



Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Laminar flame speed and markstein length characterisation of steelworks gas blends

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HIGHLIGHTS

- Flame speeds and Markstein lengths of steelworks gas mixtures have been quantified.
- COG composition initially tested using previously benchmarked experimental technique.
- Blended COG/BFG mixtures quantify dampening influence resulting from H₂ variation.
- The specified mixtures also analysed in regard to change in CV and Wobbe index.
- Analysis of chemical kinetic mechanism performance undertaken for each mixture.

ARTICLE INFO

Article history:

Received 29 October 2013

Received in revised form 9 April 2014

Accepted 11 April 2014

Available online xxx

Keywords:

Laminar burning velocity

Flame speed

Outwardly-propagating spherical flame

Flame stretch

Blast furnace gas

Coke oven gas

ABSTRACT

An outwardly propagating spherical flame configuration has been used to characterise the combustion of different blended steelworks gas compositions, under atmospheric ambient conditions. A nonlinear extrapolative technique was used to obtain values of laminar burning speed and Markstein length for combustion with air and change in equivalence ratio. Peak burning speed was shown to reach almost 1 m s^{-1} for the combustion of coke oven gas under marginally rich conditions, and the influence of flame stretch on burning speed also shown to increase with equivalence ratio. The molar fraction of coke oven gas (COG) was then blended in the range 0–15% with four blast furnace gas mixtures (BFG) containing 1–7% H₂ fractions, representative of the inherent compositional fluctuation experienced in production. Profiles for change in burning speed resulting from this addition of COG are presented, and the dampening extent of fluctuation resulting from the H₂ variation has been quantified. Results are also presented for the relative change in gross calorific value and corresponding Wobbe index of the variable blended gases across the tested limits. Modelled results were generated using the PREMIX coded CHEMKIN-PRO, and the performance of specified chemical reaction mechanisms evaluated relative to the experimental data.

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1. Introduction

The Steel industry is estimated to account for 6–7% of global anthropogenic CO₂ emissions [1], with various techniques applicable for the process. The primary integrated works method of reducing ores in a blast furnace, followed by decarburisation, is the least efficient technique, and widely employed in almost 50 countries throughout the world. The approach recommended by the Inter-governmental Panel on Climate Change to improve efficiency is a combination of best available technologies, and maximising the use of by-products indigenous to the integrated works method [2]. Two of the chief by-products are fuels generated at different stages in the process, and are investigated in this study.

Blast furnace gas (BFG) (N₂, CO₂, CO and H₂) results from the ferruginous reduction of iron ores with coke, and other resources. Preheated air (the blast) is introduced to the furnace through base-level tuyeres, with upward gaseous flow catalysing reactions to form molten pig-iron, and simultaneously produce the by-product [3]. Volumetric BFG composition typically comprises a significant quantity of diluent CO₂ and N₂ (75%), with remaining fractions of CO, and a small variable percentage of H₂ (1–7%) [4,5]. Consequently, the calorific value of BFG is low, however its significance results from the vast quantities continuously produced.

Coke Oven Gas (COG) (H₂, CH₄, N₂, CO₂, and CO) is generated through destructive distillation of coal, as a result of the high temperature carbonisation process undertaken for the production of metallurgical coke. The resultant gaseous composition contains

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much larger fractions of combustible constituents, predominantly H_2 , together with CO , CH_4 and other higher hydrocarbons [4].

Typically the gases will be used to fuel steelmaking process operations, however surplus gas can be used in power plants, with improvements in efficiency offering potential for significant energy savings. This increases the importance for investigation into the variable performance of steelworks gases as fuels. This is something that can potentially act to dissuade engineers from usage in more complex technologies, leading to more research in this area [4–8].

1.1. Aim of this work

A fundamental physiochemical property of a fuel often used to characterise combustion performance is the Laminar burning speed (u_L) (sometimes termed laminar burning velocity, or burning rate), and is directly related to operational instabilities such as blow-off and flashback [9,29]. Previous work undertaken by the authors quantified the significant changes in u_L possible with small variation of H_2 fraction within BFG composition, inherent from operational changes made to the blast furnace [10]. Fig. 1.1 presents the fluctuation in u_L for BFG comprising molar fractions of 23% CO and CO_2 , 54% N_2 , with displacing H_2 added in the range of 1–7%, for atmospheric conditions.

The results show a possible rise in u_L of over 200% as H_2 fraction increases across the tested limits. The aim of the current work is to quantify the effectiveness of blending small amounts of COG to dampen out this fluctuation for the same level of compositional variation. This was achieved by applying the widely used method of analysing propagation of spherical flames within a constant-volume combustion bomb. This technique also allows for examination of the influence of stretch on flame speed, as characterised by the burned gas Markstein length (L_b) [11–26]. Kinematic changes in the flame surface geometry influence propagation in relation to the diffusion of heat and reactants, and it is important to evaluate this behaviour for considerations in practical turbulent (highly stretched) combustion systems: Inasmuch that change in stretch influence can further alter flame stability and extinction characteristics.

Results are presented for blends of COG and BFG in different ratios, at ambient conditions of 303 K and 0.1 MPa. The same four BFG H_2 fractions were tested, with COG added in the range of 0–15% of total fuel fraction. The molar fractions of all tested fuel

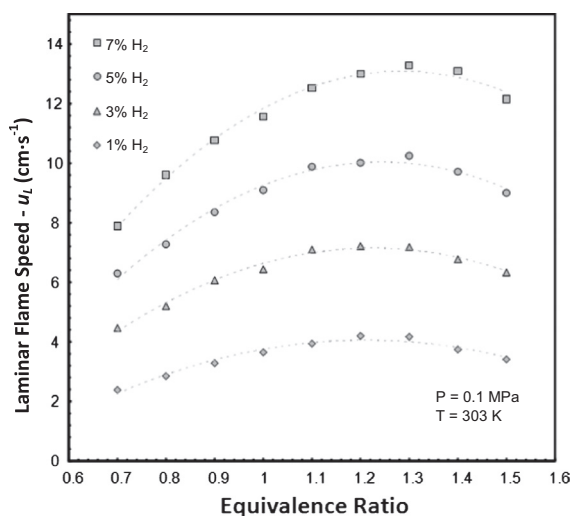


Fig. 1.1. Laminar flame speeds of different BFG compositions [9].

compositions, including the specified COG values (from [5]), are shown in Table 1.1.

The fluctuation in additional fuel characteristics of gross calorific value and corresponding Wobbe index have also been calculated for all tested fuels. Comparisons were made with several published chemical reaction mechanisms using the PREMIX coded CHEMKIN-PRO package, aiming to assess the most suitable for modelling steelworks gas combustion.

2. Materials and methods

A schematic layout of the constant-volume combustion bomb used in this study is shown with additional components in Fig. 2.2. The cylindrical bomb has a working volume of approximately 34 L, an internal diameter of 260 mm, a height of 720 mm, and is designed to allow for a sufficiently long experimental time window in the pressure unaffected region of flame expansion [27]. Eight external band-heaters and four thermocouples are employed in a PID control system to regulate the ambient temperature of the internal reactants.

Diametrically opposed windows allow for high-speed capture of flame propagation through the use of a widely employed Schlieren optical technique [11–20]. The method generates an image of the working area in a collimated light beam, exploiting the change in refractive index resulting from variation in gas density. A converging mirror is used to collimate a light source through 100 mm quartz viewing windows, with a secondary reflection then used to focus the light beam onto an aperture. The refracted portion of the beam unblocked by the edge focuses imperfectly, thereby creating light intensity gradients. These produce edges used to identify the isotherm representative of the flame front boundary [18] (the offset of light intensity thresholds from the ‘flame front’ are taken to be uniform in the applied differential of specified data). The light is captured by a charge-coupled device in a photron FASTCAM APX-RS high-speed camera. The system accommodates a spatial resolution of 0.14 mm per pixel, with diametric propagation rates obtained through bespoke software employing commercially available edge-detection algorithms.

Gas mixtures were introduced to the system through a manifold with a fine needle valve control. The constituent fuel fraction and equivalence ratios were controlled by filling the chamber to calculated values of partial-pressure. This is enabled through the use of an ASG 0–2000 mbar sensor, with a resolution of 0.1 mbar, and a real-time TIC 3 instrument controller readout. Between each test the CVCB was evacuated twice, firstly to remove the products from the previous test, then again subsequent to purging with compressed air to account for errors arising from imperfect vacuum (<1%). This meant the residual pressure remaining after the second evacuation could be added to the air fraction of the partial-pressure calculation, with a resultant contamination error in the order of 0.01%. Adjacent internal fans are then used to blend the gases after filling to the required ratios.

Capacitor discharge ignition was achieved through the use of a variable voltage supply and fine electrodes introduced at 45° to the plane of measurement. Experiments were triggered by simultaneous 5 V signals from a pulse generator, feeding both ignition and data acquisition systems.

3. Numerical theory

Results were obtained from the optical system in the form displayed in Fig. 2.2. The shadowed edge of each frame is computationally scaled, eventually giving values for the propagating Schlieren radius (r_{sch}). Limits were set on the range of usable radii in order to account for the spark influence during early flame

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