Multi-Ignition in Partitioned Gaseous Mixtures

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1 Elements of modelling and results

A simple modelling initially developed as part of a novel study on ignition and combustion of classical propulsive powders has been presented in order to predict the main characteristics of these explosions in a closed or a vented vessel[1]. Then, the model has been adapted to the explosion of dust suspensions and more recently to gaseous mixtures such as methane or propane.
A calculation methodology allows to adapt the numerical simulation to the transmission of the explosion from one compartment to another adjacent compartment by the means of the hot flow through the shared orifice and finally to generalise this methodology to a complex multi-partitioned structure. The aim of this work is to study the chain propagation of a gaseous explosion and the effects induced by a multi-source ignition in a partitioned vessel and a wide energy range ($E_{ign} \leq 5000$ J). Simulated predictions have been compared with results of various experimental works available in the literature for gaseous mixtures.
The combustion of the gaseous fuel (methane/propane) results from collisions between all the particles in the gaseous phase. The reactive system is composed of molecules in gaseous phase, active molecules and condensable molecules. The energy flux brought to the gaseous fuel leads to its degradation by active or condensable molecules and to the dissociation by the other molecules in the gaseous phase. All those phenomena contribute to the destruction of the gaseous fuel[1].
The combustion of the gaseous fuel takes place in a closed partitioned vessel .In the course of the ignition process, a little amount of gaseous fuel is initially destroyed. The destruction of the molecules of fuel implies the formation in the reactive mixture of active or condensable species. These species induce a destruction energy flux which contribute to develop the reaction and to increase the internal energy and the temperature in the mixture. Then, the reaction is initiated. The various adjacent compartments in the vessel are connected by inner openings with a variable surface which allow the propagation of the reaction and the progressive establishment of a thermodynamical equilibrium. Each compartment is considered as a perfectly well-stirred reactor which may be fitted with a vent[1]. The total mass rate of gaseous substances due to the difference of pressure between two adjacent compartments or the surrounding atmosphere is given by the standard orifice equations[2].The amount of the gaseous fuel and the mass rate of each species transferred between two adjoining areas or discharged through the vent are calculated assuming a global mass rate partition[1] among the different species in each compartment.
The knowledge of the chemical process and the amount of transferred molecules allows to know by successive time steps, the number of molecules and the mass of each species remaining in each compartment. The numerical integration of the equations gives the access for the whole structure to thermodynamical factors and

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to the calculation of the time evolution of the pressure, the rate of pressure rise and the reduced pressure in the case of vented explosions and a multi-source ignition.

Figure 1 presents experimental and theoretical curves relative to methane-air mixtures in the case of the time evolution of the pressure and a single compartment. The experimental curves are due to Leuckel[3] for a large spherical vessel volume such as V_o = 1000 *l*. The first case corresponds to stoichiometric conditions. The theoretical characteristics of this explosion are then P_{max} = 730 kPa and a Bartknecht's K_g factor such as K_g = 5.17 MPam/s. The maximum pressure given by Leuckel is P_{max} = 680 kPa and experimental results due to Bartknecht[4] in the same conditions lead to P_{max} = 740 kPa and K_g = 5.5 MPam/s. The rise times are also quite comparable with values comprised between 380 ms and 400 ms.

The second case corresponding to a lean mixture (p = 7.8 % CH_4) shows a good agreement between experimental and theoretical results with correct maximum pressures around 570 kPa and comparable rise times close to 550 ms.

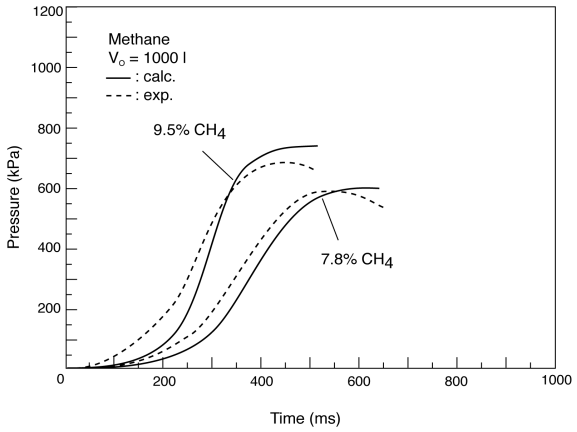

Fig 1 Pressure of explosion vs time.

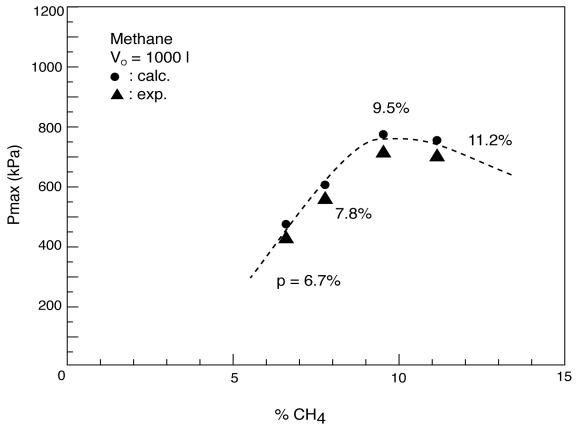

Fig 2 Maximum pressure for different % CH_4

Figure 2 compares the theoretical and experimental evolutions of the maximum pressure for different percentages in the explosion limits of methane. The maximum pressure is calculated from pressure-time curves. Then, the data obtained are plotted in the figure. The experimental values are deduced from Leuckel's experiments[3] in a closed spherical vessel such as V_o = 1000 *l*. A dotted line has been plotted, connecting the different points in order to give the general trend of the evolution of the maximum pressure. It can be noticed that the maximum pressure is obtained over the stoichiometry in slightly rich mixtures, which is classically known[4]. Different elementary cases with only two compartments may also be analysed from methane-air or propane-air mixtures in order to test the model predictions.

Figure 3 gives the time evolution of the absolute pressure in each compartment for a small inner opening a = 100 cm^2 in the case of methane at the stoichiometry or propane in a slightly rich mixture (p = 5%). A vertical steel plate allows to define two compartments with respective volumes such as $V_{o1} = V_{o2}$ = 1000 *l*. Both compartments are connected by a small inner opening positioned in the centre of the plate. Several plates may be envisaged corresponding to various inner openings[5]. The combustion of the gaseous mixture may be carried out in both compartments by the means of a central initiation. The reference ignition energy corresponds to 68 J. The ignition occurs in the first compartment and induces there a quicker pressure rise. This effect involves a molecule transfer towards the adjacent compartment, which modifies the concentrations in the reactive mixture and therefore, the maximum pressures reached. At the end of the reaction, a thermodynamical equilibrium is obtained in the mixture and the pressure evolution is shared by both compartments[5]. It can be observed that the maximum of pressure obtained is higher in the adjacent compartment than in the initial one, where ignition occurs . The effective overpressure ΔP = 80 kPa for methane or ΔP = 60 kPa for propane is much more reduced than in the case of kerosene droplets[5] but quite consistent with experimental results[4]. According to Bartknecht, for identical combined vessels, the length of the connecting line does not significantly influence the course of the explosion, but in the second vessel the maximum explosion pressure may be increased by approximately 10% for

gaseous mixtures[4]. The observed phenomena do not depend on the mixture which may be rich, lean or stoichiometric[4].

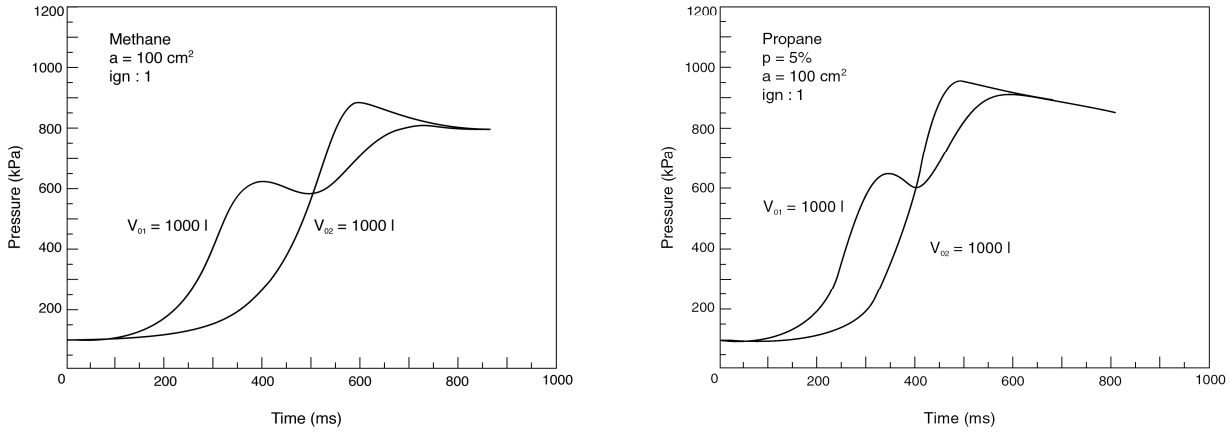

Fig 3 Pressure vs time in both compartments for different gaseous mixtures (methane/propane).

Figure 4 shows the time evolution of the absolute pressure in each compartment of a vessel composed of nine identical compartments (3x3) such as $V_{ok} = 1000\ l$ and $1 \le k \le 9$, for a methane-air mixture in stoichiometric conditions (p = 9.5%). All the adjoining compartments are connected by a small inner opening $a = 100\ cm^2$.
The first part of the figure corresponds to an ignition in compartment 1 which defines one of the corners of the structure. The ignition energy corresponds to 500 J. The reaction progressively expands in the adjoining areas with a delay time and leads to the formation of a progressive overpressure. On account of a possible symmetry in the thermal exchanges and the transfers of matter in the course of the reaction, the overpressure in each compartment corresponds to approximately constant rise times between 1000 and 1200 ms. The pressure is the same in the symmetrical compartments in comparison with the ignition compartment. The maximum of pressure reached varies between 800 kPa in the first compartment, and 1000 kPa in the furthest compartment, which is consistent with many experimental results[6].
The second part of the figure is obtained in the same conditions, but for a much higher ignition energy such as E_{ign} = 5000 J. The increase of the ignition energy classically corresponds to an increase of the maximum of pressure reached and a decrease of the rise times.

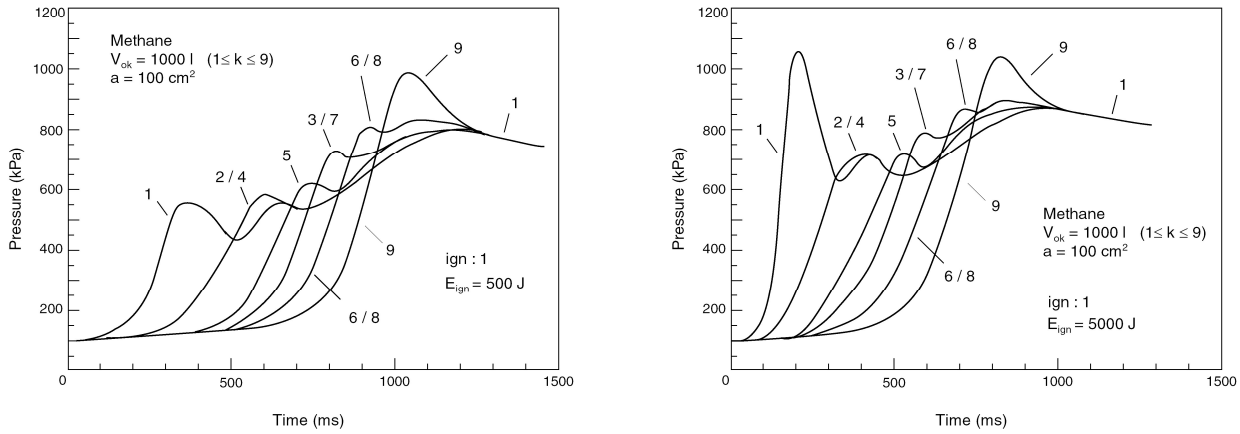

Fig 4 Pressures vs time for a side ignition and different ignition energies.

This effect is particularly evident for the ignition compartment where the maximum pressure reaches 1050 kPa with a rise time shortened to 200 ms in comparison with the first case. The effect is strongly reduced in the intermediate area and completely mitigated in the furthest part which keeps an approximately constant behaviour. The main result is the progressive disappearance of the pressure pilling for very high ignition energies.

Figure 5 corresponds to a central ignition in compartment 5 for ignition energies such as E_{ign} = 1000 J and E_{ign} = 5000 J. The pressure evolution due to the symmetry is the same in different compartments. In the first part of the figure, a very slight overpressure about 30 kPa exists between the corners of the structure and the central compartment for rise times in the region of 800 ms.

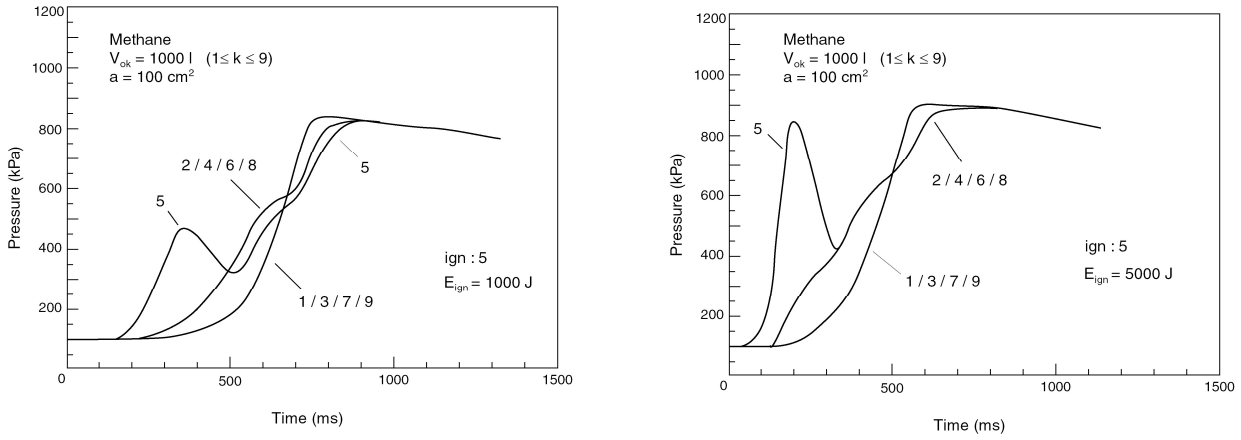

Fig 5 Pressures vs time for a central ignition and different ignition energies.

The second part of the figure shows a relatively similar evolution with higher pressures and quicker rise times. The overpressure observed is practically the same around 20 kPa. In both cases, the pressure evolution is relatively homogeneous in the different areas of the structure except in the ignition compartment where the rise time is strongly shortened . The overpressure observed remains very limited and is practically independent of the ignition energy. So, it appears now interesting to study the influence of a multi-source ignition on the pressure evolution.

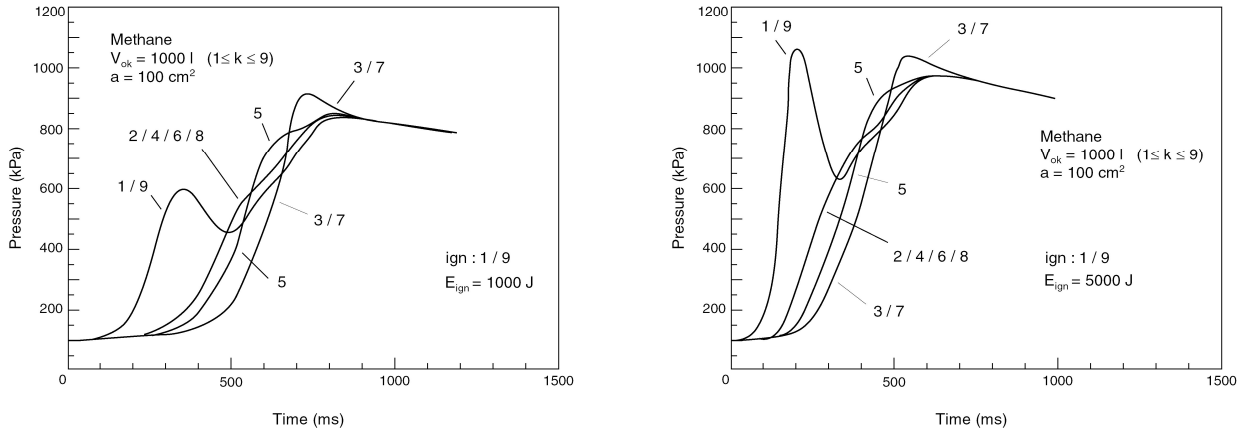

Fig 6 Pressures vs time for different locations and ignition energies.

Figure 6 gives the time evolution of the pressure for a same two-source ignition in compartments 1 and 9 which define two opposite corners of the structure. The first part of the figure corresponds to an intermediate ignition energy E_{ign} = 1000 J. The reaction is initiated around the ignition compartments (1-9) and progressively expands with the formation of a limited overpressure. The maximum pressure close to 920 kPa is reached in the furthest areas corresponding here to symmetric compartments 3 and 7. The evolution obtained is similar to the case of a single ignition in a corner of the structure in the same conditions, but the overpressure observed is reduced of about 50% around 100 kPa.
The second part of the figure corresponds to a strong ignition energy E_{ign} = 5000 J. A decrease of the rise times and a strong increase in pressure up to 1150 kPa may be noticed in the ignition compartments. As previously, for a high ignition energy, these effects are widely softened in the intermediate areas and the pressure pilling phenomenon completely mitigated in the furthest area.
Figure 7 shows the time evolution of the pressure for a same three-source ignition in compartments 1,2 and 4 confined in one corner of the structure. The first part of the figure corresponds to an intermediate ignition energy E_{ign} = 1000 J. It can be noticed, that the successive adjacent compartments are again the aim of a progressive overpressure with a maximum around 1000 kPa in the furthest compartment corresponding to compartment 9. The main result is that the overpressure is slightly higher around 220 kPa when the number of ignition sources increases in a localised part of the structure.

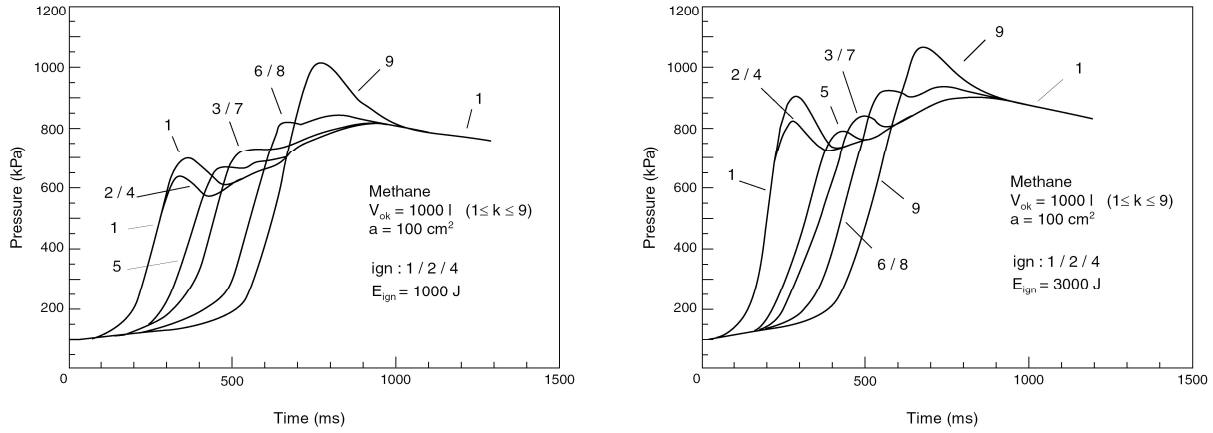

Fig 7 Pressures vs time for different locations and ignition energies.

The second part of the figure corresponds to a strong ignition energy E_{ign} = 3000 J. The pressure evolution is similar to the previous one, but the higher energy supply is dissipated in the form of a pressure increase, essentially in and around the ignition areas without important modification of the overpressure.
In conclusion, all the cases observed for gaseous mixtures indicate two kinds of situations :

- in the course of a central or a scattered ignition with high energies, the pressure evolution in each compartment is close to the pressure obtained in the global volume without partitioning. The maximum pressure reached is as much higher as the ignition energy is stronger, but there is no pressure pilling phenomenon.
- in the course of a strongly confined multi-source ignition with low energies located in a side compartment, a noticeable overpressure progressively forms with a maximum in the furthest part of the structure.

Then, the location of the ignition energy considerably influences the thermodynamical evolution of the mixture and the possible destruction of the structure. So, it seems interesting to precise experimentally this evaluation by studying more complex multi-partitioned structures.

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