

Review

Dynamics of Pressure Evolution during Gaseous Ethane–Air Mixture Explosions in Enclosures: A Review

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Abstract: The study here presents data from the literature regarding the characteristic parameters of explosion propagation in gaseous ethane–air mixtures. The maximum explosion pressures, maximum explosion times, maximum rates of pressure increase, and deflagration indices from experimental measurements are discussed and analyzed against the initial pressure, initial temperature, and equivalence ratio, as well as the explosion vessel characteristics. Ethane is used for ethylene production, as a refrigerant in cryogenic systems, as an alternative clean fuel in the power generation industry and automotive propulsion, and for many other applications. Therefore, the explosion characteristics of its mixtures with air are of great interest for explosions occurring after accidentally forming flammable mixtures, as well as for the prediction of combustors’ performances and/or engines that work in different conditions.

Keywords: ethane; maximum explosion pressure; explosion time; maximum rates of pressure rise; deflagration index



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1. Introduction

A significant part of the energy currently used by modern society is obtained from the controlled combustion of fossil fuels. An important part of these fossil fuels is formed from gases, usually hydrocarbons. These gaseous fuels are stored in closed vessels, and sometimes there are accidental gas leaks. Under certain conditions, these leaks can lead to accidental fires and/or explosions because of their high flammability. The risk of a gas explosion in a given situation depends on a combination of the probability of occurrence and its effects, directly related to its sensitivity and severity. Fortunately, accidental explosions involving gaseous fuels are few. Not all gaseous emissions lead to an explosion. This is schematically represented in Figure 1. Therefore, preventing unwanted fires and explosions requires the knowledge of the characteristic explosion parameters of these gaseous fuels, besides knowing their flammability limits, so that they can be used safely.

The characteristic explosion parameters are grouped into the following three categories: (a) ignition parameters; (b) propagation parameters; (c) extinguishing parameters. The parameters that characterize the ignition process of an explosion are the following: (i) the critical ignition temperature, the critical ignition energy, and the induction period (which describe the ignition with hot bodies’ process); (ii) the minimum ignition current and the minimum ignition energy (which describe the ignition with electric sparks). The main parameters that characterize the propagation process of an explosion are, firstly, the laminar burning velocity and the propagation speed. Besides, these are parameters typical for closed-vessel combustions (the maximum explosion pressure, maximum explosion time, maximum rates of pressure increase, and the deflagration index), which are essential for safety recommendations. Among them, the maximum explosion pressure and maximum rates of pressure increase are the most important parameters used for assessment of the hazard of a process and for the design of enclosures or protection devices.

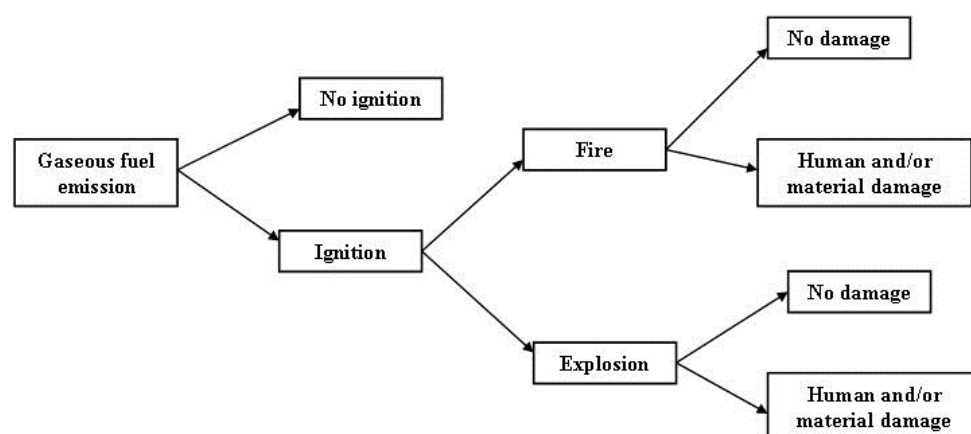


Figure 1. The consequences of an accidental leakage of a gaseous fuel.

The parameters that characterize the extinguishing process of an explosion are the maximum safe gap and the quenching distance.

Natural gas, widely used nowadays as a clean fuel, contains methane and ethane as its main constituents. The ethane concentration in natural gas can reach up to 6%, depending from region to region [1]. Besides being a natural gas component, ethane is separated from petroleum gas (a mixture of gaseous hydrocarbons) resulting from some operations implying the coal-carbonization and refinery of oil. Additionally, ethane is used for materials synthesis (e.g., ethylene production), as a refrigerant in cryogenic systems, as an alternative clean fuel in the power generation industry and automotive propulsion, and for many other applications. Bound to these applications, the explosion characteristics of ethane are of great interest for explosions occurring after accidentally formed flammable mixtures as well as for the prediction of combustors' performances and/or engines that work in different conditions.

Studies on explosion propagation parameters in enclosures (maximum explosion pressures, maximum explosion times, maximum rates of pressure increase, and deflagration indices) of ethane–air mixtures were reported by some researchers in various initial conditions (pressure, temperature, and equivalence ratio) using measurements in cylindrical [2–4] or spherical [5–10] vessels. In addition to the experimental measurements, numerical simulations of the explosion process have been used in the study of the explosion parameters of ethane–air mixtures [8–11]. There are a number of factors that influence these parameters, including the following: the composition, pressure, and temperature of the fuel–air mixture (factors that determine the rate of heat release), the volume and the shape of the enclosure, the ignition source size, energy and position, and the pre-existing or combustion-created turbulence [12–14].

This paper delivers a literature study on the maximum explosion pressures, maximum explosion times, maximum rates of pressure increase, and deflagration indices of ethane–air mixtures to characterize the explosivity of this gaseous fuel.

2. The Maximum Explosion Pressures ($p_{\max}$) and Maximum Explosion Times ($\theta_{\max}$) of Ethane–Air Mixtures

The maximum explosion pressure (or peak explosion pressure), $p_{\max}$, is defined as the extreme value of pressure achieved during an explosion in a closed vessel, under specific conditions of the gaseous mixture (composition, temperature, pressure), and enclosure (volume, aspect ratio, position of the ignition source). This parameter reflects the energy distribution of the propagating explosion wave [10]. The value of the maximum explosion pressure, $p_{\max}$, is reached at time $\theta_{\max}$.

The values of the maximum explosion pressures are necessary to calculate the laminar burning velocities from experiments performed in closed vessels or for the characterization of the transmission of explosions in interconnected vessels to design explosion-proof enclosures.

At a constant initial equivalence ratio, the maximum explosion pressures developed in closed vessels depend on the equivalence ratio, the initial temperature and pressure of the gas mixture, the asymmetry factor (or “aspect ratio”) of the explosion vessel, the position of the ignition source, and the existence of multiple sources of initiation, etc. [12,14–16].

The variation of the maximum explosion pressure of ethane–air mixtures with the equivalence ratio is presented in Figure 2. Here, data at room temperature and 0.1 MPa collected from measurements in spherical and cylindrical vessels are depicted. During this study, the pressure was expressed as absolute pressure.

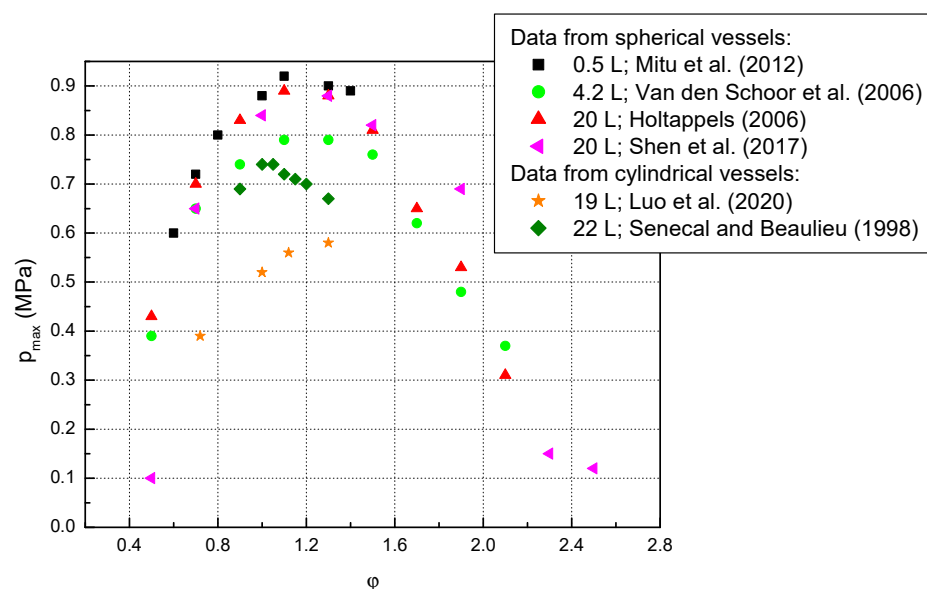


Figure 2. The variation of the maximum explosion pressure with the equivalence ratio; data from spherical [6–8,10] and cylindrical vessels at room temperature and 0.1 MPa [2,4].

The dependence of the maximum explosion pressure on the equivalence ratio of an ethane–air mixture has the shape of a parabola with the concavity orientated towards the axis of the equivalence ratio. The maximum of the parabola is not observed at stoichiometric composition corresponding to the complete combustion of ethane to CO_2 and H_2O , but at a mixture composition slightly higher than the stoichiometric concentration (around 1.1–1.2) [6–8,10].

Keeping constant the initial temperature (298 K), the initial pressure (0.1 MPa), and the equivalence ratio ($\phi = 1.0$), the maximum explosion pressures of ethane–air mixtures depend on the vessel’s volume and shape. This behavior can be seen from the data provided in Table 1.

Table 1. The influence of vessel volume and shape on the maximum explosion pressures; central ignition in all vessels.

Vessel	Volume (L)	$p_{\max}$ (MPa)	Reference
Spherical	0.5	0.88	Mitu et al. [8]
	0.5	0.89	Movileanu et al. [17]
	4.2	0.79	Van den Schoor et al. [7]
	5.0	0.78	Bartknecht [5]
	20.0	0.89	Holtappels [6]
	20.0	0.78	Rudy et al. [9]
	20.0	0.85	Shen et al. [10]
	20.0	0.78	NFPA 68 [18]
Cylindrical	19.0	0.52	Luo et al. [4]
	22.0	0.74	Senecal and Beaulieu [2]

From Table 1, we observe that the lower values of maximum explosion pressures for the aforementioned conditions are reported for cylindrical vessels compared with

spherical ones. This happens because the asymmetry of the vessel leads to significant heat losses in the course of the flame propagation and accounts for the systematically lower explosion pressures in cylindrical vessels compared to spherical ones. When we compare vessels with the same aspect ratio but with different volumes, we notice that the maximum explosion pressure is affected by the volume of the vessel. This is because, in large vessels, there is the possibility of developing wrinkled wavefronts with much larger surfaces than the undisturbed spherical fronts. On the other hand, in vessels with very large volumes (e.g., $V > 10 \text{ m}^3$), the maximum explosion pressures have values lower than the pressures developed in vessels with volumes 10–100 times smaller. This is due to the occurrence of preferential ascending flame propagation, determined by the difference between the density of burned and unburned gas. In this way, the spherical symmetry of the flame is not preserved, and the flame comes into contact with the upper part of the explosion vessel before the combustion is completed. This effect has been shown in the case of mixtures in which the fuel and oxidant show large differences in molecular weight, for example, CH_4 -air and NH_3 - H_2 -air mixtures [19,20].

Another parameter that influences the maximum explosion pressure is the initial temperature. At constant initial composition and pressure, the maximum explosion pressures decrease when the initial temperature increases. An example of such behavior is depicted in Figure 3, where data collected from measurements in spherical vessels at various initial temperatures and $p_0 = 0.1 \text{ MPa}$ are given.

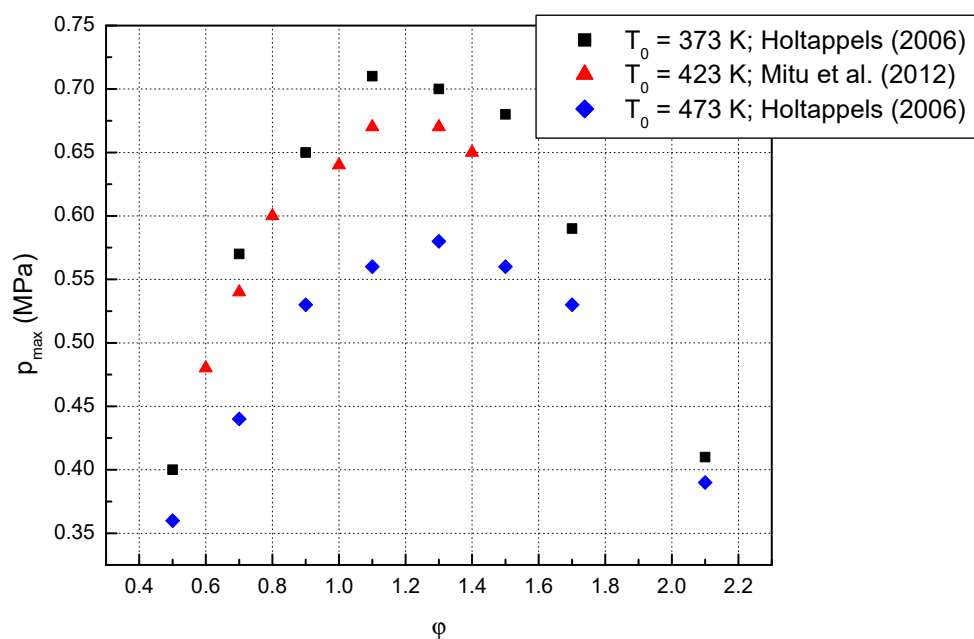


Figure 3. The variation of the maximum explosion pressure with initial temperature; data from spherical vessels at $p_0 = 0.1 \text{ MPa}$ [6,8].

In Figure 4, the variation of maximum explosion pressure on initial temperature for ethane–air mixtures at $\phi = 0.7$ and $p_0 = 0.1 \text{ MPa}$ is presented. In this figure, data collected from experiments in spherical vessels are plotted. Such behavior was highlighted not only for ethane–air mixtures but also for other fuel–air or fuel–air–inerts mixtures as follows: methane–air [21], synthetic biogas–air [22], propane–air–inerts [23], n-hexane–air [24], LPG–air [25]. The decrease in the maximum explosion pressures in preheated flammable mixtures can be due to the decrease in the density of the burning charge, which leads to a lower amount of released heat [26].

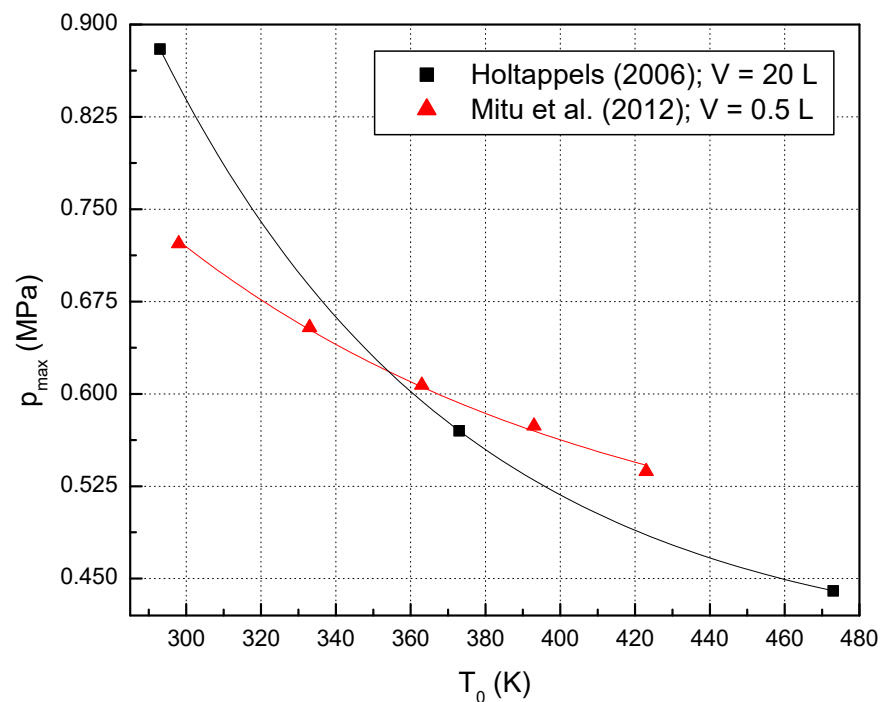


Figure 4. The variation of the maximum explosion pressure with initial temperature; data from spherical vessels at $\phi = 0.7$ and $p_0 = 0.1$ MPa [6,8].

The initial pressure of the gaseous ethane–air mixture also influences the maximum explosion pressure. The influence of this parameter on the maximum explosion pressures is given in Figure 5a,b. In Figure 5a, data collected from measurements in a spherical vessel at $T_0 = 298$ K and various equivalence ratios are plotted. In Figure 5b, data collected from measurements in a cylindrical vessel obtained at $T_0 = 298$ K for ethane–air mixtures near the flammability limits (LEL and UEL, respectively) are presented. The data from Figure 5 shows that the maximum explosion pressures increase as the initial pressure of the ethane–air mixture increases.

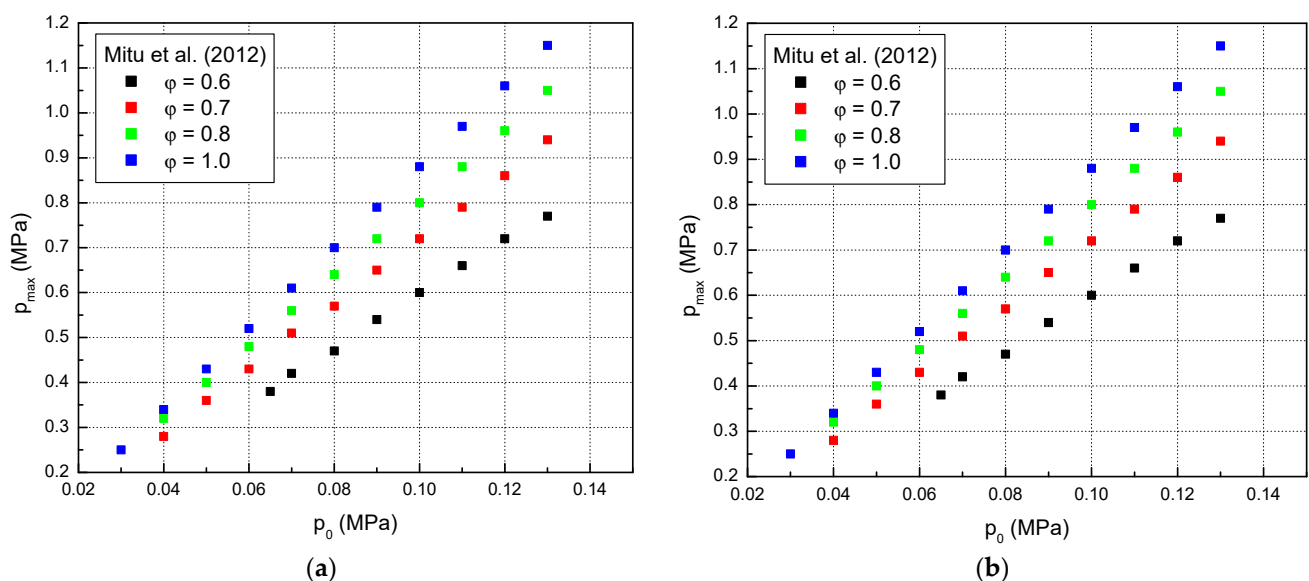


Figure 5. The variation of the maximum explosion pressure with initial pressure: (a) data from a spherical vessel measured at various initial equivalence ratios and $T_0 = 298$ K [8]; (b) data from a cylindrical vessel measured at $T_0 = 298$ K for ethane–air mixtures near LEL and UEL [3].

It was pointed out that, at constant initial temperature and mixture composition, the maximum explosion pressure depends on the initial pressure of the fuel-oxidizer gaseous mixture according to a linear relationship as follows [27]:

$$p_{\max} = a \cdot p_0 - b \quad (1)$$

In Equation (1), the constants a and b depend on the vessel's shape and aspect ratio, the initial gas temperature, and the nature of the gaseous mixture. The values of parameters a and b are necessary to evaluate the maximum explosion pressures for any value of the initial pressure (other than ambient), for which there are no experimental data, as long as the combustion occurs as deflagration.

As previously stated in [8,17,23], an equation derived from the analysis of the heat balance during the combustion of ethane–air in a closed vessel can be used for a better understanding of the influence of the initial temperature (T_0) and pressure (p_0) on maximum explosion pressures as follows:

$$p_{\max} = p_0 \left(\xi + \frac{r_l}{v_l} \cdot \frac{\Delta_c U'}{\bar{C}_{e,V} \cdot T_0} \right) - q_{tr} \cdot \frac{\gamma_e - 1}{V_0} \quad (2)$$

In Equation (2) ξ represents the molar ratio of combustion n_e/n_0 (n_0 is the initial number of moles; n_e is the number of moles at the end of combustion); r_l represents the mole fraction of the limiting component of the mixture (n_l/n_0); v_l represents the stoichiometric coefficient of the limiting component in the mixture; $\Delta_c U'$ represents the molar heat of combustion at constant volume and T_0 , corrected for the endothermic processes; $\bar{C}_{e,V}$ represents the molar heat capacity of the end gaseous mixture, averaged for the end components and for the temperature between T_0 and $\bar{T}_{e,V}$; q_{tr} represents the heat transferred to the explosion vessel before the end of combustion; γ_e represents the adiabatic compression coefficient of the end products; V_0 represents the volume of the experimental vessel.

According to Equation (2), the initial temperature increase leads to a decrease in the maximum explosion pressure; the initial pressure increase leads to an increase in the maximum explosion pressure. Both variations are confirmed by the data plotted in Figures 3–5.

Besides the experimental measurements of the maximum explosion pressures, adiabatic explosion pressures were reported by researchers. The maximum explosion pressure under adiabatic conditions can be calculated from thermodynamic data assuming that, during combustion, chemical equilibrium is achieved in the flame front. An alternative way to determine the adiabatic explosion pressure is to correct the values of the maximum explosion pressures obtained at various initial pressures from experiments in enclosures with cubic or cylindrical symmetry (in which high thermal losses appear) with the values of pressure increase reached at the end of combustion [20]. Some representative data regarding the adiabatic explosion pressures of ethane–air reported in the literature are presented in Figure 6. Values from this figure refer to mixtures at ambient initial conditions and at various equivalence ratios.

In real conditions, the maximum explosion pressure is lower than the adiabatic explosion pressure because it depends on the shape of the vessel, the position of the ignition source, and the presence of any turbulence in the gas before ignition. Another parameter that influences the explosion pressure in real conditions is the heat loss from the flame front to the vessel walls by convection, conduction, and radiation. These losses are greater in vessels with shapes other than spherical. For an adiabatic explosion (without heat losses), the adiabatic explosion pressure is dependent only on the nature, composition, temperature, and initial pressure of the explosive mixture. As Kunz highlighted [28], the differences between the adiabatic pressures and experimental explosion pressures can be used to roughly determine the amount of energy lost during the combustion process.

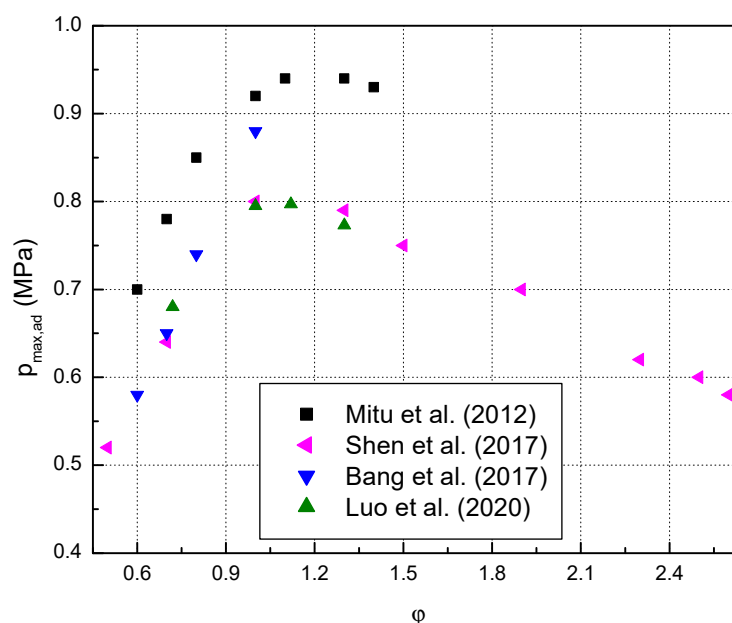


Figure 6. Adiabatic explosion pressures of ethane–air at ambient initial conditions [4,8,10,11].

From Figure 6, it can be observed that, for lean mixtures, similar results were reported by Luo et al. [4], Shen et al. [10], and Bang et al. [11]. For rich mixtures, only the data reported in [4,10] agree well.

Another set of data related to the stoichiometric ethane–air mixture obtained using various computing programs, at ambient initial pressure and temperature is given in Table 2.

Table 2. Adiabatic explosion pressures of stoichiometric ethane–air mixtures at ambient initial conditions.

$p_{\max,ad}$ (MPa)	Code	Reference
0.80	FLACS	Luo et al. [4]
0.88	FLACS	Bang et al. [11]
0.80	GASEQ	Shen et al. [10]
0.92	ECHIMAD	Mitu et al. [8]
0.92	ECHIMAD	Movileanu et al. [17]
0.92	COSILAB	Movileanu et al. [17]
0.93	STANJAN	Kunz [28]

Considering the adiabatic explosion pressure as an intrinsic property of the ethane–air mixture under certain conditions of temperature and pressure, it was expected that the values obtained by different researchers would be similar for the same mixture composition and initial conditions. Unfortunately, there are substantial discrepancies in the adiabatic explosion pressures reported by different researchers for the same flammable mixture, as shown by data from Figure 6 and Table 2. The observed differences are due to the different computing programs used to obtain the adiabatic explosion pressures. For example, in the study conducted by Mitu et al. [8], the ECHIMAD was used. Shen et al. [10] used the GASEQ program. Other authors [17] used the COSILAB package. These differences can be due, on the one hand, to the reaction mechanisms, chemical reactions, and the number of species used by each individual program, and on the other hand, to the initial thermodynamic data introduced in these programs to obtain the adiabatic explosion pressures. For example, ECHIMAD [29] has an algorithm based on the thermodynamic criterion of chemical equilibrium as follows: the minimum of Gibbs free energy (at constant temperature and pressure), or the minimum of Helmholtz free energy (at constant temperature and volume). It considers as production compounds a number of 15 compounds (among them one solid compound— C_{graphite}). The COSILAB [30] is based on a general algorithm designed to

compute the equilibrium composition of products for any fuel-oxidizer gaseous mixture using the same thermodynamic criterion of chemical equilibrium as ECHIMAD. This program considers a total of 53 compounds as combustion products. The STANJAN [28] package is based on the JANNAF thermochemistry data and the minimization of Gibbs energy. It calculates maximum pressure, maximum temperature, mean mass densities of reactants and products, and other thermodynamic key data for a given gas mixture and initial conditions. GASEQ software [10] can calculate chemical equilibria involving ideal gases and is based on the hypothesis of adiabatic expansion inside the vessel. FLACS [4,11] is a specialized computational fluid dynamics (CFD) tool for safety applications that uses a second-order scheme to resolve diffusive terms and a second-order hybrid scheme to resolve convective terms.

Movileanu et al. [31] used ECHIMAD and COSILAB to obtain the adiabatic flame temperatures and adiabatic explosion pressures of several fuel–air mixtures. The authors observed differences in mole fractions of several species within the flame front (CO, NO, H, OH, and H) obtained with two codes that led to deviations in adiabatic flame temperatures and adiabatic explosion pressures within -1.0 and $+1.0\%$. These differences were assigned to various thermophysical properties of significant compounds (e.g., specific heats, standard formation enthalpies, and standard entropies) involved in the calculation of the equilibrium parameters.

Although these calculation programs do not provide the same values of the explosion pressures as we would expect, they are widely used for predicting the experimental data.

The dependence of the adiabatic explosion pressures on initial pressure and temperature follows the same course as the maximum explosion pressures described above as follows: they decrease with an increase in the initial temperature and increase with an increase in the initial pressure.

The maximum explosion time, $\theta_{\max}$, represents a parameter that indicates the time scale of the combustion development. It depends on many fundamental and operational parameters, such as the concentration of the explosive gaseous mixture, the volume, and shape of the explosion vessel. In Figure 7, the influence of the vessel's shape on the maximum explosion time is depicted. In this figure, data collected from measurements in cylindrical and spherical vessels at ambient initial conditions and various equivalence ratios are given. We notice that smaller values of this parameter are achieved in spherical vessels compared to cylindrical ones. This behavior has also been reported for other gaseous compounds as follows: propane [25,32], n-butane [33], LPG [33,34], ethylene [35], and propylene [36]. It was specified [37] that, for the explosion of a flammable mixture inside vessels of different volumes, with central ignition, and high symmetry, the maximum explosion time increases systematically with the vessel volume due to the longer time necessary to burn a higher amount of flammable mixture. For such vessels, the maximum explosion pressure instead exhibits only small variations, at least for mixtures with fast burning.

The maximum explosion pressure is reached when the rate of heat release due to combustion is equal to the rate of heat loss to the vessel's walls. In the case of the spherical vessels, it corresponds to the moment when the combustion process is completed and the flame front contacts the explosion vessel. Before this moment, the pressure increases steadily, and the heat release rate is larger than the rate of heat loss. In the case of the cylindrical vessels, $\theta_{\max}$ is not associated with the time when the combustion process is completed. In these vessels, the pressure increases and reaches its maximum value at a moment located somewhere between the moment when the flame front reaches the vessel's walls and the moment when the combustion is completed. The moment when the combustion process ends in cylindrical vessels represents the moment when the rate of pressure rise reaches its minimum value [38]. However, regardless of the vessel being studied, the maximum explosion times reach a minimum at equivalence ratios of $\varphi = 1.0$ – 1.3 in the case of ethane–air mixtures.

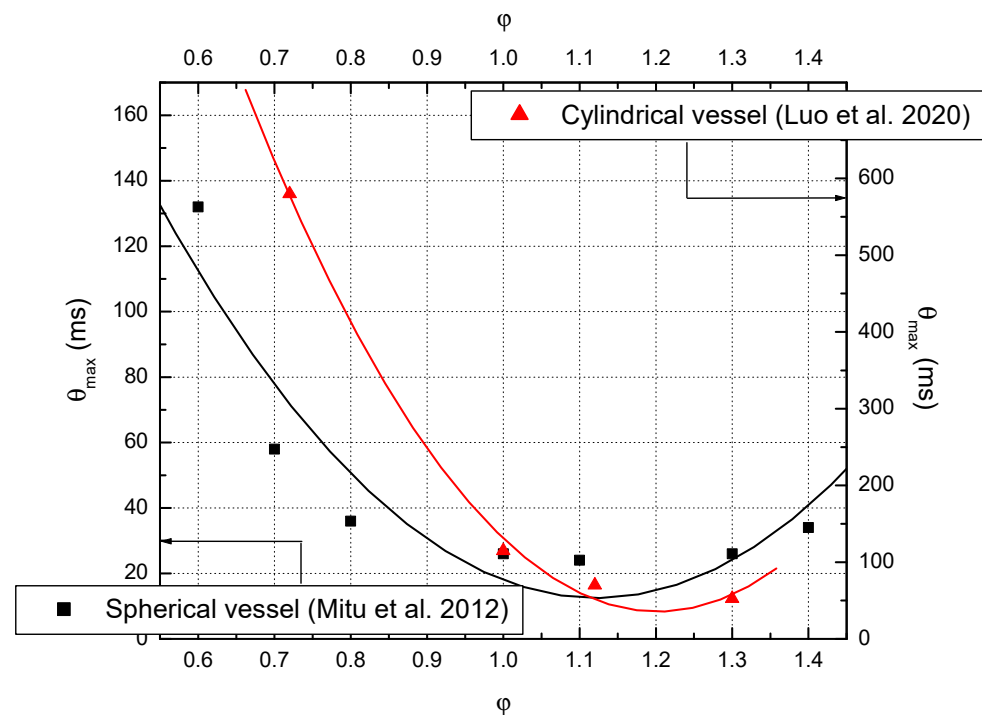


Figure 7. The times to maximum explosion pressure, for ethane–air mixtures; data from cylindrical [4] and spherical vessels at ambient initial conditions and various equivalence ratios [8].

In addition to dependence on the fuel concentration and volume of the vessel in which the explosion occurs, the time $\theta_{\max}$ also depends on the initial temperature of the fuel–oxidizer mixture. The increase in the initial temperature determines the decrease in the maximum explosion time. This is the consequence of the burning velocity rising when the initial temperature increases at a given initial pressure and composition. Although the maximum explosion time depends on the initial temperature, it does not significantly depend on the initial pressure of the gas mixture. The dependence of $\theta_{\max}$ on the initial pressure and temperature is observed in Figure 8 (where data collected from measurements in a spherical vessel at $p_0 = 0.1$ MPa, various initial temperatures, and various equivalence ratios are given) and Table 3 (where data regarding the stoichiometric ethane–air mixture collected from experiments in a spherical vessel at various initial pressures and temperatures are given). Until this moment, the initial pressure and temperature influences on explosion times of ethane–air mixtures were less examined, as can be seen from Figure 8 and Table 3.

At constant initial pressure and composition, an increase in initial temperature results in an increase in the laminar burning velocity. This increase in the laminar burning velocity leads to a decrease in $\theta_{\max}$.

Table 3. Time to maximum explosion pressure of stoichiometric ethane–air mixture at various initial pressures and temperatures; data selected from Mitu et al. [8].

p_0 (MPa)	$\theta_{\max}$ (ms)	
	$T_0 = 363$ K	$T_0 = 393$ K
0.06	43	39
0.08	45	41
0.10	45	43
0.12	47	43

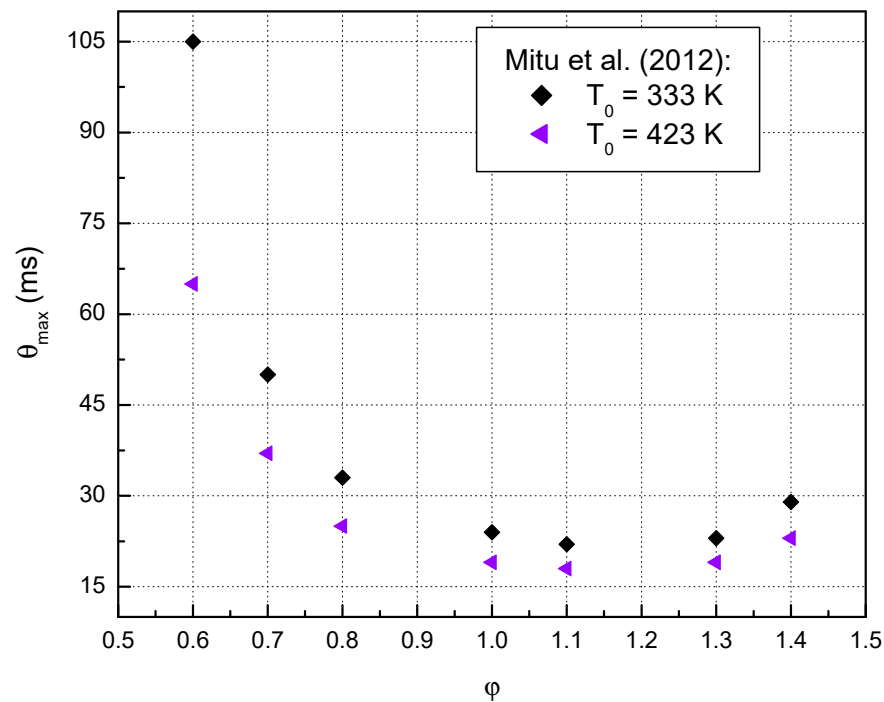


Figure 8. Times to maximum explosion pressure, for ethane–air mixtures; data from a spherical vessel at $p_0 = 0.1$ MPa, various initial temperatures and various equivalence ratios [8].

3. The Maximum Rate of Pressure Rise ($(dp/dt)_{\max}$)

The maximum rate of pressure rise during a closed vessel explosion represents the highest value of the pressure rise rate reached at a given fuel concentration, under specific initial temperature and pressure conditions.

Along with the maximum explosion pressure, the maximum rate of pressure rise is one of the key explosion parameters used for assessing the hazard of a gaseous explosion, for the design of the enclosures able to withstand an explosion, or for the design of the relief devices used against damage produced by gaseous explosions.

Similar to the maximum explosion pressure, the maximum rate of pressure rise in closed vessel explosions depends on several important factors, such as the following: composition, temperature, and initial pressure of the explosive gaseous mixture (factors that determine the rate of heat release); the size (volume) and shape of the explosion vessel; the state of turbulence of the gas during the explosion; the position of the source of ignition and the energy transferred by it to the gaseous mixture [12–14].

The variation of the maximum rates of pressure rise with the equivalence ratio of ethane–air mixtures is presented in Figure 9. Here, data at room temperature and 0.1 MPa collected from measurements in spherical and cylindrical vessels are shown. As in the case of the maximum explosion pressure, the dependence of the maximum rates of pressure rise on the equivalence ratio of ethane–air mixture also has the shape of a parabola with the concavity orientated towards the axis of the equivalence ratio. His behavior is valid for mixtures with a given initial pressure and temperature. The maximum of the parabola is also observed for mixtures with a slightly higher concentration than the stoichiometric concentration.

The data scattering observed in Figure 9 suggests that the maximum rates of pressure rise depend on the volume of the vessel, in which the explosion occurs, its aspect ratio, and on the position of the ignition source. Lower values of the parameter $(dp/dt)_{\max}$ were recorded in large volume vessels compared with small volume vessels. This behavior has already been reported for other fuel–air mixtures (e.g., LPG–air mixture [32], methane–air mixtures [39]).

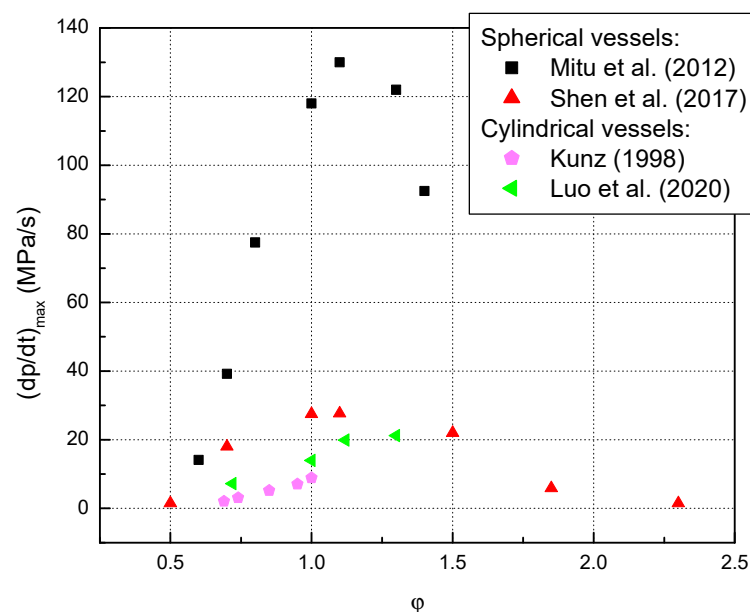


Figure 9. The variation of the maximum rates of pressure rise of ethane–air mixtures with the equivalence ratio; data from spherical [8,10] and cylindrical vessels at room temperature and 0.1 MPa [4,28].

When we compare the shape of the explosion vessels, we can observe that the smaller values of the rates of pressure rise are obtained for cylindrical vessels compared with spherical ones due to heat loss to the explosion vessel walls. This behavior can be observed not only in Figure 9, but also in Table 4, where data regarding the stoichiometric ethane–air mixtures at ambient initial conditions are given. In cylindrical vessels, the heat losses appear earlier compared with spherical vessels and reach important values much before combustion is ended. Thus, the rate of heat release in these vessels is higher than in spherical ones, and this leads to a “milder” explosive combustion and lower rates of pressure rise [40].

Table 4. Influence of vessel volume and shape on the maximum rates of pressure rise.

Vessel	Volume (L)	$(dp/dt)_{\max}$ (MPa/s)	Reference
Spherical	0.5	118	Mitu et al. [8]
	20.0	42.0	Rudy et al. [9]
	20.0	27.5	Shen et al. [10]
Cylindrical	19.0	14.0	Luo et al. [4]
	407.0	8.9	Kunz [28]

Besides the composition of the gaseous explosion mixture and vessel shape and volume, the maximum rate of pressure rise depends on the initial pressure and temperature. The initial temperature and pressure influence on the maximum rates of pressure rise of ethane–air mixtures were less examined. Only data reported by Mitu et al. [8] are available as can be seen in Figure 10 (where data at ambient initial temperature and various initial pressures are presented) and Figure 11 (where data at ambient initial pressure and various initial temperatures are given). However, for gaseous fuel–air mixtures of a given composition and temperature, an increase in initial pressure leads to an increase in the maximum rate of pressure rise, as in the case of the maximum explosion pressure described before.

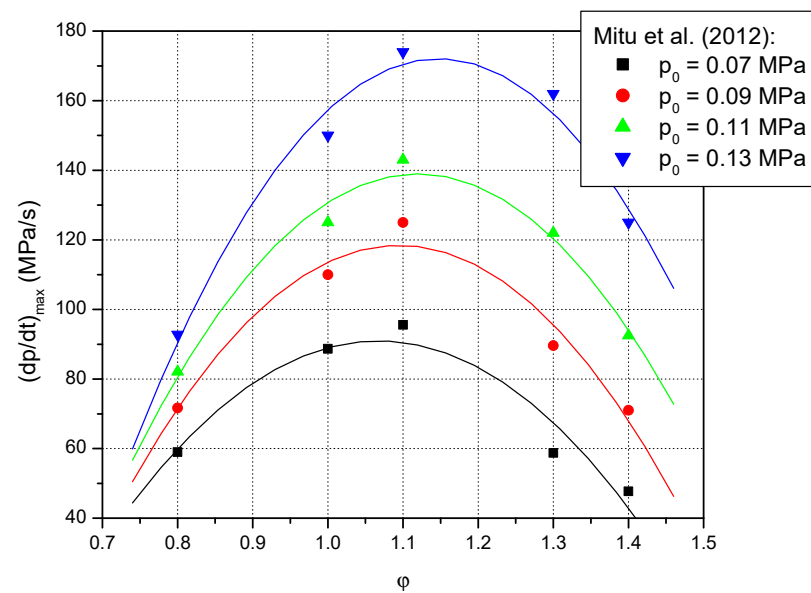


Figure 10. The variation of the maximum rates of pressure rise with initial pressure, for ethane–air mixtures; data from a spherical vessel at ambient initial temperature [8].

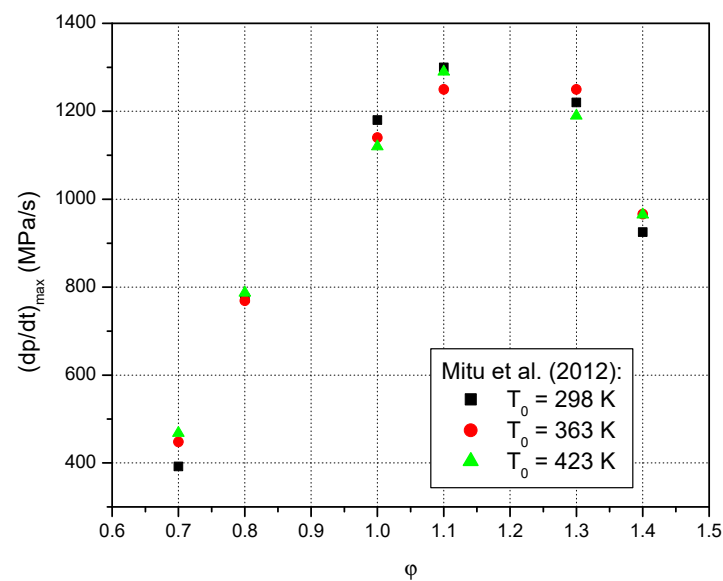


Figure 11. The variation of the maximum rates of pressure rise of ethane–air mixtures with the initial temperature; data from a spherical vessel at 0.1 MPa [8].

The dependence of this explosion parameter on the initial pressure can be described using the following linear correlation [27]:

$$\left(\frac{dp}{dt}\right)_{\max} = m + n \cdot p_0 \quad (3)$$

In Equation (3), m and n are empirical coefficients necessary for the evaluation of the maximum rate of pressure rise reached at any initial pressure within (or close to) the examined range during a deflagration process. This equation is valid as long as the mixture being studied is far from auto-ignition conditions, when partial oxidation reactions may occur in the unburned gas before its ignition and no turbulence appears in the explosion vessel [40].

Data reported in [8] for ethane–air mixtures with constant initial composition and pressure showed that the maximum rates of pressure rise slightly decrease or remain

constant when the initial temperature is increased. A weak influence of initial temperature on the maximum rates of pressure rise was also observed for other alkane-air mixtures examined in closed explosion vessels [6,23,41,42]. This behavior can be due to two opposite phenomena that alter the reaction rate (and hence the laminar burning velocity). The first phenomenon is represented by the decrease in both the reaction rate and the amount of heat released due to a decrease in the amount of fuel from the burning charge; the second phenomenon is represented by the acceleration of the reaction rate determined by the initial temperature increase [23].

Bradley and Mitcheson [43] proposed an equation that correlates the rate of pressure rise with the laminar burning velocity (S_u) and the transient pressure as follows (p):

$$\frac{dp}{dt} = \frac{3S_u\rho_u}{R\rho_0}(p_e - p_0) \left[1 - \left(\frac{p_0}{p} \right)^{1/\gamma_u} \left(\frac{p_e - p}{p_e - p_0} \right) \right]^{2/3} \quad (4)$$

In this equation, ρ_0 is the initial density of unburned gas; R is the explosion vessel radius; p_0 is the initial pressure; p_e is the end explosion pressure.

Equation (4) shows not only the dependence of $(dp/dt)_{\max}$ on the laminar burning velocity and on the transient pressure but also on the unburned gas density at a given moment (ρ_u) and on the adiabatic coefficient of unburned gas (γ_u). The opposite influences of the laminar burning velocity and transient pressure on the rate of pressure rise, which are manifested by the decrease in maximum explosion pressure and by the increase in the laminar burning velocity, can explain the low sensitivity of the maximum rates of pressure rise to the initial temperature of the mixture being studied, at least from a qualitative perspective.

4. The Severity Factor (K_G)

The maximum rates of pressure rise are used to obtain the severity factor (or “deflagration factor”), K_G , of gas explosions in enclosures with the following volume V :

$$K_G = \sqrt[3]{V} \left(\frac{dp}{dt} \right)_{\max} \quad (5)$$

Usually, the severity factors are obtained for spherical vessels with central ignition. Data collected from measurements in spherical vessels are plotted in Figure 12 for ethane–air mixtures at ambient initial conditions and various equivalence ratios.

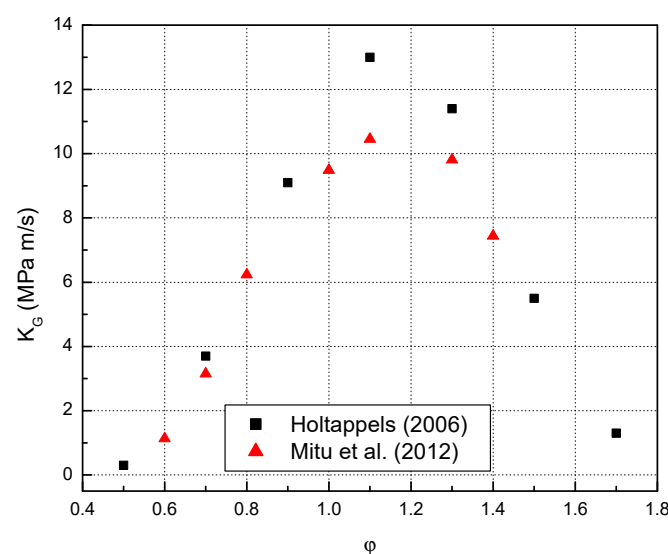


Figure 12. The variation of the severity factors of ethane–air mixtures with the equivalence ratio; data from spherical vessels at room temperature and 0.1 MPa [6,8].

From a practical perspective, it is considered that the severity factor of an explosion occurring at ambient initial temperature and pressure represents a constant that depends only on the mixture composition and does not depend on the volume of the sphere in which the gaseous explosion occurs [17]. Therefore, this is the reason why the severity factors of gaseous mixtures, at standard pressure and temperature, can be used to scale the explosions occurring in such enclosures. However, the experimental data reported by researchers showed that this parameter depends to a certain degree on the volume of the explosion vessel. At constant composition and state of the flammable ethane–air mixture, the severity factors increase slightly with the volume of the explosion vessel [39], as shown by results from Table 5. In this table, data on stoichiometric ratio and ambient initial conditions are presented. Nevertheless, K_G is considered a flammability parameter of wide interest.

Table 5. Influence of the vessel volume on the severity factors of ethane–air explosions.

Vessel	Volume (L)	K_G (MPa m/s)	Reference
Spherical	0.5	9.49	Mitu et al. [8]
	5.0	10.60	Bartknecht [5]
	20.0	10.60	NFPA 68 [18]
Cylindrical	20.0	7.80	Senecal and Beaulieu [2]
	407.0	6.60	Kunz [28]

It is also possible to determine the severity factors for cubic or cylindrical vessels. The severity factors for these enclosures also depend on the volume of the vessel, but their values are strongly influenced by other parameters. On one hand, they are influenced by the aspect ratio of the explosion vessel and, on the other hand, by the computation method used by different researchers to smooth $p(t)$ curves and to extract the correct values of the maximum rate of pressure rise, as already mentioned in [39]. A set of representative values of severity factors is presented in Figure 13a for data measured in cylindrical vessels and in Figure 13b for data measured in cubic vessels. All the data from these figures were obtained at ambient initial conditions and various equivalence ratios. Other values of severity factors collected from experiments in cylindrical vessels are given in Table 5.

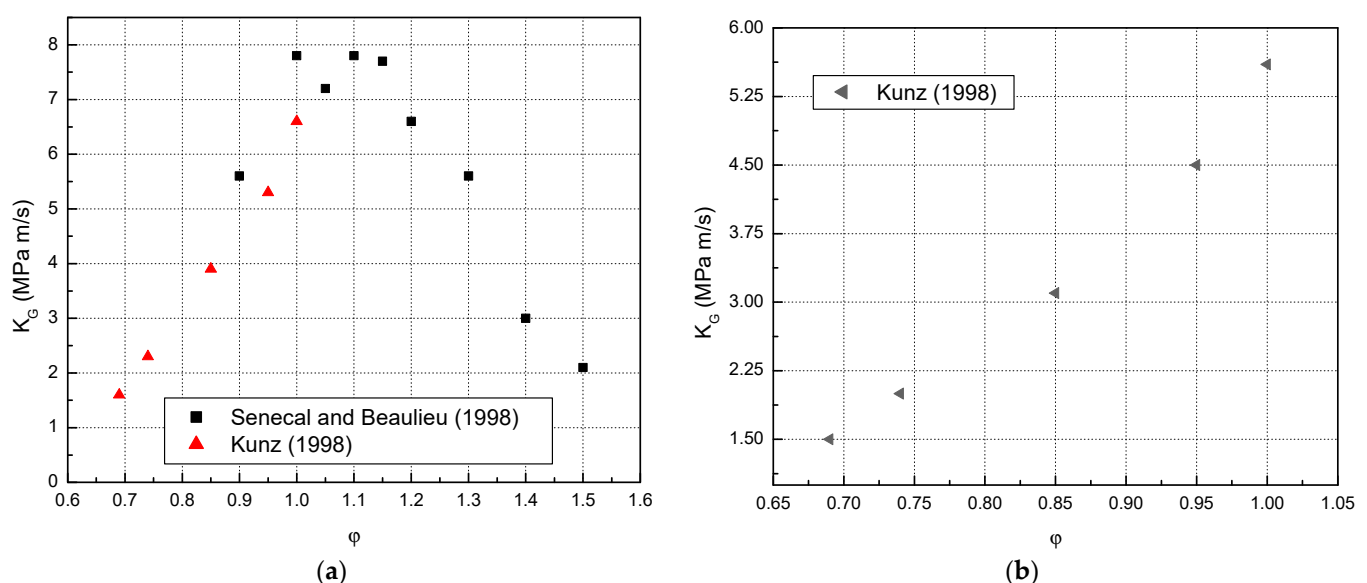


Figure 13. The variation of the severity factors of ethane–air mixtures with the equivalence ratio, at room temperature and 0.1 MPa: (a) data from cylindrical vessels [2,28]; (b) data from a cubic vessel [28].

The discrepancies between data obtained from experiments in spherical vessels and data obtained from experiments in cylindrical vessels of the same volume are due to heat loss. In cylindrical vessels, the heat losses start earlier compared to spherical vessels and become significant much before the combustion has ended. Therefore, the rate of pressure rise in cylindrical vessels is small compared with spherical ones, thus leading to a decrease in the severity factors.

Studies of the influence of the initial temperature on the severity factors are poor; only the data reported by Holtappels [6] at two initial temperatures different from ambient and 0.1 MPa are available. Holtappels reported a weak dependence of K_G on the initial temperature and pointed out that K_G values increase at the initial temperature increase only for rich-fuel ethane–air mixtures ($\varphi \geq 1.5$). This behavior can be observed in Figure 14.

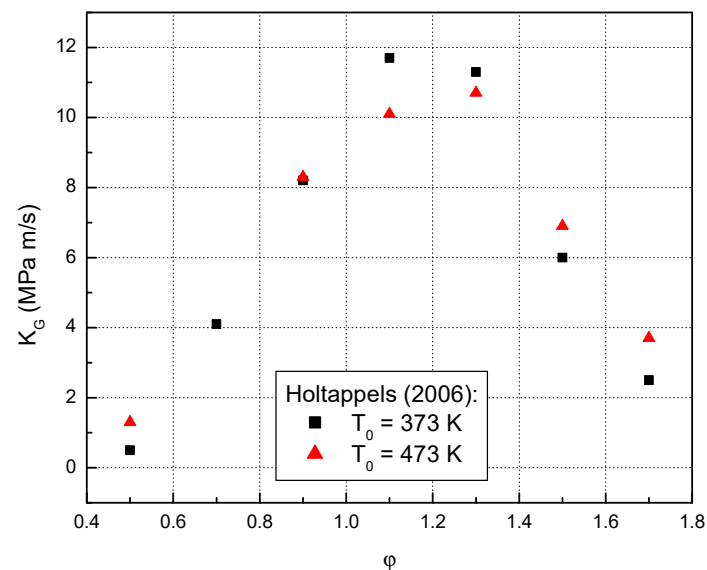


Figure 14. The variation of the severity factors of ethane–air mixtures with the initial temperature; data from a spherical vessel at 0.1 MPa [6].

A weak dependence of the deflagration index on the initial temperatures was also observed for other fuel–air mixtures as follows: H_2 –air [42], n-butane–air [41], and ethylene–air mixture [6].

The influence of the initial pressure on the severity factors of ethane–air mixtures has not yet been reported.

5. Conclusions

In the present paper, the available literature regarding the dynamics of pressure evolution during gaseous ethane–air mixture explosions in enclosures have been reviewed. The maximum explosion pressures, the maximum explosion times, the maximum rates of pressure increase, and the deflagration indices from experiments and computations were discussed and analyzed against the initial pressure, initial temperature, and equivalence ratio, as well as the characteristics of the explosion vessel. The results are summarized as follows:

- The dependence of the maximum explosion pressures on the equivalence ratio of ethane–air mixture has the shape of a parabola with the peak at a composition slightly higher than the stoichiometric concentration;
- At constant initial temperature, pressure, and equivalence ratio, the maximum explosion pressures of ethane–air mixtures depend on the vessel’s volume and shape as well as on the position of the ignition source;
- At constant initial composition and pressure, the maximum explosion pressures decrease with the initial temperature increase;

- (d). At constant initial composition and temperature, the maximum explosion pressures increase as the initial pressure of the fuel–air mixture increases;
- (e). The maximum explosion pressures from experimental measurements are lower than the adiabatic explosion pressures;
- (f). The explosion time depends not only on the initial pressure and temperature of ethane–air mixtures but also on their equivalence ratio; the lowest values were obtained for the fuel composition slightly higher than stoichiometric concentration;
- (g). Smaller values of the explosion times are achieved in spherical vessels compared to cylindrical ones;
- (h). The maximum rates of pressure rise and severity factors show the same variation with the initial pressure, equivalence ratio, and volume of the explosion vessel as the maximum explosion pressure;
- (i). A weak dependence of the severity factor on the initial temperature was reported for all examined compositions of ethane–air mixtures.

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