems such as Stirling engines, gas burners and micro-turbines [8]. However, engine/burner design and the operating parameters must be optimised to suit the producer gas composition and its thermo-chemical properties. Laminar burning velocity (u_l) is one of the most important properties governing the combustion behaviour of a fuel. Measurement of laminar burning velocities is also important to the development and validation of chemical kinetic mechanisms of unconventional fuels, as well as for development of predictive models to estimate the performance and emissions of combustion equipment, and to prevent and control possible explosion hazards.

Laminar burning velocity is classically defined in relation to one-dimensional, steady and unstretched flames. These are also the assumptions typically adopted in most theoretical combustion models, such as the CHEMKIN code [9] adopted in the currently reported study, for the calculation of theoretical laminar burning velocities. However, for experimental spherically expanding flames similar to those in the combustion chamber of an SI engine or in the combustion bomb described below, flame curvature and aerodynamic strain cause the premixed flame front to become stretched. Differences between experimentally observed laminar burning velocities and ideal planar and theoretical unstretched values may be attributed to the stretch rate experienced by 'real' laminar flames. Additionally, instability resulting from hydrodynamic disturbances associated with thermal expansion of the burnt gas may wrinkle and break the flame front into small combustion cells, causing an increase in effective flame front area, and associated acceleration of the combustion process [10]. This phenomenon, very prevalent at high pressures and particularly for fuels containing significant concentrations of hydrogen, is usually known as cellularity, which might be thought of as an intermediate regime between laminar and turbulent combustion. Much of the variation in values of laminar burning velocity reported in the literature, generated using different experimental and theoretical methods, can be associated with neglect of flame stretch rate and cellularity effects.

The non-dimensional Markstein number (Ma) is another important parameter for a burning mixture, characterising its flame stability and the response of its laminar burning velocity to stretch rate effects. A fuel's Markstein number decreases with pressure and is strongly related to its Lewis number (Le), Prandtl number and the activation energy of the combustion process [11]. In non-equidiffusive mixtures, flame stability is also affected by thermo-diffusive effects, characterised by Lewis number (defined as the mixture's thermal diffusivity divided its mass diffusivity). An effective Le for a reacting mixture has been defined by Matalon et al. [12], although for non-stoichiometric mixtures it approaches the Lewis number based on the deficient species. A flame having $Le<1$ may show thermo-diffusive instability, whereas for $Le>1$ thermo-diffusive effects tend to stabilise the flame front [13].

Although laminar burning velocities have been experimentally determined for a wide range of pure conventional fuels (e.g. isooctane [14], propane [15] and methane [16]), there is a dearth of reliable corresponding data for alternative and renewable fuel/air mixtures; this is particularly so for H_2/CO rich fuels such as the producer gas coming from biomass gasification. Huang et al. [17] have determined the burning velocity of mixtures of primary reference fuels and H_2/CO/N_2 mixtures for a counterflow burner at room pressure and temperature (1 bar and 298 K), using digital particle image velocimetry. They showed that the laminar burning velocity of isooctane increased with the addition of H_2/CO/N_2. Han et al. [18] studied the effect of adding simulated reformer gas (22.1% H_2–7.4% CO, by volume) to a methane/diluent mixture. They employed a cylindrical combustion vessel and processed combustion event pressure records to show an increase in burning velocity and reduction in equilibrium NO concentration with increasing reformer gas concentration. Hassan et al. [19] analysed shadowgraph flame images for a range of H_2/CO/air mixtures, with H_2 concentration in the fuel mixture up to 50 vol%. They suggested that, for low H_2 concentration, the effect of stretch rate was insignificant and that laminar burning velocity peaked at an equivalence ratio close to two. A number of other workers have provided theoretically derived values of laminar burning velocity for such fuels on the basis of chemical kinetic modelling of the flame front. Sung et al. [20] used the CHEMKIN code in conjunction with their own reaction mechanism to show an increase in laminar burning velocity of *n*-butane and isobutane with the addition of reformer gas (30% H_2–25% CO–45 %N_2, by volume). Calculations were made for combustion pressures of up to 20 atm. and the separate effects of H_2 and CO were investigated; these showed that H_2 led to both an

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