

Influence of a Dispersed Ignition in the Explosion of Two-Phase Mixtures

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1 Introduction and model elements

Two-phase mixture explosions (dust + gas) often have in the past created dramatic situations and consequences. The study of these mixtures has concerned in numerous cases coal dusts in order to improve the general knowledge on safety in industrial plants and more particularly in mines. The association of coal dusts with a gaseous energetic fuel such as methane was frequently envisaged. On the contrary very few studies have been interested in the association of agricultural dusts with such gaseous energetic substances (methane or propane).

Nevertheless, the risk of explosion exists in any agricultural process that implies the handling or stocking of pulverized combustible material. If different works have tried to improve the present knowledge on safety [1], it remains generally difficult to predict the explosive properties of a two-phase mixture in partitioned industrial or agricultural plants. It has been experimentally verified for gaseous mixtures that very important overpressures went on in all the adjoining areas of the ignition compartment for multi-partitioned vessels [2],[3]. Otherwise, over the last past years, a simple modelling initially developed as part of a novel study on ignition and combustion of dust suspensions [4] has been presented in order to predict the main characteristics of these explosions in a closed or a vented one-compartment vessel. The aim of this work is to extend the model to study the effects induced by a multi-source ignition on the flammability of a two-phase mixture and more particularly the pressure history in a partitioned structure with a wide energy range ($E_{\text{ign}} \leq 20000 \text{ J}$).

The combustion of the two-phase mixture is supposed to be described by collisions between particles of the gaseous phase and those of the solid phase [4]. The reactive system is composed of molecules in gaseous phase and active molecules. In the course of the ignition process, a little amount of solid fuel is initially destroyed which implies the formation in the reactive mixture of active species. These species induce a destruction energy flux brought to the mixture which leads to its degradation by the active molecules and to the dissociation by the other molecules in the gaseous phase [4]. All those phenomena contribute to develop the reaction, to increase the internal energy and the temperature in the mixture. These assumptions seem to be particularly adapted to a multi-source ignition which remains essentially dispersed inside the structure.

The combustion of the two-phase mixture takes place in a closed partitioned vessel. The initial conditions are supposed to be homogeneous in the vessel. The various adjacent compartments are connected by inner openings with a variable surface which allow the propagation of the reaction and

the formation of a progressive thermodynamic equilibrium in the vessel. Each compartment is considered as a perfectly well-stirred reactor which may be fitted with a vent. The vent breaking is obtained when the pressure in the medium reaches the static venting pressure [5]. The initial thermodynamic characteristics of the medium are determined (pressure P_0 , temperature T_0) or may be calculated (internal energy, total number of gaseous molecules) from oxygen-nitrogen-fuel amounts in the vessel [4]. The evolution of the active or gaseous species is based on the chemical kinetics of the reaction and takes into account collisions on the solid fuel, collisions on the wall or in the gaseous medium [4]. 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 the pressure history [4] and more generally to the time evolution of all thermodynamic variables.

2 Comparison with experimental results

The maximum pressure calculated from the model (full line) is given in figure 1 as a function of the concentration with only cornstarch. This evolution is compared to various experimental results indicated in the figure and to another theoretical simulation (dotted line) calculated by the means of the Quatuor code matched by Lemos [6]. This code gives the calculation of the product properties of a chemical reaction for ideal conditions (homogeneous mixture, adiabatic reaction and a complete thermodynamic equilibrium. It cannot predict the time evolution of the pressure and does not take into account the losses at the wall.

Two hypotheses are considered in the calculation :

- All the combustion products are only gaseous substances.
- Solid carbon is also a combustion product.

For lean mixtures, the maximum pressure predicted by our model progressively increases towards an approximately constant level for intermediate concentrations ($0.25 \leq \Delta \leq 0.5 \text{ kg/m}^3$). Then, the maximum pressure decreases for rich mixtures. These results seem to be in good accordance with experimental data whose mean evolution is comparable with the model.

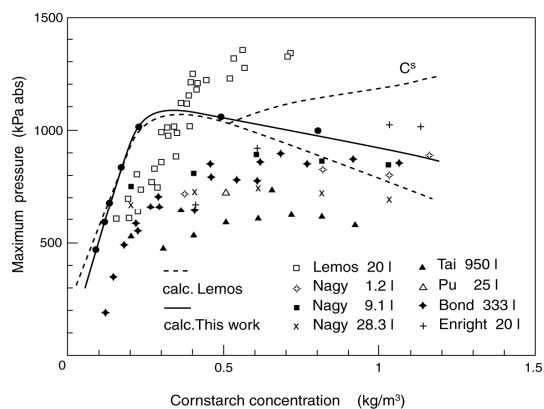


Fig. 1 Maximum pressure vs cornstarch concentration. Experiments and calculations.

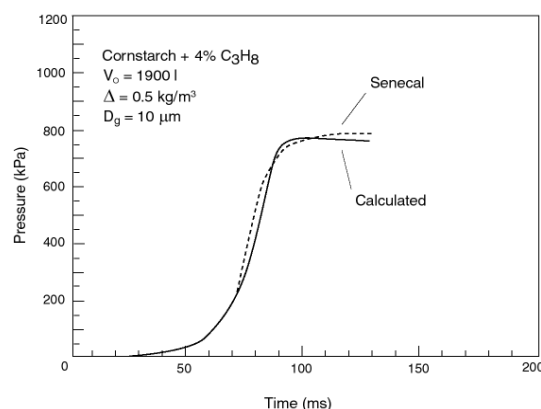


Fig. 2 Pressure of explosion vs time.

Furthermore, we observe a very good correlation of our model with the Quatuor code for concentrations such as $\Delta \leq 0.5 \text{ kg/m}^3$. For higher values, our result appears as intermediate between both hypotheses of the Quatuor code.

Figure 2 presents experimental and theoretical curves relative to a cornstarch + 4% C_3H_8 mixture in the case of the time evolution of the pressure. The experimental curve is due to Senecal [7] for a large spherical vessel volume such as $V_0 = 1900 \text{ l}$. A very good correlation between theory and experiment

is noticeable, which brings a first validation of the model for two-phase mixtures. It is also noticeable that the maximum pressure is close to the pressure obtained for $\Delta = 1 \text{ kg/m}^3$ and without propane [4]. It empirically appears that addition of 1% C_3H_8 produces a medium experimental overpressure of about 100 kPa. This point is comparable with experimental results due to Leuckel [8] for slight amounts of methane. In addition the K_{st} factor may be calculated according to Bartknecht's formula [9]. The theoretical value $K_{st} = 43.6 \text{ MPa.m/s}$ approximately corresponds to the experimental value $K_{st} = 42 \text{ MPa.m/s}$ given by Senecal for the cornstarch + 4% C_3H_8 mixture. The latter point is also important for a good time calibration of the model. The influence of the concentration or the vessel volume are also interesting parameters that may be studied to compare with experimental data.

The time evolution of the pressure is presented for methane and for different cornstarch concentrations in figure 3. For the smallest solid concentrations ($\Delta = 0.125; 0.15$ and 0.2 kg/m^3), the increase of the percentage of methane first leads to a progressive increase of the maximum pressure and to a decrease of the rise time. The system gets nearer to stoichiometric conditions. It appears that addition of 1 % of methane in a lean mixture leads to a medium overpressure around 60 kPa. This result is consistent with the results deduced from Leuckel's experiments [8]. Furthermore, the increase of the solid concentration for a given gaseous supply in a lean mixture also leads to a more important maximum pressure and to a shorter rise time. These elements present a strong analogy with phenomena observed for mixtures only composed of dust suspensions or even liquid fuels. Then, addition of solid fuel or gas progressively creates a rich mixture whose evolution is reversed in comparison with lean mixtures and remains in accordance with the previous results. It appears that supplementary addition of energetic gaseous substances in a lean mixture is favourable to the combustion of these two-phase mixtures. The evolution towards stoichiometric conditions creates a considerable overpressure (10 to 15 % of overpressure for 1 % of added gas).

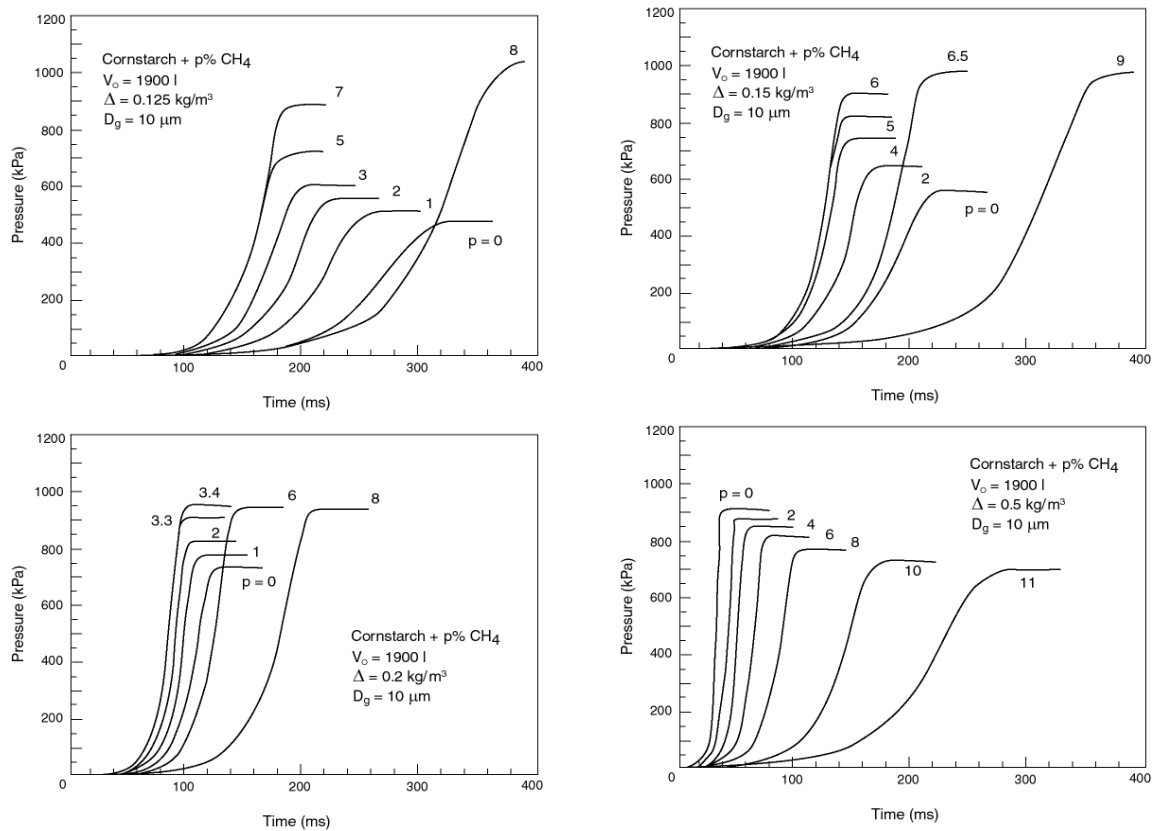


Fig. 3 Pressure vs time for different % CH₄ and different cornstarch concentrations.

This process may produce explosive reactive systems for very short times and slight gas amounts about 3 to 7 % for methane. For higher solid concentrations ($\Delta > 0.253 \text{ kg/m}^3$ for cornstarch), it appears that the maximum pressure regularly decreases as a function of the percentage of added gas. This evolution is the same for various gases and is specific of initially rich mixtures.

On the other hand, the rise time becomes progressively longer when p increases and strongly longer beyond a certain threshold. All the results are quite compatible with Leuckel's experiments obtained for rich gaseous mixtures [8]. It can be noticed that addition of energetic gaseous substances is not favourable to the development of the combustion in the case of initially rich two-phase mixtures.

All the results presented in a single compartment seem to be in good agreement with experimental works about one or two-phase mixtures and bring a first validation of the model.

It appears therefore interesting to study the influence of a variable dispersed ignition on the pressure evolution in a particular partitioned vessel composed of nine identical compartments (3×3) such as $V_{ok} = 1000 \text{ l}$ and $1 \leq k \leq 9$, for a two-phase mixture. All the adjoining compartments are connected by a small inner opening $a = 100 \text{ cm}^2$.

3 Influence of a multi-source ignition and conclusion

Figure 4 gives the time evolution of the pressure for a same two-source ignition in compartments 1 and 3 which define two corners of the structure. The studied mixture is near the stoichiometry with a cornstarch concentration $\Delta = 0.125 \text{ kg/m}^3$ and 6% of methane. The modelling conditions have been chosen for a diameter of the cornstarch grain such as $D_g = 10 \mu\text{m}$ and different ignition energies. The effective nominal energy is supposed to represent 10% of these values.

The first part of the figure corresponds to an intermediate ignition energy $E_{\text{ign}} = 1000 \text{ J}$. The reaction expands around the ignition areas and leads to the formation of a progressive overpressure. The maximum of pressure reached varies between 840 kPa in the corners and 1100 kPa in the furthest symmetric area corresponding to compartment 8. The picture obtained is quite similar to the case of a single ignition in a corner of the structure and in the same conditions with the corresponding overpressure around 260 kPa.

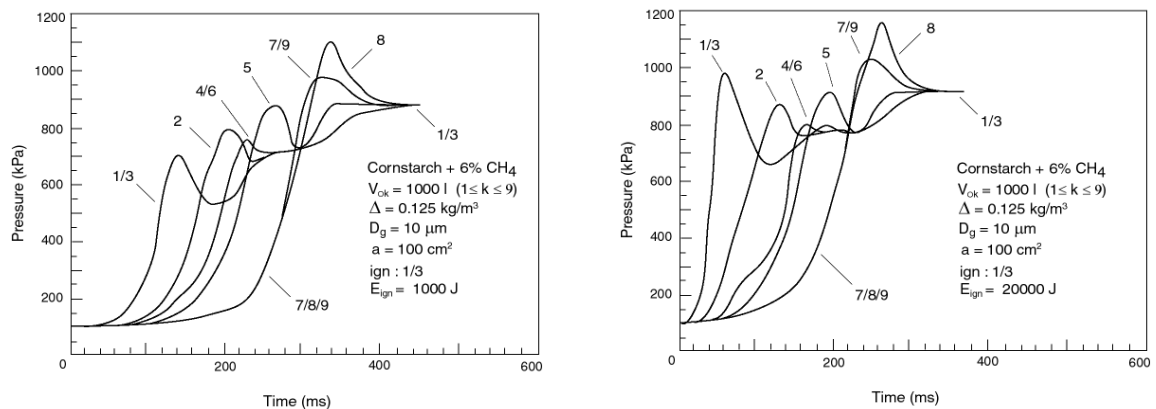


Fig. 4 Pressures vs time for different locations and ignition energies.

The second part of the figure corresponds to a strong ignition energy $E_{\text{ign}} = 20000 \text{ J}$. A decrease of the rise times and a marked strengthening of the maximum pressure close to 980 kPa may be noticed in the ignition compartment without big modifications in intermediate regions. It can be observed for a high ignition energy, that the pressure pilling phenomenon is completely mitigated in the furthest part of the structure in comparison with the ignition compartment.

Figure 5 shows the time evolution of the pressure for a same three-source ignition in compartments 1,3 and 7 which define three corners of the structure. The first part of the figure corresponds to an intermediate ignition energy $E_{ign} = 1000$ J. The figure shows the formation of a progressive overpressure which varies between 840 kPa in the corners and 1110 kPa in the furthest symmetric area corresponding to compartment 9.

The main result is that there is no significant variation of the overpressure when the number of ignition sources located in various points of the structure increases.

The second part of the figure corresponds to a strong ignition energy $E_{ign} = 15000$ J. The pressure evolution is practically the same as previously except a strong increase in pressure in the ignition compartment without global effect on the whole structure.

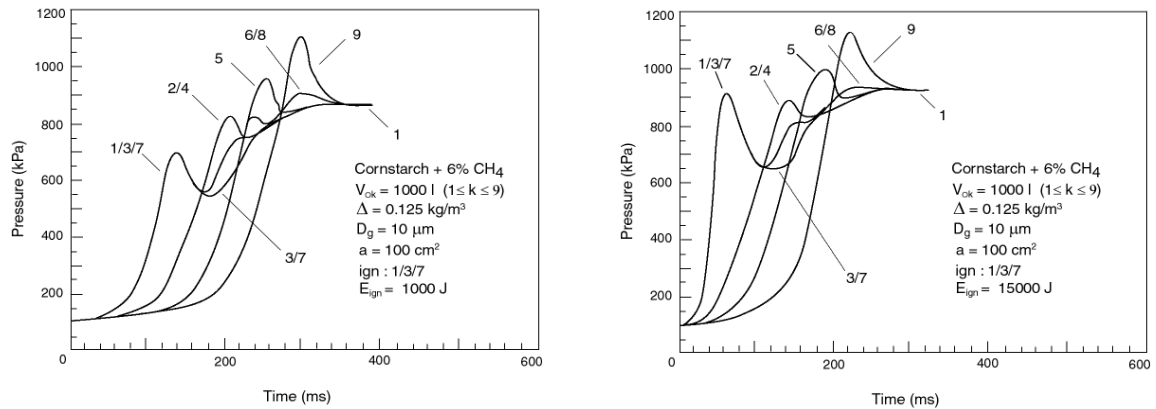


Fig. 5 Pressures vs time for different locations and ignition energies.

Figure 6 shows the time evolution of the pressure for a same four-source ignition in compartments 1,2,4 and 5 located in a corner of the structure. In the first part of the figure, we have chosen an intermediate ignition energy $E_{ign} = 1000$ J. As previously, the figure shows the formation of a progressive overpressure which varies between 840 kPa in the ignition area and 1120 kPa in the furthest part corresponding also to compartment 9.

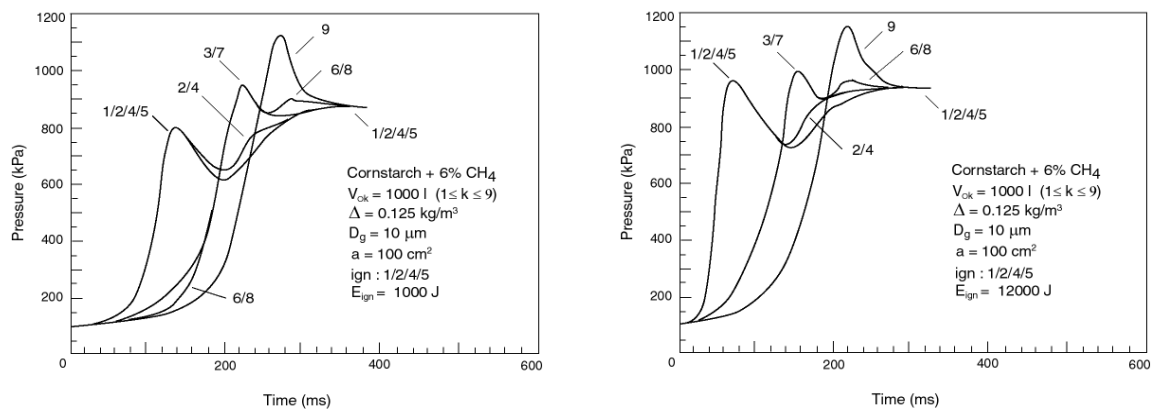


Fig. 6 Pressures vs time for different locations and ignition energies.

Despite a choice of multiple sources relatively dispersed in the vessel the evolution of the overpressure remains limited around 280 kPa.

The second part of the figure corresponds to a strong ignition energy $E_{\text{ign}} = 12000 \text{ J}$. 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 the ignition area with a slight decrease of the overpressure.

These evolutions are verified for all dispersed ignitions and similar data may be observed if the ignition compartments are fitted with vents, but the pressures obtained are evidently reduced.

Finally in conclusion, all the cases observed lead to the following results :

- in the case of a dispersed ignition, a noticeable overpressure progressively forms with a maximum in the furthest part of the structure corresponding to a pressure pilling phenomenon. This effect is as much reduced (up to 70%) as ignition is central.
- except in the ignition compartment where the pressure is as much higher as the ignition energy is stronger, the maximum pressure reached does not generally depend on the nature, the location or the energy supply of the initiation.

Comparable results with higher overpressures are obtained with dust suspensions. Some interesting differences may be observed with gaseous substances [2] which gives to two-phase mixtures a specific and intermediate behaviour. The partitioning effect is more important than for gaseous mixtures [2] and there is no global evolution of the pressure increase in all compartments for high ignition energies or for a multi-source initiation. The description proposed seems to be globally in good agreement with experimental data and it seems possible to extend the simulation to the description of more complex multi-partitioned structures

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