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Explosion parameters of wood chip-derived syngas in air

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ABSTRACT

The wood gasification process poses serious concerns about the risk of explosion. The design of prevention and mitigation measures requires the knowledge of safety parameters, such as the maximum explosion pressure, the maximum rate of pressure rise and the gas deflagration index, K_G, at standard ambient temperature (25 °C) and pressure (1 bar) conditions. However, the analysis at specific process conditions is strongly recommended, as the explosion behavior of gas mixtures may be completely different.

In the work presented in this paper, the explosion behavior of mixtures with composition representative of wood chip-derived syngas ($CO/H_2/CH_4/CO_2/N_2$ mixtures with and without H_2O) was experimentally studied in a closed combustion chamber. Experiments were run at two temperatures, 300 °C and 10 °C, and at atmospheric pressure. Test conditions were requested by the safety engineering designer of an existing industrial-scale wood gasification plant. In order to identify the specific fuel–air ratios to be analyzed, thus reducing the number of experimental tests, a preliminary thermo-kinetic study was performed.

Results have shown that the mixtures investigated can be classified as low-reactivity mixtures, the higher value of K_G found (~36 bar m/s) being much lower than the K_G value of methane (55 bar m/s @ 25 °C).

1. Introduction

Wood is one of the main organic materials used as gasification feedstock (Di Blasi, 2008). The wood gasification process poses serious concerns about the risk of explosion (Elsdon and Pal, 2011). During plant start-up, at shutdown or in the case of uncontrolled air intake (due to leakages), a gasification plant passes through the flammability range of the produced syngas. As reported in Speight (2011), the flammability range of wood-derived syngas (i.e., wood gas) in air is very wide (12–74 % v/v). Wood gas/air mixtures with composition within the flammability range may be triggered by sparks (in the wood layer) or hot spots, thus leading to an explosion in the top section of the gasifier or in the filtering section.

For the safe use of wood gas, explosion data are strongly needed. The design of prevention and mitigation measures requires the knowledge of safety parameters, such as the maximum explosion pressure, the maximum rate of pressure rise and the gas deflagration index, K_G, at standard ambient temperature (25 °C) and pressure (1 bar) conditions. However, the evaluation of such parameters under specific process conditions is strongly recommended, as the explosion severity may differ significantly (see, e.g., Cammarota et al., 2009, 2010; Di Benedetto et al., 2011; Salzano et al., 2012a, 2012b).

When evaluating safety parameters for complex fuels with extremely variable composition, such as wood gas, strong assumptions are needed unless a large number of experimental tests are affordable in terms of cost and time. Indeed, the simple evaluation at stoichiometric fuel–air ratio does not necessarily correspond, either in terms of thermochemistry (adiabatic pressure) or kinetics (burning velocity or rate of pressure rise), to the maximum values that can be measured. As a consequence, a wide range of concentrations around the stoichiometric fuel–air ratio have to be explored as a standard, leading to large experimental costs, often unacceptable for companies.

In the work presented in this paper, the explosion behavior of mixtures with composition representative of wood chip-derived syngas was experimentally studied in a closed combustion chamber. More specifically, the maximum pressure, the maximum rate of pressure rise and the deflagration index were measured at the process conditions (in terms of composition, temperature and pressure) requested by the safety engineering designer of an existing industrial-scale wood gasification plant. In order to identify the specific fuel–air ratios to be analyzed, thus reducing the

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number of experimental tests, a preliminary thermo-kinetic analysis was performed.

2. Methodology

In this work, the maximum pressure, the maximum rate of pressure rise and the deflagration index were experimentally determined for syngas/air mixtures under the conditions (temperature and syngas composition) summarized in Table 1 (pressure = 1°bar). Results only apply to such specific conditions.

2.1. Preliminary thermodynamic and kinetic study

In order to reduce the number of experimental tests, preliminary thermodynamic and kinetic analyses were performed to predict the fuel–air equivalence ratio resulting in maximum pressure and maximum rate of pressure rise.

In the thermodynamic study, the GASEQ chemical equilibrium program with the extended equilibrium scheme was used (Morley, 2005). For all conditions of Table 1, this study provided the adiabatic pressure (i.e., the maximum theoretical pressure), P_{ad}, for different fuel–air equivalence ratios.

In the kinetic study, the laminar burning velocity, S_l, was calculated by means of simulations of the one-dimensional, planar, adiabatic, steady, un-stretched, laminar flame propagation. Simulations were run using the Sandia PREMIX code (Kee et al., 1985) of the CHEMKIN software (release 10101) (www.reactiondesign.com) coupled with the GRI-Mech 3.0 reaction scheme (Smith et al., 1999). We ran PREMIX/GRI-Mech calculations of the laminar burning velocities for CH_4/H_2/air (Di Sarli and Di Benedetto, 2007), $CH_4/O_2/N_2/CO_2$ and $H_2/O_2/N_2/CO_2$ (Di Benedetto et al., 2009) mixtures. A satisfactory agreement between numerical predictions and experimental data was found.

The code, which adopts a hybrid time-integration/Newton-iteration technique to solve the steady-state mass, species and energy conservation equations, was set up to simulate a freely propagating flame with mixture-averaged formulas. In the computations, first order windward differences were used for convective terms and second order central differences for diffusion terms. The model uses a non-uniform grid that is successively and automatically adapted based on solution gradients determined on an initially coarse grid. Relative gradient and curvature parameters, which determine the extent to which the solution is refined for each case, have to be provided. In our study, these parameters for the grid refinement were set to 0.2. The total length of the calculation domain was chosen as 12 cm. Further increases in mesh resolution and domain size resulted in less than 1 cm/s difference in the calculated laminar burning velocities. For all conditions of Table 1, S_l was computed as a function of the fuel–air equivalence ratio.

2.2. Experimental set-up

Experimental tests were run using the rig schematized in Fig. 1. This rig includes a stainless steel (AISI 316SS) cylindrical chamber (volume equal to 5 dm^3; length-to-diameter ratio equal to 3; MAWP = 200 bar @ T = 350 °C).

Table 1
Conditions investigated in this work (temperature [°C], composition [% v/v]).

Conditions	T	CO	H_2	CH_4	CO_2	N_2	H_2O
1	300.0	24.0	2.0	2.0	21.0	44.0	7.0
2	300.0	55.8	2.8	0.8	26.8	6.9	6.9
3	10.0	26.2	2.2	2.2	22.2	47.2	0
4	10.0	60.0	3.0	1.0	29.0	7.0	0

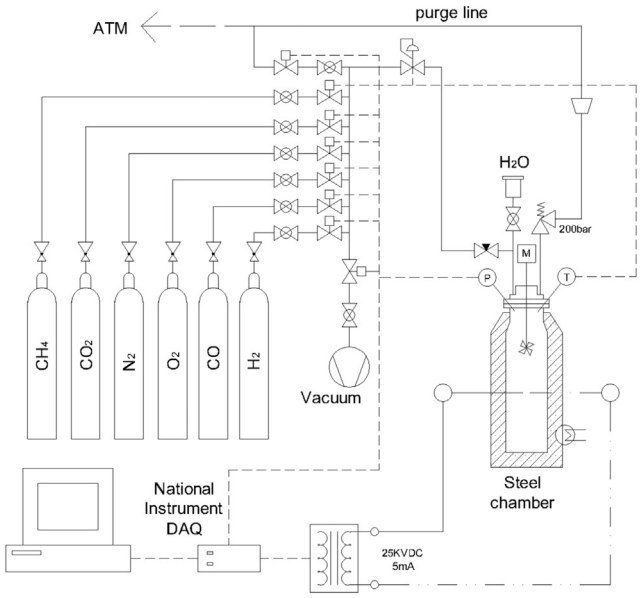

Fig. 1. Scheme of the experimental rig.

Spark ignition was provided at the center of the reactor (starting from rest) by using an electric arc produced by high-voltage power generator (25 kV, AC 5 mA). The circuit was automatically controlled by solid state relays through NI electrical board. The spark gap was set to 1 mm. A top rotating fan, moved by magnetic rotor, ensured good mixing between reactants before ignition.

For pressure measurements, a high-precision Kistler piezoelectric transducer (type 601A) was installed at the top of the vessel. A high-resolution acquisition system (up to 1 Msample/s) by National Instruments (NI USB-6251) was employed. Data were filtered by using a non-linear algorithm based on Savitzky–Golay (SG) method (21 points).

In order to obtain properly averaged results and standard deviations, each test was repeated at least 3 times.

Stoichiometric mixtures of methane in air were tested several times in the same equipment. A typical average value of maximum rate of pressure rise was found to be about 140 bar/s. When assuming the length of the vessel (0.4 m) as the characteristic length, this value agrees almost perfectly with the tabulated value for the gas deflagration index, K_G, of methane (55 bar m/s) (NFPA 68, 2002). This assumption was also made in the calculations of K_G performed in this work.

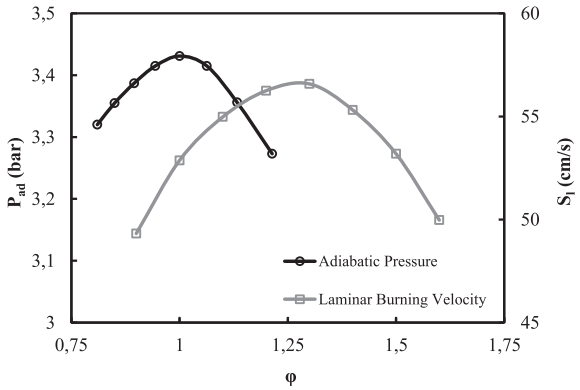

Fig. 2. Adiabatic pressure, P_{ad}, and laminar burning velocity, S_l, versus fuel–air equivalence ratio, φ, for conditions 1 of Table 1.