CO$_2$ EFFECT ON THE FLAME VELOCITY IN GASEOUS FLAMMABLE MIXTURES. PRELIMINARY TESTS ON STOICHIOMETRIC ETHYLENE-AIR MIXTURE

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abstract: Paper presents several tests regarding the effect of CO$_2$ on the flame propagation in stoichiometric ethylene-air mixture, at atmospheric and subatmospheric initial pressures. Results are discussed and compared with literature data. The apparent activation energy of the propagation process is also determined in the presence of CO$_2$ (526 kJ/mol).

1. Introduction

There has been a great interest regarding the precautions that have to be paid against accidental explosions; authorities issued reports and thoroughly discussed the implementation of safety rules in central and eastern European countries, in light of their admission within European Union [1]. These precautions fall into two categories, namely *prevention* and *protection*. The preventive actions are meant to ensure that the conditions under which an explosion becomes possible never occur and the protective ones aim to minimize the effects of explosions that it is assumed will occur [2].

The use of inert diluents, as CO$_2$, in gaseous environments that exhibits explosive hazard, is one prevention method, and it aims both to reduce the oxidant content bellow necessary requirements to support combustion and to take over the excess of energy dissipated by the chemical reaction.

The paper presents some work in progress results on how CO$_2$ affects the flame velocity of ethylene-air mixture.

2. Experimental

Stoichiometric (6.54 vol%) ethylene-air mixtures with CO$_2$ addition between 0 and 16 vol% have been prepared based on partial pressures additivity. Ethylene (99.97% purity) has been purchased from SIAD RG Italy. Air was provided using a compressor type HP 1.5 made by OMA Compressori Italy.

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The explosion cell [3,4] was fitted with an ionisation gauge that was placed at a small distance, r_{gauge}, from the spark gap, monitoring the flame propagation. The space velocity of the flame was calculated by the following approximation:

$$S_s = \frac{dr}{dt} \cong \frac{r_{gauge}}{t_{flame}} \tag{1}$$

assuming that in the early stage of explosion, the process is still isobaric; t_{flame} is the time from the explosion initiation to the maximum of the ionisation gauge signal.

The normal burning velocity, S_u, is then calculated based on:

$$S_u = \frac{1}{E_0} \cdot \frac{dr}{dt} \tag{2}$$

where E_0 represents the expansion factor, at initial constant pressure, that has been evaluated from the thermodynamic properties of each mixture [5]. The measurements were made at initial ambient temperature, and atmospheric and subatmospheric initial pressures.

3. Results and Discussion

Table 1 presents the experimental burning velocities for ethylene-air system of stoichiometric concentration (6.54 vol% of ethylene in air), at various initial pressures, with CO_2 addition ranging from 0 to 16 vol%.

The first observation is that, at ambient initial conditions, an addition of CO_2 higher than 10 vol% significantly affects the burning velocity, decreasing it four times, and at the highest CO_2 addition covered by this investigation (e.g. 16%) the burning velocity almost reaches the transition to self-quenching condition (below 0.05 m/s).

Table 1. Influence of CO_2 addition to normal burning velocities, S_u, for stoichiometric ethylene-air mixture, at atmospheric and subatmospheric initial pressures, p_i

% CO_2	t_{flame} (s)	S_s (m/s)	E_0	S_u (m/s)
		p_i = 101.3 kPa		
0	0.0059	3.27	8.06	0.41
4	0.0076	2.55	7.79	0.33
8	0.0184	1.06	7.51	0.14
12	0.0207	0.94	7.23	0.13
16	0.0362	0.54	6.95	0.08
		p_i = 81.3 kPa		
0	0.0113	1.72	8.06	0.21
4	0.0174	1.12	7.79	0.14
8	0.0228	0.85	7.51	0.11

% CO$_2$	t_{flame} (s)	S_s (m/s)	E_0	S_u (m/s)
12	0.0331	0.59	7.23	0.08
16	0.0465	0.42	6.95	0.06
		$p_i = 71.3$ kPa		
0	0.0134	1.45	8.06	0.18
4	0.0163	1.19	7.79	0.15
8	0.0231	0.84	7.51	0.11
12	0.0318	0.61	7.23	0.08
16	0.0465	0.42	6.95	0.06
		$p_i = 61.3$ kPa		
0	0.0131	1.48	8.06	0.18
4	0.0184	1.05	7.79	0.14
8	0.0244	0.79	7.51	0.11
12	0.0344	0.56	7.23	0.08
16	0.0476	0.41	6.95	0.06
		$p_i = 51.3$ kPa		
0	0.0162	1.20	8.06	0.15
4	0.0163	1.19	7.79	0.15
8	0.0234	0.83	7.51	0.11
12	0.0294	0.66	7.23	0.09
16	0.0355	0.55	6.95	0.08
		$p_i = 41.3$ kPa		
0	0.0149	1.30	8.06	0.16
4	0.0124	1.57	7.79	0.20
8	0.0197	0.98	7.51	0.13
12	0.0221	0.88	7.23	0.12
16	0.0244	0.79	6.95	0.11
		$p_i = 31.3$ kPa		
0	0.0165	1.18	8.06	0.15
4	0.0195	1.00	7.79	0.13
8	0.0167	1.17	7.51	0.16
12	0.0160	1.21	7.23	0.17
16	0.0305	0.64	6.95	0.09
		$p_i = 21.3$ kPa		
0	0.0174	1.12	8.06	0.14

% CO_2	t_{flame} (s)	S_s (m/s)	E_0	S_u (m/s)
4	0.0163	1.19	7.79	0.15
8	0.0197	0.98	7.51	0.13
12	0.0195	1.00	7.23	0.14
16	0.0281	0.69	6.95	0.10

The second observation is that as one moves towards lower initial pressures, the effect of CO_2 decreases in amplitude, so that at 21.3 kPa, it shows a rather insignificant effect on the burning velocity. This behaviour is somewhat as expected because, at very low initial pressures, the gaseous mixture is more disperse, so that the role of CO_2 as diluting agent do not affect significantly the propagation behaviour.

When compared with literature data one mentions that, at atmospheric initial pressure, the normal burning velocity is almost twice smaller than that reported by Gibbs and Calcote [7], 0.68 m/s, or Gunther and Janisch [8], 0.78 m/s, using Bunsen burner method.

A possible explanation of this difference could originate in the flame stretch, a significant process in the early stages of spherical flame propagation [9,10]. Also, another explanation is the existence of an induction time necessary to obtain the minimal flame.
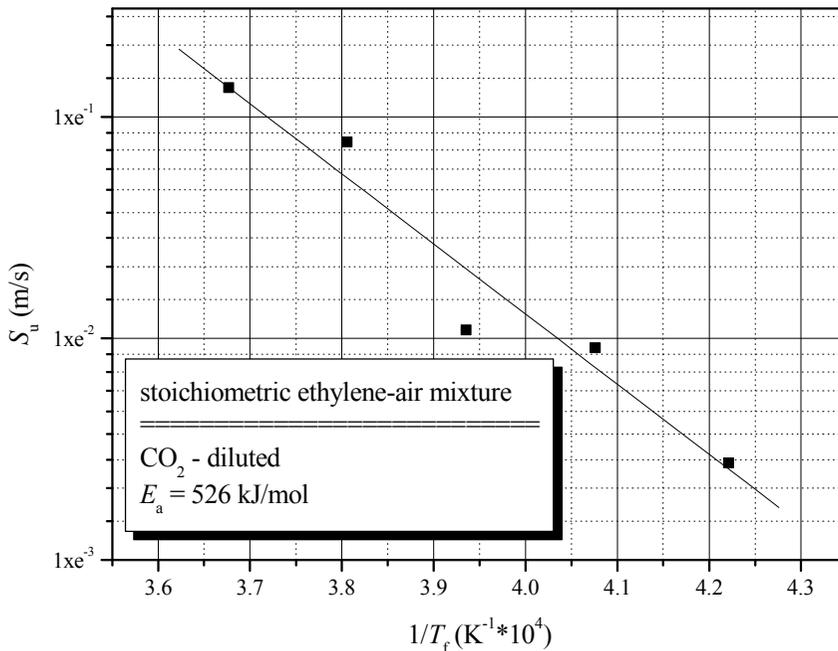

Fig. 1. *Flame temperature dependence of the normal burning velocity;*
initial pressure 101.3 kPA; initial temperature 298 K; semilogarithmic scale.

Based on previous research [3,6] the burning velocity dependence on the adiabatic flame temperature, T_f, can be used to evaluate the overall activation energy of the flame propagation process, using the dilution method:

$$S_u \ \sim \ f_1\left(T_{flame}\right) \cdot \mathrm{e}^{-\frac{E_a}{2RT_{flame}}} \tag{3}$$

where E_a represents the apparent activation energy, in J×mol^{-1}, R is the gas law constant, in J×mol^{-1}×K^{-1}, T_{flame} is the adiabatic flame temperature, in K, and $f_1\left(T_{flame}\right)$ is an intricate function of the T_{flame}. The adiabatic flame temperature has been also calculated from the thermodynamic data [5]. For T_f ranging from 1700 K to 2500 K, $f_1\left(T_{flame}\right)$ does not vary as much as the exponent in eqn. (3), so that the semilogarithmic dependence:

$$\ln S_u = f\left(T_{flame}^{-1}\right) \tag{4}$$

gives the possibility of evaluating E_a.

Fig. 1 shows the flame temperature dependence of the normal burning velocity at ambient initial temperature and pressure, with CO$_2$ addition in the range taken into consideration by this paper. The value reported herein is 526 kJ/mol.

The possibility of increasing CO$_2$ content, as well as replacement of CO$_2$ by other diluents or suppressants is under current investigation and the results will be published shortly.

Conclusions

Burning velocities for stoichiometric ethylene-air mixture with CO$_2$ addition between 0 and 16 vol% have been determined using a very simple method. The experimental data show that an addition of CO$_2$ higher than 10 vol% significantly affects the burning velocity, decreasing it four times, at atmospheric initial pressure, but has insignificant effect at initial pressures below 31.3 kPa.

Also, based on the inert dilution effect, the apparent activation energy of the flame propagation process has been determined from the temperature dependence of the burning velocity.

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