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Partitioning effect on a dust explosion

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Extended abstract :

Dust explosions often have in the past created dramatic situations and consequences. These phenomena are actually the subject of very advanced studies. However, if different works have tried to improve the present knowledge on safety, it remains difficult to predict the explosive properties of a reactive dust suspension in partitioned industrial or agricultural plants. Over the last past years, a simple modelling[1] 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. Furthermore, it has been experimentally verified for gaseous mixtures[2] that very important overpressures went on in all the adjoining areas of the ignition compartment for a multi-partitioned vessel. We envisage now, to clarify the existence of such phenomena in the case of dust explosions. The aim of this work is to extend the model validation to usual dust suspensions such as cornstarch, cellulose or aminophenazone and to study the chain propagation of a dust explosion inside a partitioned vessel. We consider that the combustion of the solid fuel (dust suspension) may be described by collisions between particles of the gaseous phase and those of the solid phase. The reactive system is composed of molecules in gaseous phase and active molecules[1]. The energy flux brought to the solid leads to its degradation by the active molecules and to the dissociation by the other molecules in the gaseous phase. All those phenomena contribute to the solid destruction. The combustion of the solid fuel takes place in a closed partitioned vessel[1]. 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 thermodynamical 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[3] P_v. The initial thermodynamical characteristics of the medium are determined (pressure P_o , temperature T_o) or may be calculated (internal energy, total number of gaseous molecules) from oxygen-nitrogen-fuel amounts in the vessel. 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[1].
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 equations gives the access for the whole structure to thermodynamical factors and to the calculation of the time evolution of the pressure, the rate of pressure rise and the regression velocity of the solid grains.
The model is applied to various solid fuels with different physico-chemical characteristics and different grain sizes such as D_g = 10 μm for cornstarch, D_g = 35 μm for cellulose and D_g = 8 μm for aminophenazone. The indicated numerical values correspond to medium distribution values, that are representative of experimental results.

Figure 1 presents experimental and theoretical curves relative to a cornstarch-air mixture in the case of the time evolution of the pressure. The experimental curve is due to Senecal[4] for a large spherical vessel volume such as V_o = 1900 *l* and a cornstarch concentration Δ = 1 kg/m^3 corresponding to a rich mixture (Δ_{sto} = 0.254 kg/m^3).
The theoretical characteristics of this explosion are then P_{max} = 807 kPa and a Bartknecht's K_{st} factor such as K_{st} = 24.95 MPam/s. The experimental values given by Senecal[4] in the same conditions lead to P_{max} = 810 kPa and K_{st} = 24 MPam/s. The rise times are also quite comparable with values around 130 ms. A good correlation between both curves may be observed.

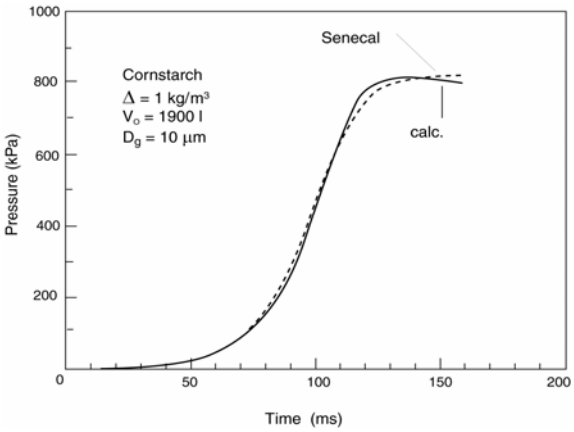

Fig 1 Pressure of explosion vs time.

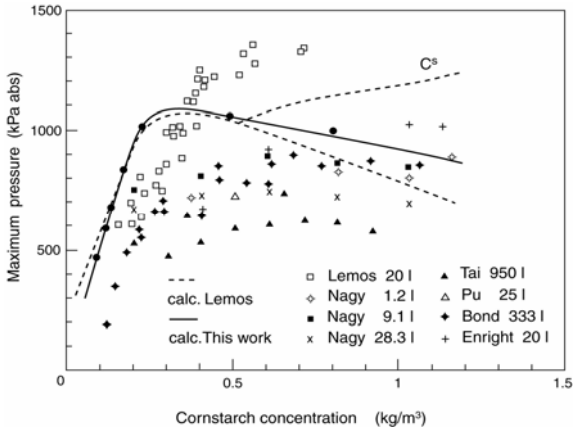

Fig 2 Maximum pressure vs cornstarch concentration. Experiments and calculations.

The maximum pressure calculated from the model (full line) is given in figure 2 as a function of the concentration in the case of cornstarch. This evolution is compared to various experimental results[5] indicated in the figure and to another theoretical simulation (dotted line) calculated by the means of the Quatuor code[5]. This code gives the calculation of the product properties of a chemical reaction for ideal conditions (homogeneous mixture, adiabatic reaction and a complete thermodynamical 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 ($0.25 \le \Delta \le 0.5$ 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. Furthermore, we observe a very good correlation of our model with the Quatuor code for concentrations such as $\Delta \le 0.5$ kg/m^3. For higher values, our result appears as intermediate between both hypotheses of the Quatuor code.

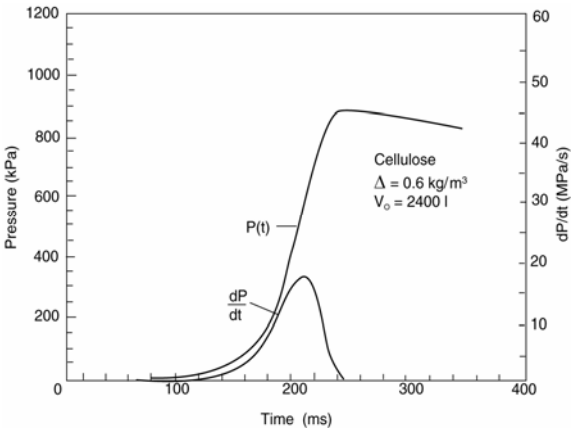

Fig 3 Pressure and rate of pressure rise vs time.

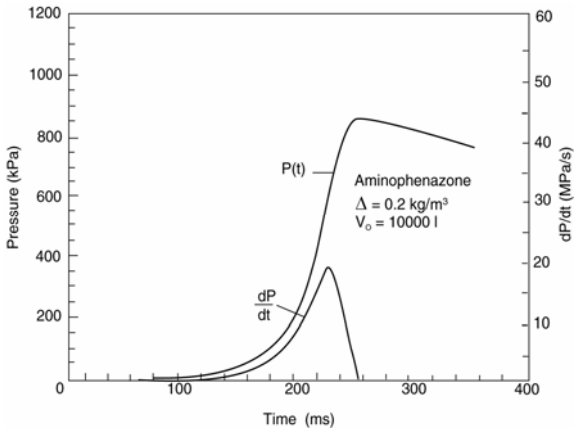

Fig 4 Pressure and rate of pressure rise vs time.

Figure 3 shows the time evolution of the pressure and the rate of pressure rise for a vessel volume such as V_o = 2400 *l* and a cellulose concentration Δ = 0.6 kg/m^3. The theoretical characteristics of the explosion are then P_{max} = 903 kPa and K_{st} = 23 MPa m/s. Experimental results due to Bartknecht[6] in the same conditions lead to P_{max} = 900 kPa and K_{st} = 20.2 MPa m/s.
The time evolution of the pressure and the rate of pressure rise for a vessel volume such as V_o = 10 000 *l* and a concentration Δ = 0.2 kg/m^3 of aminophenazone are presented in figure 4. The theoretical characteristics of the explosion are P_{max} = 870 kPa and K_{st} = 38 MPa m/s. Bartknecht's experiments[6] give in the same conditions P_{max} = 890 kPa and K_{st} = 30.1 MPa m/s.
Figure 5 shows the evolution of the reduced maximum explosion pressure as a function of the vent area for a static venting pressure P_v = 10 kPa in a large vessel volume such as V_o = 10 000 *l* and a slightly rich mixture with a concentration Δ = 0.2 kg/m^3.
The theoretical curve is obtained plotting the different values of P_{red} calculated for each vent opening. The general trend of the curves has the aspect of a decreasing hyperbola with a very good correlation between experimental and theoretical data.

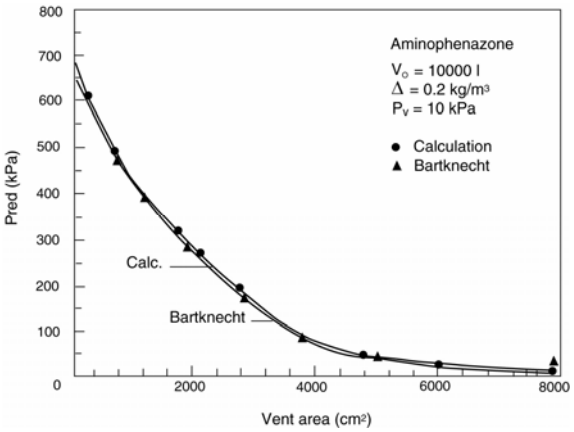

Fig 5 Evolution of the reduced maximum explosion pressure with the vent area.

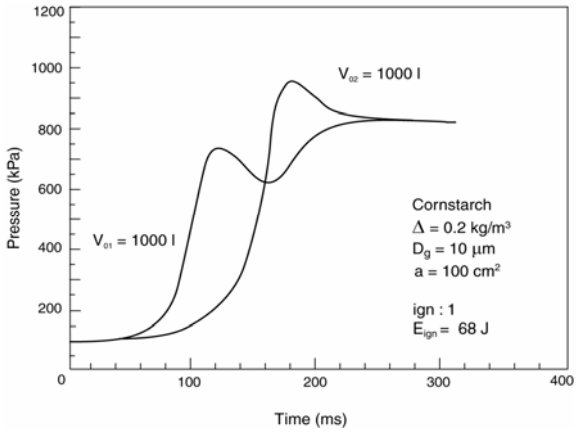

Fig 6 Pressure vs time in both compartments.

Then, different elementary cases with 2 compartments have been analysed in order to test the partitioning effect and the model predictions.
The existence of overpressures in the adjoining areas of the ignition compartment has been experimentally observed in industrial installations with interconnected vessels[6]. After ignition in the first vessel, the flame is accelerated when it enters the second one and becomes very turbulent. According to Bartknecht[6], for identical combined vessels, the maximum explosion pressure in the second vessel may be increased by approximately 10 %. This value may be modified and strongly increased when the explosion propagates from the larger vessel into the smaller one.
In fact, very few quantitative data are available about dust explosions in partitioned vessels and between the different results, the partitioning effect leading to a pressure pilling phenomenon seems interesting to investigate by the simulation. So, we consider a set-up composed of a cylindrical vessel with a global volume such as V_o = 2000 *l*. 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. The thermodynamical conditions are supposed to be homogeneous in the vessel. The combustion of the dust-air mixture may be carried out in both compartments by the means of a central ignition corresponding to 68 J.
Figure 6 gives the time evolution of the absolute pressure in each compartment for a small inner opening a = 100 cm^2 in the case of a cornstarch-air mixture near the stoichiometry.
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.
It can be observed that the maximum pressure obtained is higher in the adjacent compartment than in the initial one, where ignition occurs . The effective overpressure ΔP = 150 kPa is stronger than Bartknecht's experimental results[6] for comparable volumes (about 10% of overpressure) but remains consistent with results obtained by Hu[2] for gaseous mixtures in partitioned vessels.
Furthermore, the maximum pressure reached at the end of the reaction nearly corresponds to the value obtained in a closed vessel with a single compartment such as V_o = 2000 *l*. The observed phenomena do not depend on the mixture which may be rich, lean or stoichiometric.
It is therefore interesting to study the time evolution of the pressure in similar conditions, but for dissymmetric volumes. These evolutions are plotted in figures 7 and 8 for vessel volumes such as V_{o1} = 5000 *l* and V_{o2} = 1000 *l* .

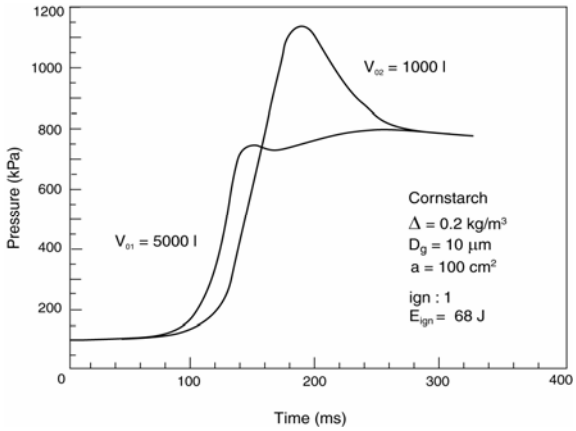

Fig 7 Pressure vs time in both compartments and different locations of the ignition energy.

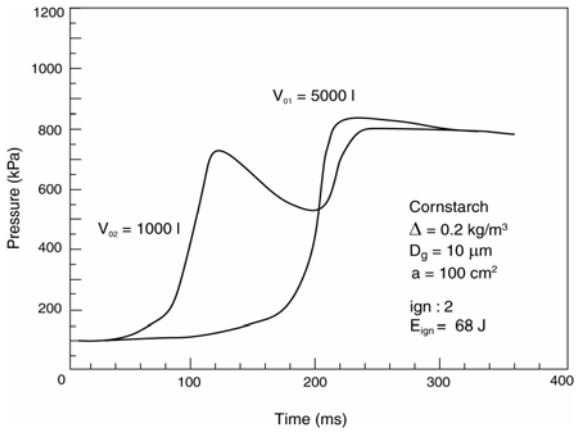

Fig 8 Pressure vs time in both compartments and different locations of the ignition energy.

The ignition may occur in the first or in the second compartment. In both cases and as previously, an overpressure appears in the compartment adjacent to the ignition compartment but both behaviours however remain very different.
The overpressure is very strongly marked when it occurs in the small compartment. In this case, the effective overpressure ΔP = 340 kPa is increased by approximately 40 % in comparison with the ignition compartment with rise times close to 180 ms. Similar data with sometimes more important overpressures have been observed by Bartknecht[6] for comparable interconnected volumes. Experimental data depend strongly enough in this case on the inner opening and on the turbulence created by the propagation of the flame front. The volume effect created in these conditions is maximum and can lead to the destruction of the vessel structure.
On the contrary, when ignition occurs in a small compartment (V_{o2} = 1000 *l*), the initial reaction, limited by the number of available molecules is quickly slowed down by the molecular transfers and the overpressure increases faster in the adjacent compartment than in the initial one. The rise time in the large compartment is delayed and the effective overpressure remains very limited (ΔP = 50 kPa). Similar results are obtained by Bartknecht[6] with an effective overpressure of the order of 7 to 8 %. Finally, more detailed studies show that the delay is all the shorter since the mixture is close to stoichiometric conditions. These different examples clearly show the existence of a partitioning effect but also the influence of a volume effect in each compartment.
Figure 9 starts the same kind of study again, with a more developed structure composed of nine identical cubic compartments (3x3) such as V_{ok} = 1000 *l* and $1 \leq k \leq 9$. 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 reaction progressively expands in the adjoining areas with a delay time and leads to the formation of a progressive overpressure.

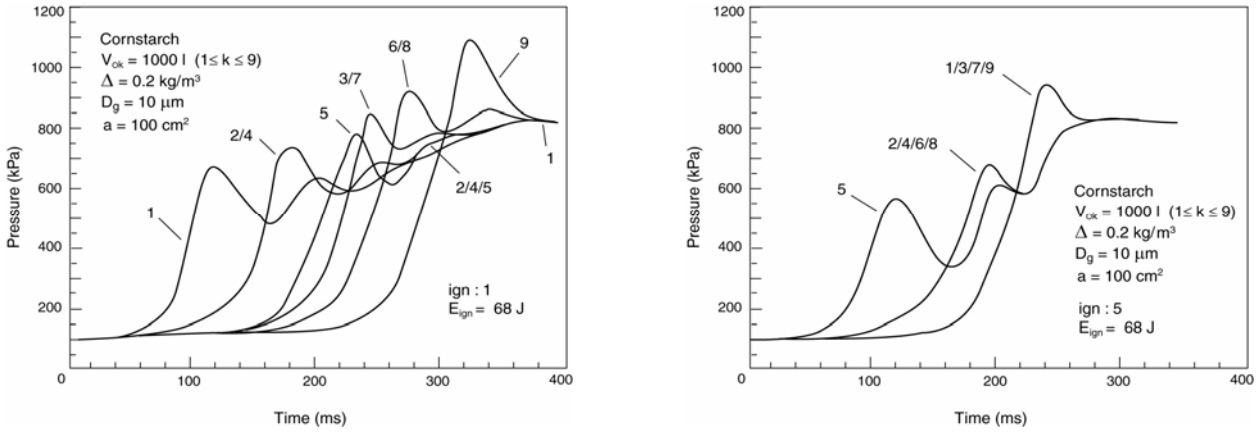

Fig 9 Pressure vs time in a simple partitioned structure and different locations of the ignition energy.

On account of a possible symmetry in the thermal exchanges and the transfers of matter in the course of the reaction, the maximum pressure in each compartment corresponds to relatively close rise times between 320 and 360 ms. The pressure is the same in the symmetrical compartments in comparison with the ignition compartment.

The maximum pressure reached varies between 800 kPa in the first compartment, and 1100 kPa in the furthest compartment (about 35 %), which confirms the amplification of the pressure pilling in the course of the flame propagation.

The second part of the figure, corresponds to a central ignition in compartment 5.

The pressure evolution due to the symmetry is the same in different compartments.

A reduced overpressure about 100 kPa exists between the corners of the structure and the central compartment for final rise times comprised between 250 and 280 ms.

All the cases observed indicate two kinds of situations :

- in the course of a central ignition, the overpressure remains limited and the maximum pressure in each compartment does not sensibly differ from the pressure obtained in the global volume without partitioning.
- in the course of a side ignition, a very important overpressure progressively forms with a maximum in the furthest part of the structure.

The location of the ignition compartment considerably influences the thermodynamical evolution of the mixture and the possible destruction of the structure. The partitioning effect is still more noticeable than for gaseous mixtures[2]. The description proposed for partitioned systems seems to be globally in good agreement with experimental data and it seems interesting to verify this evaluation by studying more complex multi-partitioned structures.

References :

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