Experimental study of inhibition of premixed flames

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1 Introduction

The present paper describes an experimental study investigating the effect of a number of flame inhibitors and mixtures thereof on premixed propane-air mixtures.

One of the most important parameters describing premixed combustion is the laminar burning velocity. Hence in the present study study the effect the inhibitors have on the laminar burning velocity of propane-air is chosen to describe the effect of inhibitors on premixed flames. The laminar burning velocities were derived from pressure-time histories obtained in a 20-l sphere. The inhibitors investigated were injected pneumatically. The injection process causes the mixture to be turbulent. Hence the presented approach implicitly assumes that the effect of the inhibitor is similar for turbulent and laminar flames.

All inhibitors investigated are solids and are introduced as fine particles.

2 Test program and method

The tests were performed with the following flame inhibitors and flame inhibitor mixtures:

Irgafos 168 (also called Irganox 168), Irganox 1076, a mixture of Irganox 1076 and sodium bicarbonate, a mixture of Irganox 1076, Irgafos 168 and sodium bicarbonate, pure sodium bicarbonate and pure sodium chloride. Some of the flame inhibitors were crushed before use to improve their flame inhibiting properties. The particle size distribution after crushing is presented in Table 1.

The explosion vessel is an explosion resistant hollow sphere made of stainless steel, with a volume of 20 l. The vessel has a double wall. In between the walls a water jacket serves to cool the inner wall for heat generated by the explosions (initial temperature for all tests is 20 ºC). For testing, the vessel is first evacuated. The desired amount of gas is introduced via a valve and controlled by a pressure monitoring system (concentration determined on the basis of the method of partial pressures, assuming a final pressure of 1 bar). Next air is introduced until the pressure in the sphere is 0.4 bar absolute. The desired amount of flame inhibitor is dispersed into the sphere from a pressurised container via a fast acting valve and a rebound nozzle. The fast acting valve is pneumatically opened and closed by means of an auxiliary piston. After injection of the flame inhibitor the pressure in the 20-l sphere is equal to 1000 mbar.

The valves for the compressed air are activated electrically.

The ignition source is located in the centre of the sphere. Ignition is effected 60 ms after injection of the flame inhibitor started. The ignition source was a chemical igniter (ignition energy 100 J).

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The pressure measuring system includes two pressure sensors; recording and control equipment.

Table 1: Sieving analysis results for particle size distribution for some of the inhibitor compounds tested

Quantity/particle size range	**Irgafos 168 (as received)**	**Irganox 1076 (crushed)**	**Sodium bicarbonate (as received)**	**Sodium bicarbonate (crushed)**	**Sodium bicarbonate (after dispersion)**
% < 1000 µm	100	100	100	100	100
% < 500 µm	98.85	99.3	98.97	100	98.6
% < 250 µm	91.18	89.2	65.05	90.58	80.48
% < 125 µm	41.61	68.63	17.59	73.02	39.65
% < 63 µm	15.87	45.04	4.93	66.37	17.5

The extraction of laminar burning velocities from the pressure-time histories measured in the 20-l vessel is based on combustion theory.

The empirical data for turbulent combustion of gaseous mixtures gathered in [1], was summarised in a simple equation by [2]. This simple equation was reformulated in [3] as:

$$S_T = 15.1 \cdot S_L^{\,0.784} \; u'^{\,0.412}_{rms} \; \ell_I^{\,0.196}$$

where S_T = turbulent burning velocity, S_L = laminar burning velocity, u'_{rms} = turbulence intensity and ℓ_I = integral turbulence length scale.

Further on the basis of estimates of the decay of turbulence intensity [4], estimates of the turbulent integral length scale [5], a thin flame approximation can be used to estimate the laminar burning velocity from the pressure-time history at its inflection point (t_{ip}) (where effects of the strong ignition and cooling effects by the wall are expected to be minor), giving:

$$S_L(t_{ip}) = 0.0315 \cdot \left[S_T(t_{ip})\right]^{1.276} \cdot \left[u'_{rms}(t_{ip})\right]^{-0.526} \cdot \left[\ell_I(t_{ip})\right]^{-0.250}$$

According to [6] the described method results in estimates of laminar burning velocities which are approximately 5-10 % higher than established values of laminar burning velocities of hydrocarbon fuels.

3 Results

The results are presented in the form of normalised burning velocities using the respective laminar burning velocities for pure propane-mixtures as a reference value: normalised burning velocity is measured burning velocity with inhibitor divided by measured burning velocity for the respective pure propane-air mixtures.

Figure 1 presents the results of the effect of sodium bicarbonate on propane-air mixtures varying the equivalence ratio of these mixtures. The Figure shows that the effect of the inhibitor is much stronger for lean propane-air mixtures than for rich mixtures. At a relatively low inhibitor concentration (< 100 g/m^3) ignition could no longer be achieved for lean mixtures whereas for the stoichiometric composition the inhibitor concentration had to exceed 550 g/m^3 to prevent ignition. For the rich propane-air mixtures the maximum inhibitor concentration tested was 600 g/m^3. Ignition could be effected for all tested compositions. The test results clearly demonstrate a reduced chemical inhibiting effect for rich mixtures.

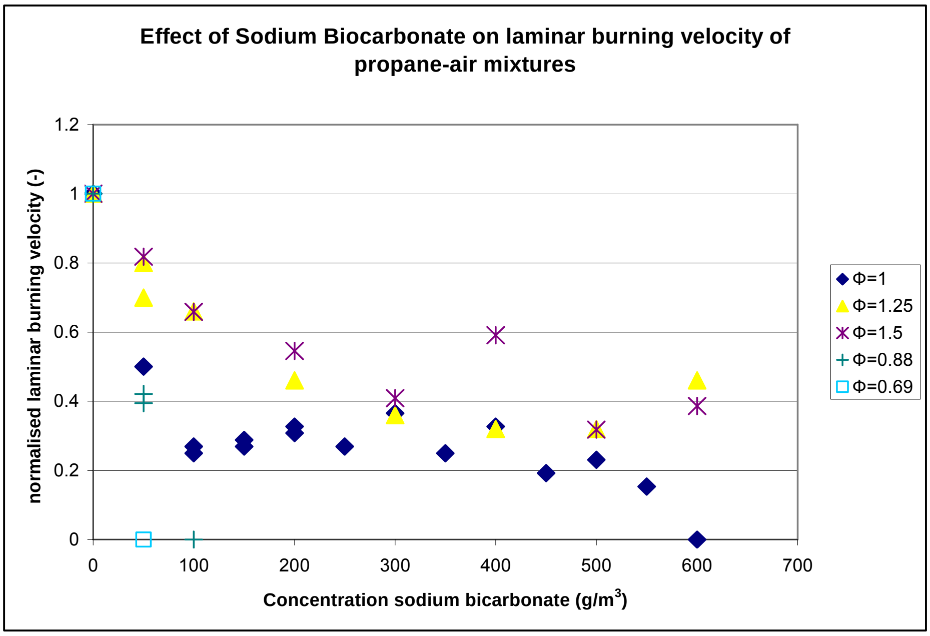

Figure 1. Effect of adding sodium bicarbonate to propane-air mixtures of different equivalence ratios on the normalised laminar burning velocity of these mixtures.

The results for sodium chloride show the same tendencies as seen for sodium bicarbonate. Sodium chloride is however a less effective inhibitor which can be seen from the higher sodium chloride concentrations necessary to achieve full flame quenching for lean propane-air mixtures and the higher normalised laminar burning velocities at similar inhibitor concentrations (measured in g/m^3). Both sodium chloride and sodium bicarbonate capture H and OH radicals. In an attempt to improve the efficacy of the inhibitors it was proposed to use a mixture of one of the aforementioned inhibitors and inhibitors capturing R· (Irgafos 168) or ROO· radicals (Irganox 1076). Both substances are well-known antioxidants and release free radicals avoiding discoloring of plastics. The effect of the pure inhibitors on stoichiometric propane-air mixtures is shown in Figure 2. Very little effect is seen for the two anti-oxidants. The main effect seen can probably be attributed to heat absorbance.

The effect of combinations of H and OH capturing inhibitors and R· or ROO· capturing inhibitors is shown in Figure 3. The Figure shows the effect of a 50 % w/w – 50 % w/w mixture of Irganox 1076 and sodium bicarbonate on the normalized burning velocity. No improvement of the efficacy of the inhibiting properties of the mixture compared to pure sodium bicarbonate is seen. Comparing the results of the inhibitor mixture to results of pure sodium bicarbonate for the same sodium bicarbonate concentration one can note an impeding effect of adding Irganox to the flame inhibitor mixture, i.e. adding Irganox 1076 causes sodium bicarbonate to be a less effective flame inhibitor. Similar observations were made for a mixture of 50 % w/w sodium bicarbonate, 25 % w/w Irganox 1076 and 25 % w/w Irgafos 168.

3 Discussion

The effect of equivalence ratio on the effectiveness of flame inhibitors has so far been shown to be limited [6]. In the present study however a big difference is seen. All previous studies on the effect of equivalence ratio on the effectiveness of flame inhibitors were however performed for laminar premixed flames. The combustion from which laminar burning velocities are derived in the present study is turbulent. Strain and quenching by turbulence therefore seems to be contributing to the effectiveness of flame inhibitors. Considering the main reactions occurring for lean and rich propane-air mixtures especially the reaction CO + OH = CO_2 + H seems to loose influence [7]. A comparison of a typical chemical induction time and the lifetime of turbulent eddies as suggested by [8] to estimate the relative importance of turbulence on the combustion rate shows typical values of respectively 5.10^{-4} s and 0.01 s respectively indicating that turbulent strain would not have a big influence on the combustion and that other parameters need to considered as well.

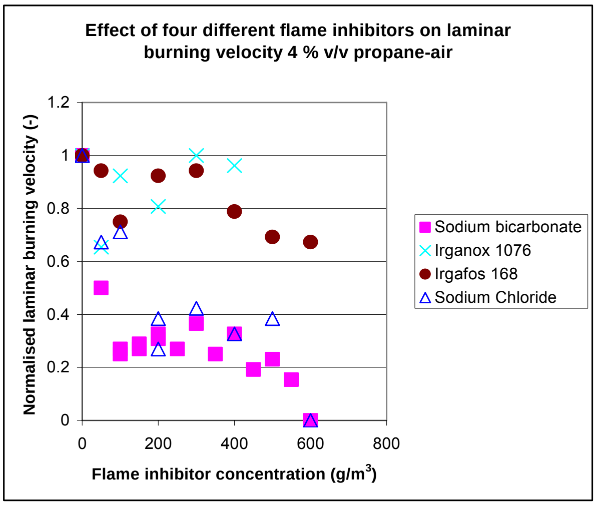

Figure 2. Effect of adding sodium bicarbonate, sodium chloride, Irganox 1076 and Irgafos 168 to 4 % v/v propane-air mixtures.

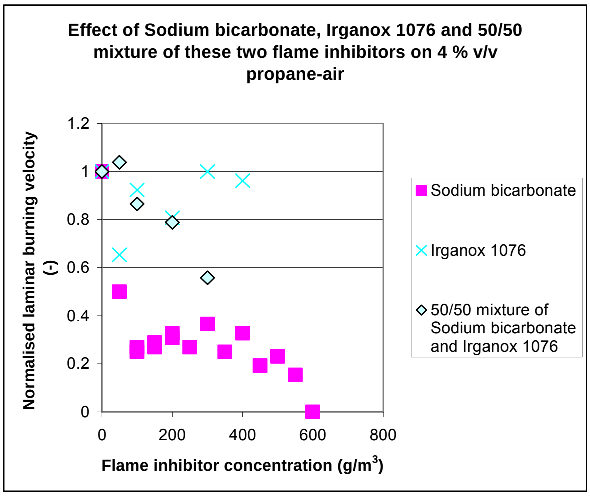

Figure 3. Effect of adding a 50 % w/w – 50 % w/w mixture of sodium bicarbonate and Irganox 1076 to 4 % v/v propane-air mixtures.

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