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The rate of pressure rise of gaseous propylene–air explosions in spherical and cylindrical enclosures

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Abstract

The maximum rates of pressure rise of propylene–air explosions at various initial pressures and various fuel/oxygen ratios in three closed vessels (a spherical vessel with central ignition and two cylindrical vessels with central or with top ignition) are reported. It was found that in explosions of quiescent mixtures the maximum rates of pressure rise are linear functions on total initial pressure, at constant initial temperature and fuel/oxygen ratio. The slope and intercept of found correlations are greatly influenced by vessel's volume and shape and by the position of the ignition source — factors which determine the amount of heat losses from the burned gas in a closed vessel explosion. Similar data on propylene–air inert mixtures are discussed in comparison with those referring to propylene–air, revealing the influence of nature and amount of inert additive. The deflagration index K_G of centrally ignited explosions was also calculated from maximum rates of pressure rise.

Keywords: Explosion; Closed vessel; Rate of pressure rise; Deflagration index; Propylene combustion; Inert additive

1. Introduction

The maximum rate of pressure rise during a closed vessel explosion, $(\mathrm{d}p/\mathrm{d}t)_{\max}$, is defined as the highest value of pressure rise rate observed at a given fuel concentration, under specific initial temperature and pressure conditions [1]. Besides the explosion pressure, the maximum rate of pressure rise is one of the most important safety parameters for assessing the hazard of a process and for design of vessels able to withstand an explosion or of vents used as relief devices of enclosures against damages produced by gaseous explosions [2–5].

Maximum rates of pressure rise are used for calculating the severity factor (or "deflagration index") K_G, of gas explosions in enclosures:

$$K_G = \sqrt[3]{V}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_{\max} \quad (1)$$

defined by analogy to the severity factor of dust–air explosions, K_{st}, introduced by Bartknecht and Zwahlen [2]. For practical purposes, it was assumed that K_G is constant regardless of spherical vessel's volume V, depending only on the composition of fuel–oxidant mixture [2,3] so that K_G of gas mixtures at standard temperature and pressure may be used for scaling explosions in such vessels. Experimental evidence has shown that K_G increases much more as Eq. (1) accounts for, when V increases [3], but it is still a flammability index of wide interest.

Maximum rates of pressure rise in closed vessel explosions are influenced by the composition, pressure and temperature of the fuel–air mixture (factors which determine the rate of heat release) and by the volume and shape of the enclosure, the ignition source size, energy and position, the pre-existing or combustion-created turbulence (factors which determine the amount of generated heat as well as the amount of heat losses during flame propagation) [6–10].

The explosion pressure and the flame temperature of constant volume combustion can be determined by computation, based only on initial flammable mixture composition, pressure and temperature, assuming the flame propagation is adiabatic. In contrast, the maximum rate of pressure rise is not ready to be calculated without knowledge of heat release and heat transfer

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Nomenclature

h	height
K	deflagration index
p	pressure
S	burning velocity
t	time
T	temperature
V	volume

Subscripts

f	referring to flame
G	referring to gas
max	maximum value
s	referring to spherical vessel S
u	unburned gas
v	referring to spherical vessel V
0	referring to the initial state of mixture

Greek symbols

γ	adiabatic coefficient
μ	thermic exponent of burning velocity
ν	baric exponent of burning velocity
φ	equivalence ratio
Φ	diameter

rates from flame in various moments of its propagation. Earlier attempts of modelling the flame propagation inside a closed constant volume vessel were successful in predicting the peak pressure of explosion, but failed to predict the time to peak pressure and the rate of pressure rise in various stages of the process [11–14]. Later on, the development of comprehensive computer packages afforded accurate predictions of pressure evolution during explosions in enclosures in all stages, including those where the flame is close to the walls [15,16]. Some other studies were focused on modelling the flame propagation during the closed constant volume vessel, in order to compute the laminar burning velocity from the rate of pressure rise [16–18]. In a recent publication [19], adiabatic values of deflagration index $(K_G)_{max}$ were calculated for several reference fuel–air mixtures using a one-parameter correlation, based on the linear relationship derived by Lewis and von Elbe between the fraction of mass burned and pressure [20]. Such “upper limit values” are quite useful for practical purpose.

Many articles report experimental values of maximum rates of pressure rise and/or explosion index from measurements on homogeneous gaseous mixtures in spherical and in cylindrical enclosures [4,6–11,21–26]. Published data refer mainly to H_2–air [9,10], CH_4–air [2,4,9,10,16,23,25,26] and C_3H_8–air mixtures [9–11], but also to ethylene–air [9] and fluorinated derivatives of methane–air and ethylene–air [24,25] mixtures. Data were obtained in spherical vessels with various volumes, e.g. $V = 4.2$ L [25]; 5 L [2]; 20 L [4,10,16]; 40 L [26]; 120 L [10] and even 25 m^3 [6,7], in cylindrical vessels with low L/D ratio [10,11,26] or in elongated cylinders [8,9,23].

Such information is completed by the data in the present article: values of maximum rate of pressure rise and explosion index of propylene–air mixtures at various initial pressures and various fuel/oxygen ratios in three closed vessels: a spherical vessel with central ignition and two cylindrical vessels with central or top ignition. For several propylene–air mixtures, the adiabatic explosion index was calculated and compared to values derived from measurements in the spherical and cylindrical vessels with central ignition. Results on explosions of propylene–air mixtures in the presence of various amounts of argon, carbon dioxide and exhaust gas of propylene in air (burned gas from previous explosions) are also given and discussed, in connection to the nature and amount of additive.

2. Experimental

The experimental set-up contains a vacuum and gas-feed line, which interconnects the vacuum pump, the gas cylinders with fuel and air, the metallic cylinder for mixture storage and the explosion vessels. The vacuum pump maintains a vacuum of 0.1 mbar in the explosion vessel, after each experiment. The gas-feed line is tight at pressures between 0.1 mbar and 1.50 bar. More details were recently given [27,28].

Fuel–air, fuel–air inert and fuel–oxygen inert mixtures were obtained by the partial pressure method in gas cylinders and were used 24 h after mixing the components, at a total pressure of 4 bar. Propylene–air mixtures diluted with their own exhaust gas were prepared directly in the explosion vessel, according to the following steps: (a) the propylene–air mixture was admitted at a desired pressure then ignited and allowed to become quiescent; (b) the burned gas was evacuated down to the required partial pressure; (c) fresh propylene–air mixtures was added into the vessel and the new mixture (fuel–air + exhaust gas) was allowed 20 min to become homogeneous. After igniting and capturing the signals of the acquisition system, the burned gas was completely evacuated. A new cycle consists of burning the fuel–air mixture, evacuating the burned gas at a different partial pressure and preparing a new (fuel–air) + exhaust gas by adding fuel–air.

Experiments were performed in three explosion vessels, tight at vacuum and at pressures up to 40 bar: vessel S — a spherical vessel with the radius $R = 5$ cm; vessel C – a cylinder with $h = 15$ cm and $\Phi = 10$ cm and vessel V – a cylinder with $h = \Phi = 6$ cm. In vessel V only a limited number of experiments was made, using a stoichiometric propylene–air mixture. The initial pressure of explosive mixtures was measured using a strain gauge manometer Edwards EPSA-10HM.

Ignition was made with inductive–capacitive sparks produced between stainless steel electrodes by a standard auto induction coil; the spark gap was usually located in the geometrical centre of the vessel. Vessel C was fitted with a supplementary pair of electrodes, able to produce sparks 5 mm below the centre of the top lid. Both vessels S and C were equipped with an ionization probe used to monitor the arrival time of the flame front, mounted in equatorial position. The tip of an ionization probe was usually mounted 5 mm away from the wall. The sparks triggered the time-base of the acquisition system, by means of a low voltage signal.