Contents lists available at ScienceDirect

Process Safety and Environmental Protection

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

Propagation of ethylene–air flames in closed cylindrical vessels with asymmetrical ignition

C. Movileanu*, V. Gosa, D. Razus

"Ilie Murgulescu" Institute of Physical Chemistry, 202 Spl. Independentei, Bucharest, Romania

ARTICLE INFO

Article history:
Received 13 February 2015
Received in revised form 21 May 2015
Accepted 22 May 2015
Available online 3 June 2015

Keywords:
Explosion
Elongated closed vessel
Bottom ignition
Ethylene
Flame
Pressure oscillations

ABSTRACT

A study of explosions in several elongated cylindrical vessels with length to diameter $L/D = 2.4$–20.7 and ignition at vessel's bottom is reported. Ethylene–air mixtures with variable concentration between 3.0 and 10.0 vol% and pressures between 0.30 and 1.80 bara were experimentally investigated at ambient initial temperature. For the whole range of ethylene concentration, several characteristic stages of flame propagation were observed. The height and rate of pressure rise in these stages were found to depend on ethylene concentration, on volume and asymmetry ratio L/D of each vessel. High rates of pressure rise were found in the early stage; in later stages lower rates of pressure rise were observed due to the increase of heat losses. The peak explosion pressures and the maximum rates of pressure rise differ strongly from those measured in centrally ignited explosions, in all examined vessels. In elongated vessels, smooth $p(t)$ records have been obtained for the explosions of lean C_2H_4–air mixtures. In stoichiometric and rich mixtures, pressure oscillations appear even at initial pressures below ambient, resulting in significant overpressures as compared to compact vessels. In the stoichiometric mixture, the frequency of the oscillations was close to the fundamental characteristic frequency of the tube.

1. Introduction

Closed vessel explosions of fuel–air gaseous mixtures are characterized by specific parameters: the peak explosion pressure, the time to peak explosion pressure, the maximum rate of pressure rise, the propagation speed and the normal burning velocity described by European Standard (2003). These characteristic flammability properties depend on initial composition, pressure and temperature of the flammable mixture, on vessel's form and volume, on ignition source position and energy. Their measurement allows the assessment of explosion risks for flammable mixtures in various conditions and the formulation of safety recommendations against the damaging effect of such explosions. At the same time, the characteristic parameters of confined deflagrations are necessary input data for venting systems design and for modeling the flame propagation in various conditions.

Specific features appear when the deflagration takes place in elongated vessels, such as chemical reactors or pipes connecting fuel tanks. Kirkby and Wheeler (1928) reported data on CH_4–air flame propagation in a tube of $L/D = 20$ with end ignition, in comparison with a sphere with central ignition; they showed that the average flame speed was higher in the pipe. Markstein (1964) was the first to point out that three different stages can be observed during flame propagation in elongated closed vessels; the pressure evolution has specific features in each of these periods, characterized by different flame speeds. Leyer (1970) examined the flame propagation of propane–air mixtures of variable strength in closed elongated vessels with various L/D between 1 and 19 discussing the appearance of instabilities and cellular flame structure. Experiments of Starke and Roth (1986) involving photographic recordings of flame propagation and flame shape of C_2H_2–air mixtures, and measurements of pressure and flow velocities

* *Corresponding author*. Tel.: +40 21 3167912; fax: +40 21 3121147.
E-mail addresses: cmovileanu@icf.ro, crinamov@yahoo.com (C. Movileanu).
http://dx.doi.org/10.1016/j.psep.2015.05.008

Nomenclature

a	surface area (m^2)
c	specific heat ($J\,mol^{-1}\,K^{-1}$)
D	diameter (m)
L	length (m)
m, n	slope and intercept of linear correlation $p_{max} = m \cdot p_0 - n$
N	mole number (–)
p	pressure (bar)
q	heat amount (J)
R	universal gas constant ($J\,mol^{-1}\,K^{-1}$)
S	velocity ($m\,s^{-1}$)
t	time (s)
T	temperature (K)
V	volume (m^3)

Greek

γ	adiabatic coefficient
Δ	variation
θ	time (s)
υ	frequency (Hz)

Subscripts, superscripts

d	adiabatic value
end	end value
exp	(measured) value
max	maximum value
p	isobaric process
0	initial value
tr	transferred
V	isochoric process

offered an important support for understanding the mechanism of "tulip" formation for these flames. Measurements of the flow field of the combustion generated flow, described by Dunn-Rankin (2009), suggested that the flame behaves as a fluid mechanical discontinuity, deflecting the gas passing through it. As the flame quenches at the side walls of the vessel, the flow deflection generates a vortex in the burned gas which remains near the flame front, modifying the unburnt gas field. As a consequence the flame propagates more quickly near the wall than at the center, getting the characteristic 'tulip' front. Phylaktou et al. (1990) and Phylaktou and Andrews (1991) studied the deflagrations of several fuels (CH_4, C_3H_8, C_2H_4 and H_2) in air using tubes of large L/D between 6.2 and 21.6. They found that the pressure rise observed in the first stage has a short duration (5–10% of the total explosion time) and the high rate of pressure rise in this stage is related to the highest mean flame speed, characteristic of deflagrations in pipes. Other features of fuel–air deflagrations in tubes with asymmetrical ignition were outlined by Fairweather et al. (1999), Kindracki et al. (2007), Cammarota et al. (2009), and Xiao et al. (2011, 2012, 2013a): (a) with the increase of L/D for pipes with same diameter, the maximum explosion pressure decreases, but the maximum flame speed and the position where it occurs increase proportionally; (b) the decrease of the maximum pressure, observed in experiments with ignition at the end of tube, is due to a longer time of the heat exchange between hot combustion products and vessel walls.

Numerical simulations of fuel–air flames propagating in elongated vessels were performed by Bielert and Sichel (1998) and Bi et al. (2012) for methane–air flames (data from Kindracki et al. (2007)), and by Bychkov et al. (2007) for propane–air flames (data from Clanet and Searby, 1996). Other recent publications of Xiao et al. (2011, 2012), Dunn-Rankin (2009), Zhang et al. (2013), and Mat Kiah and Kasmani (2014) examine the flame propagation in tubes, paying attention to the appearance of the characteristic tulip flame. The propagation of flames in elongated vessels was examined by Ciccarelli and Dorofeev (2008) in connection with the Deflagration-to-Detonation Transition (DDT), a process frequently met in such conditions.

Explosions in oxygen-enriched air of CH_4 or of syngas (H_2/CO) in the presence of CO_2 in an elongated vessel were examined by Di Benedetto et al. (2011) and Salzano et al. (2012) in connection with an anomalous behavior named "combustion-induced Rapid Phase Transition" (c-RPT). In these experiments, the oscillating pressure–time histories were analyzed and assigned to the cycles of condensation and vaporization (at the vessel walls) of the water produced during combustion.

The present paper reports data for asymmetrically ignited explosions (at vessel's bottom) of ethylene–air propagating in several closed vertical cylindrical vessels, at ambient initial temperature and various initial pressures. Ethylene, used for production of important compounds such as ethylene oxide, 1,2-dichloroethane or polyethylene, was chosen due to explosion hazards associated with its mixtures with air, oxygen or other oxidizers.

Explosions of gaseous ethylene–air mixtures in enclosures were studied under various conditions: in spherical and in cylindrical vessels, at initial pressures from 1 to 20 bar and initial temperatures from 20 to 200 °C, using mixtures with variable ethylene concentration within the flammable range. Crescitelli et al. (1977) examined the pressure rise during deflagrations of near-limit ethylene–air mixtures in experiments performed in a 14 L spherical vessel. Phylaktou et al. (1990) studied the propagation of C_2H_4–air flames in a tube of $L/D = 21.6$ with side ignition and reported the rates of pressure rise and the flame speeds in various stages of flame propagation. Explosion characteristics of the stoichiometric ethylene–air mixture was studied by Amyotte et al. (2002) in a 26 L cylindrical vessel (closed or vented) at various initial pressures and turbulence levels. Other results on ethylene–air explosions in closed vessels at initial pressures of 1–10 bar, initial temperatures of 20–200 °C were recently obtained during the European project SAFEKINEX (Holtappels, 2006). Movileanu et al. (2011) studied the influence of inert additives on flammability indices for explosions of stoichiometric ethylene–air diluted with Ar, N_2 or CO_2 in a spherical and a cylindrical vessel with $L/D = 1.5$. Ethylene–air explosions in elongated vessels with L/D between 1.0 and 2.4 and central ignition were experimentally investigated at ambient initial temperature and various initial pressures of 0.2 and 1.1 bar by Movileanu et al. (2012).

The present paper details asymmetrically ignited explosions of ethylene–air and reports maximum explosion pressures, explosion times and maximum rates of pressure rise reached in closed cylindrical vessels with L/D between 2.4 and 20.7. The experiments were performed at ambient initial temperature and various initial pressures of 0.3–1.8 bara. The results are compared to data on centrally ignited explosions in the same vessels, within the same range of initial pressure. All data are examined in correlation to the initial pressure and composition of ethylene–air mixtures and with