Process Safety and Environmental Protection 117 (2018) 190–199

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

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

Mitigation effects on the explosion safety characteristic data of ethanol/air mixtures in closed vessel

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ARTICLE INFO

Article history:
Received 17 January 2018
Received in revised form 21 April 2018
Accepted 30 April 2018
Available online 3 May 2018

Keywords:
Ethanol
Additive/inert
Explosion
Safety characteristic data
Burning velocity

ABSTRACT

This paper presents new results of an experimental study on the explosion characteristics: the explosion pressure, the rate of pressure rise (or the deflagration index), the explosion delay time and the laminar burning velocity for ethanol/air mixtures with ethanol concentrations between 3.5 vol% and 20.0 vol% in the presence of various diluents (nitrogen, exhaust gas, water and carbon dioxide with dilution concentrations from 0 vol% to 20 vol%), at various initial pressures from 0.25 bar to 1.0 bar and at an initial temperature of 373 K. The influence of the diluent type and amount on the explosion characteristics is examined together with the influence of the initial pressure. The effectiveness of the diluent gases examined varies from least effective to most effective in the following order: N_2, exhaust gas, H_2O, CO_2. The reported data in this paper (the explosion characteristics and the laminar burning velocity) of ethanol-air mixtures in the presence of various diluents are important safety parameters, useful for design of active protection devices and for safety recommendations.

1. Introduction

Due to the decrease of the world's petroleum reserves along with concerns of the environmental aspect of greenhouse gas emissions reduction, interest in alternative fuels is growing. Ethanol, as an alternative to petroleum-based fuels, offers long-term fuel-source regenerability, as "bio" ethanol is produced by fermenting different biomasses. Ethanol will make it possible to reduce dependence on fossil fuels and may have a reduced environmental impact due to its "neutral" CO_2 balance. The performance and emissions of gasoline engines fueled by ethanol/gasoline blends have been investigated in (Dardiotis et al., 2015; Serras-Pereira et al., 2013; Suarez-Bertoa et al., 2015; Wang et al., 2015).

Ethanol combustion was investigated using different experimental techniques and in mechanistic studies (Egolfopoulos et al., 1992; Frassoldati et al., 2010; Gerasimov et al., 2012; Leplat et al., 2011; Norton and Dryer, 1992; Saxena and Williams, 2007; Tran et al., 2013; Veloo et al., 2010). Important safety characteristics (flammability limits, explosion pressures, laminar burning velocities) have been reported for ethanol/air mixtures at various initial temperatures and pressures (Beeckmann et al., 2014; Brooks and Crowl, 2007; Eisazadeh-Far et al., 2011; Gülder, 1982; Li et al., 2015; Liao et al., 2007; Konnov et al., 2011; Mitu and Brandes, 2017), for ethanol/gasoline blends (flammability limits, auto ignition temperature, explosion points and maximum safe gap) (Brandes et al., 2006) and blends with ammonia and hydrogen (Cammarota et al., 2012; Cammarota et al., 2015). Studies on laminar burning velocities of ethanol/water/air mixtures have been carried out using the heat flux method (Haas-Wittmuss and Hermanns, 2015) or a constant-volume combustion chamber (Liang et al., 2014). Studies on laminar burning velocities of ethanol/air mixtures diluted with N_2 and CO_2 have been reported by Eisazadeh-Far et al. (2011) using constant-volume vessels. Tran et al. (2013) presented an experimental study of the structure of laminar premixed flames of ethanol/methane/oxygen/argon using a McKenna burner. While Yap et al. (2005) investigated bioethanol in homogeneous charge compression ignition (HCCI) combustion, Qi et al. (2010) used a direct injection compression ignition engine to investigate the combustion and emission characteristics of ethanol/biodiesel/water micro-emulsions. A study on the effects of exhaust gas recirculation (EGR) and its constituents on the HCCI autoignition of ethanol was presented by Sjoberg and Dec (2011).

The hazard of gas explosions widely exists in industry, during handling and transportation and with processes related to flammable gases and liquids. Knowledge of the explosion characteristics is therefore important for industry. The addition of inert

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https://doi.org/10.1016/j.psep.2018.04.024

Nomenclature

dm/dt	Mass reaction rate
dp/dt	Explosion pressure rise
p	Pressure (bar)
T	Temperature (K)
K	Deflagration index
K_k	Coefficient of nitrogen equivalency
r	Radius
S	Burning velocity (cm/s)
t	Time (s)
V	Volume (L)
R_n^2	Regression coefficient

Greek letters

φ	Volume fraction undiluted mixtures
θ	Time to peak pressure
γ	Volume fraction diluted mixture
λ	Heat conductivity
ρ	Density of the mixture
c_p	Specific heat capacity

Subscripts

0	Initial value
b	Referring to burned mixture
ex	Explosion
G	Referring to gas explosions
max	Maximum value
u	Referring to burning velocity

components to fuel–air mixtures can be used to mitigate and even suppress their explosive properties. Experimental and theoretical studies on explosion mitigation methods by adding inert gases were amongst others conducted by (Ma et al., 2010; Mitu et al., 2018; Wang et al., 2014; Zhang et al., 2014; Zeng et al., 2015).

This work addresses the explosion characteristics like explosion pressures, rates of pressure rise, explosion delay time, laminar burning velocity and deflagration index of ethanol/air mixtures diluted by nitrogen, carbon dioxide, water vapor and exhaust gas. The maximum explosion pressures, the maximum rates of pressure rise, the explosion delay time and the deflagration index are important values for explosion vent design (NFPA68, 1998; Razus and Krause, 2001), for the explosion protection measure "constructive explosion protection" such as explosion proof design (Brandes et al., 2004) and for the characterization of explosion transmission between connected vessels (Di Benedetto et al., 2005; Ferrara et al., 2005; Razus et al., 2003). The laminar burning velocity is a key property for modeling the combustion optimization of internal combustion engines, and is an important parameter in many areas of combustion science (e.g. design of burners and the prediction of explosions).

These explosion characteristics are investigated systematically over a wide range of ethanol concentrations (3.5 mol%–20.0 mol%), dilutions with N_2, H_2O, CO_2 and exhaust gases up to 20 vol% at various initial pressures (0.25 bar[1]–1.0 bar) and at 373 K initial temperature.

The dilution agents are compared and the mitigating effect of the diluents is discussed.

[1] The pressures are expressed in bar absolute.

2. Experimental details

2.1. Experimental setup

The experiments were performed in accordance with EN 15967 (2011). The experimental set-up, as given previously by Mitu and Brandes (2015), is schematically shown in Fig. 1. The experimental set-up consists of a pressure-tight 20 L explosion vessel (30 bar), an evaporator tube to evaporate the liquids, a mixing vessel to homogenize the vapor/air mixture, metering devices for ethanol, air and diluent, a heating chamber, a pressure-measuring system, a data acquisition system and a vacuum pump. A series of induction sparks between two stainless-steel electrodes (diameter: 1 mm; angle of the pointed tips: $60° \pm 3°$; distance between the tips: 5 mm ± 0.1 mm) ending at the center of the vessel was used as the ignition source. A high voltage transformer, with a root mean square of 13 kV–16 kV and a short circuit current of 20 mA–30 mA, is used for producing the ignition spark. The primary winding of the high voltage transformer is connected to the mains via a timer set to a discharge time of 0.2 s. The power of such an arrangement depends on the gas mixture and initial pressure. In air at atmospheric conditions, such an arrangement gives a power of approximately 10 W (EN 15967, 2011).

2.2. Systems investigated

Ethanol (99.9%)
Inert gas: N_2 (>99.8%) and CO_2 (>99.5%)
Water: deionized water
Exhaust gas: burned mixture after ignition. Its qualitative and quantitative composition differs at least between lean, stoichiometric and rich ignited ethanol/air mixtures. Assuming the reaction runs through the whole mixture the qualitative composition of lean mixtures consist of N_2, CO_2, H_2O, O_2, that of stoichiometric consist of N_2, CO_2, H_2O and that of reach consists of N_2, CO_2, H_2O, CO, partly oxygenated components and probably H_2. Detailed information on the quantitative composition is not available.
Initial temperature of $T_0 = 373$ K
Initial pressures p_0 between 0.25 bar and 1.0 bar
Ethanol concentration between 3.5 vol% and 20.0 vol%
Diluent concentration: 5 vol%, 10 vol%, 15 vol%, 20 vol%

2.3. Experimental procedure and conditions

Ethanol and ethanol + water was metered by a volumetric pump and evaporated using an evaporator tube. Air and the diluents N_2 and CO_2 were metered by using mass-flow controllers.

For the experiments with water vapor, the ethanol was mixed with the necessary amount of water as a liquid.

Ethanol/(air + exhaust) mixtures were prepared directly in the explosion vessel by retaining a portion of the combustion products (5%, 10%, 15% or 20% of the final starting pressure) of a previous explosion from a pure ethanol/air mixture and then adding the ethanol/air mixture. Before the experiments without exhaust were performed, the combustion vessel was flushed with air to ensure that no combustion products remained from the previous experiment. After ignition of the ethanol/(air + exhaust) mixture, the burned gas was completely evacuated. A new cycle followed: pure ethanol/air, ignition, partial evacuation, fresh ethanol/air admission, ignition, total evacuation. As previous experiments showed, potential solid residue is formed like a 'cover' on the surface of the vessel and not as a 'free floating' soot. The 'cover' has no influence on the mixture composition of the following experiment.