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Influence of a multi-source ignition on the kerosene flammability in a partitioned tank

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Abstract :

The aim of this work is to study the effects of a multi-source ignition in a wide energy range on a kerosene explosion inside a partitioned tank. The initiation is introduced in the form of internal energy and a calculation methodology, particularly interesting in the field of the risk assessment is used to simulate 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 basic characteristics of the model have been developed for the ignition and the combustion of propulsive powders and adapted to liquid fuels with appropriate parameters linked to simplified kinetics. A simple representation of the combustion phenomena based on energy transfers and the action of specific molecular species is presented. The model allows the study of various parameters such as the initial thermodynamical conditions, the different ignition energies and their locations, the size of the inner openings or the vent areas. The theoretical results have been compared with data obtained in the course of experiments performed in a small vessel volume and indicate correct preliminary tendencies.

Keywords : collisions; overpressures; compartments; ignition energy

INTRODUCTION

Over the last past years, both experimental and theoretical studies have been carried out on the combustion of liquid droplets (Aggarwal,1985) such as pentane, decane (Sirignano,1988) and in a more specific way kerosene. The combustion of kerosene droplets has received much recent attention because of its importance in power-generating equipment, especially in high output military aircraft propulsions systems. Various models have been developed to calculate the combustion velocity or determine the reaction temperatures. The physical processes involved in ignition and combustion of liquid fuels are generally complex and the theoretical predictions often remain limited, particularly in the field of the risk assessment. In the course of previous works, we have presented a simple modelling (Pascaud,1999), initially developed as part of a novel study on ignition and combustion of classical propulsive powders in order to predict the main characteristics of these explosions in a closed or a vented partitioned vessel. The reaction mechanisms and the energy transfers are explained by the action of specific molecular species (active and condensable molecules). The model needs the knowledge of some parameters linked to simplified kinetics, to energy transfers and to thermal exchanges. The pressure venting, due to the vent breaking may be calculated (Bradley,1978) from thermodynamical characteristics given by the model and taking into account the mass rate of discharge of the different products via the vent . A calculation methodology (Pascaud,2000) 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 effects induced by a multi-source ignition on the kerosene flammability in a partitioned tank and a wide energy range ($E_{ign} \leq 5000$ J).

The proposed development allows the study of varied initial conditions (pressure P_o, temperature T_o, volume V_o) which may differ for the various compartments, the influence of different parameters such as the equivalence ratio of the mixture, the supply and the location of the ignition energy (several simultaneous sources are envisaged), the venting effects and the vent sizes between the compartments. Simulated predictions have been compared with experimental results obtained in the laboratory in a two-compartment vessel $V_o = 13.2\ l$ and a special kind of kerosene (F.34).

MODELLING ELEMENTS

General hypotheses :

We consider that the combustion of the kerosene droplets may be described by collisions between particles of the gaseous phase and those of the liquid phase. The reactive system is composed of molecules in gaseous phase, active molecules and condensable molecules (Pascaud,1999).

- the active molecules are highly energetic particles which principally provide a new gaseous molecule by interaction on the liquid droplets. This phenomenon leads to increase the elastic collision rate.
- the condensable molecules are molecules of the gaseous phase which are able to condense on the liquid droplets by a change of state reaction with the corresponding energy supply.

The next assumptions (Pascaud,1999) summarise the different interactions envisaged by the model. The energy flux brought to the liquid fuel leads to its degradation by the active and condensable molecules and to the dissociation by the other molecules in the gaseous phase. All those phenomena contribute to the destruction of the liquid fuel. The combustion of the kerosene droplets takes place in a closed partitioned vessel (tank). The initial conditions for temperature and pressure are supposed to be homogeneous in the vessel.

The model takes into account the efficiencies of the active and condensable molecules, the supplementary energy supply due to collisional interactions leading to a progressive destruction of the liquid droplets, the energy release of the active molecules and the self-condensation of condensable species in the gaseous medium and the dissipative phenomena due to active, condensable or gaseous molecules on the vessel wall and by thermal losses. In the case of liquid droplets, thermal exchanges are essentially composed of convective heat transfers.

The description of these physical processes allows the model implementation in the form of a set of differential equations (Pascaud,1999).

Chemical kinetics :

Among the products which may be obtained with C_xH_y liquid fuels we only consider :

- gaseous molecules $X_i = CO_2, CO, H_2O, O_2$ and H_2.
- active molecules $X_i^* = CO_2^*, CO^*$ and H_2O^*.
- only one kind of condensable molecule C^g.

The destruction reaction of the liquid fuel with the oxygen of the air is considered with oxygen in excess and gaseous carbon able to condense. Hence equation (R) :

$$C_xH_y + mO_2 \rightarrow \alpha CO_2^* + (x-\alpha-\beta)CO^* + (2m-2r-x-\alpha+\beta)H_2O^*$$
$$+ \left(\frac{y}{2}+x+\alpha-\beta+2r-2m\right)H_2 + rO_2 + \beta C^g$$

For initial determined conditions, it is possible to calculate the equivalence ratio of the mixture and the amount m (or m_{sto} at the stoichiometry) of oxygen necessary to the combustion which implies to adapt the global chemical equation to take into account (Pascaud,2000) particularities of rich and lean mixtures.

Equivalence ratio and concentration :

The liquid fuel is introduced into the tank containing air at the initial temperature T_o. The liquid fuel evaporates . Some molecules change from the liquid phase to the gaseous phase . The equilibrium between both liquid and gaseous phases is obtained when the partial pressure of the fuel vapor reaches the saturated vapor pressure. The combustion of the kerosene is likened to the combustion of a spray or a mist of liquid droplets perfectly stirred. The combustion of small liquid droplets with a mean value of the diameter $D_g = 10\mu m$ is supposed to be similar to the combustion of the kerosene vapors . However the equivalence ratio of the mixture is completely determined by the thermodynamical conditions in the vessel and therefore by the characteristics of the gaseous phase. Using Dalton's law on the partial pressures the equivalence ratio φ of the mixture is then (Pascaud,1999) :

$$\varphi = \frac{m_{sto}}{m} = m_{sto}\frac{P_{po}}{P_o - P_{po}} \qquad (1)$$

where P_{po} is the partial pressure of the kerosene vapors.

The experimental determination of the partial pressure P_{po} of the kerosene used, has been carried out in the laboratory by I. Sochet (1998). It has been shown that the partial pressure could be written for the studied range of temperatures :

$$P_{po}(Pa) = \exp\left[\, 18.5 - 3506.6 / T_o \,\right] \qquad (2)$$

where T_o is expressed in degrees Kelvin.

It can be noticed that the partial pressure of the kerosene only depends on the initial temperature. In the same way, the equivalence ratio is completely determined by the initial conditions.
The kerosene concentration Δ may be deduced (Pascaud,1999) :

$$\Delta = \frac{M_p P_{po}}{RT_o} \qquad (3)$$

M_p is the molar mass of the liquid fuel .
R is the perfect gas constant.

Hence :

$$\Delta = \frac{M_p}{RT_o}\exp\left[\, 18.5 - 3506.6 / T_o \,\right] \qquad (4)$$

Ignition energy :

In the course of the ignition process, a little amount of kerosene is initially destroyed. The destruction of the kerosene molecules 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. However, in some cases, the deactivation of reacting species, by collisions on the kerosene droplets, collisions on the wall, energy release or self-condensation in the gaseous medium may become a predominant phenomenon and the reaction may not go on. This situation may correspond to particular initial thermodynamical conditions (for instance with low temperatures) or eventually a too weak initial destruction of kerosene molecules. Ignition appears therefore as the essential element in the development of the reaction. Several parameters directly or implicitly influence the initial evolution of the reaction. Several hypotheses such as the initial amount of kerosene burnt, the time variation linked to this destruction, the creation of a hot point in the mixture or the initial increase in the internal energy are susceptible to influence the reaction conditions. Even though these different factors give similar global evolutions, their introduction at different steps in the model also confers them a specific behaviour. The last assumption has been more particularly envisaged to obtain reactions in a range of low temperatures with high ignition energies.

So, we will consider afterwards that the total ignition energy E_{ign} initially allows to increase the internal energy U. Only a part of this energy estimated to 10% is really provided to the reactive mixture. We have then :

$$U = C_v (T - T_o) + r E_{ign} \qquad (5)$$

with r =10% and where :

T is the temperature in the gaseous phase,

T_o the initial temperature,

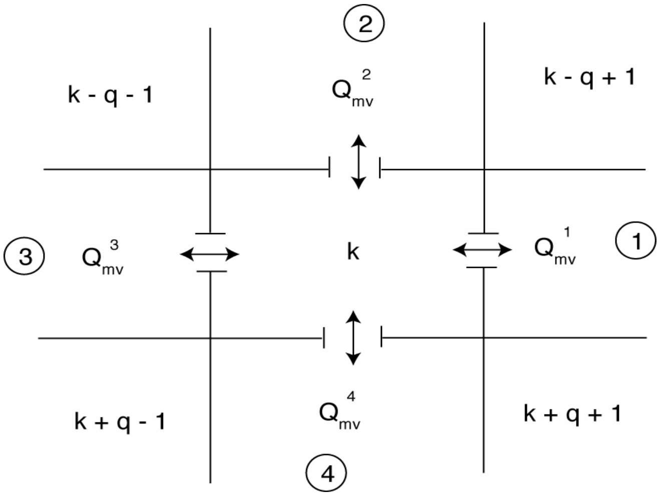
C_v the global specific heat capacity.

This assumption corresponds to a global energy transfer and seems to be adapted to a multi-source ignition which remains essentially scattered in the tank.

Partitioning effect, pressure venting and thermodynamical factors :

In the general case, the considered structure defines a surface composed of several compartments. For a surface comprising p lines and q columns the total number of compartments is pq.

For a compartment $k \in [1, pq]$ we obtain the following pattern :



The adjacent compartments are connected by inner openings with variable dimensions. The reaction expands in compartments corresponding to a given initial ignition E_{ign} (Pascaud,2000).

The difference of pressure with the adjacent compartments leads to a transfer of matter towards these compartments and particularly to a supply of active and condensable species .The destruction energy flux due to these molecules progressively increases as well as the internal energy. These processes ignite the reaction. Similar phenomena occur in all adjoining areas. The reaction goes on and a thermodynamical equilibrium is obtained.

The position of the various compartments in the considered area is linearly described. A matrix description may also be used. For a central compartment, four transfers of matter Q^{s}_{mv} (s = 1,2,3,4) are envisaged with the adjoining areas. For a compartment on the side, there is no transfer with the outer environment (Pascaud,2000).

Furthermore, for one or several specific compartments , vent areas may be fitted out on the outer surface of the tank. The characteristics of each compartment (thermodynamical conditions, surface, volume, vents and configuration of inner openings) are initially introduced in the calculation code. The transfer of matter between a reference compartment k and an adjacent compartment l occurs when the pressures are different in both compartments. The total mass rate of gaseous substances Q^{s}_{mv} due to the difference of pressure between two adjacent compartments or the surrounding atmosphere is given by the standard orifice equations due to Bradley (1978). The amount of the liquid 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 (Yao,1974) 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 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 reduced pressure in the case of vented explosions and a multi-source ignition.

RESULTS

We intend to study the kerosene explosions in a multi-partitioned structure. Different elementary cases are analysed in order to validate the model predictions. A generalisation to more complex systems may be envisaged afterwards in order to study the influence and the effects of a single or a multi-source ignition on these structures. The two-compartment system has been the aim of experimental studies (Sochet,2000) at the LEES and will be particularly used to test the model behaviour.

Experimental validation :

Experiments have been performed in a cylindrical vessel with a global volume such as $V_o = 13.2\ l$. A horizontal steel plate allows to define two compartments with respective volumes such as $V_{o1} = 4.8\ l$ in the upper part and $V_{o2} = 8.4\ l$ in the lower part. Both compartments are connected by a small inner opening positioned in the centre of the plate. Several plates may be used corresponding to various inner openings. The thermodynamical conditions are supposed to be homogeneous in the vessel. The ignition of the kerosene vapors may be carried out in both compartments by the means of an exploding wire fixed at the end of a central electrode. In the performed experiments, the ignition energy corresponds to 68 J. The effective nominal energy is supposed to represent about 10 % of this value. The vertical position of the electrode may be modified allowing different heights for the ignition. The influence of this last parameter has been experimentally studied and does not seem to be really marked. So, we will consider afterwards, that ignition is essentially a central ignition in the chosen compartment. Each compartment is fitted out with a Kistler pressure gauge (Sochet,2000).

Figure 1 shows the time evolution of the pressure in each compartment for different inner openings with a surface such as $a = 1.26\ cm^2$ or $a = 16.6\ cm^2$. The ignition compartment is indicated in each diagram. Experimental curves (Sochet,2000) are compared to the model predictions in a very rich mixture ($\varphi = 2.2$ for $P_o = 300$ kPa and $T_o = 373$ K). Experimental results indicate a difference of pressure between both compartments around a mean value which nearly corresponds to the value obtained in a closed vessel with a single compartment such as $V_o = 13.2$ *l*.

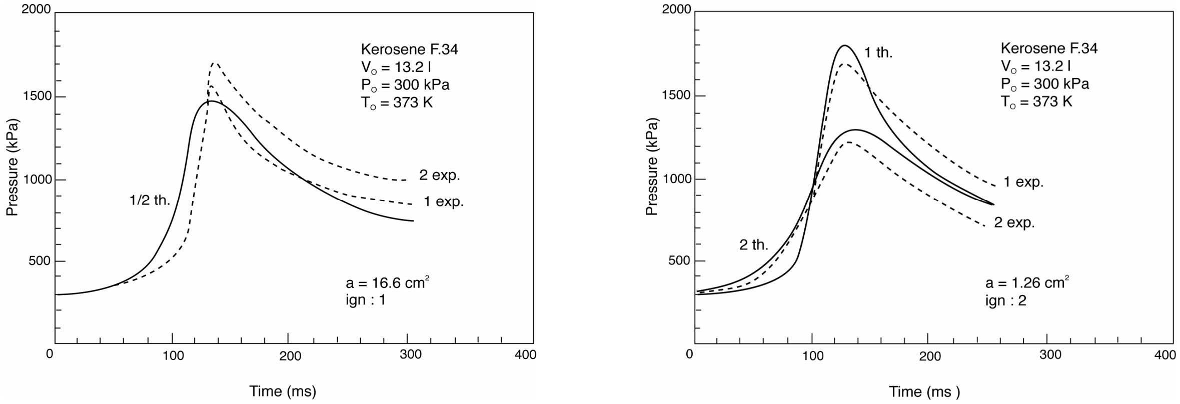


Fig 1 Pressure vs time in both compartments for different inner openings.

The rise times corresponding to the maximum pressures are also quite comparable. The observed phenomena do not depend on the mixture which may be rich, lean or stoichiometric.

The difference of pressure measured between both compartments seems to be smaller for large inner openings ($\Delta P = 600$ kPa for $a = 1.26$ cm^2 and $\Delta P = 120$ kPa for $a = 16.6$ cm^2).

On the other hand, it can be observed in all cases, that the maximum of pressure obtained is higher in the adjacent compartment than in the initial one, where ignition occurs (Fairweather,1998). This effect may be explained by a molecular transfer towards the adjacent compartment, which modifies the concentrations in the reactive mixtures and therefore, the maximum pressures reached.

The effect progressively mitigates for large vent openings. Then, the reactive system is likened to a single compartment and the pressure evolution should be the same in both parts of the vessel.

The model predictions are quite comparable with experimental results. In particular, for a small inner opening ($a = 1.26$ cm^2), the model perfectly describes the difference of pressure which is observed between both compartments, with correct rise times in the region of 120 ms. Moreover, at the end of the reaction, a thermodynamical equilibrium is obtained in the mixture and the pressure evolution is shared by both compartments.

For large inner openings ($a = 16.6$ cm^2), the theoretical pressure evolution is always the same in both compartments, whereas a reduced difference subsists in the experimental evolution.

Even though the influence of the inner opening may be improved and precised, a good enough correlation is obtained between theoretical and experimental curves, in the determination of the maximum pressures and the rise times.

Figure 2 shows the evolution of the maximum pressure for different inner openings with a surface such as $a = 1.76$ cm^2 or $a = 16.6$ cm^2. The ignition occurs in the first compartment. The experimental measures in each compartment are compared with the model predictions and the corresponding points are plotted in the figure. Experimental results indicate an overpressure in the second compartment. The difference of pressure ΔP between both compartments seems to be practically the same, for a given initial pressure, whatever the size of the inner opening. However, for large openings, a homogeneous pressure in both compartments and therefore a decrease of ΔP may be expected. The experimental evolution of ΔP is a function of the initial pressure and extends between 200 and 800 kPa. Most maximum pressures given by the model are in agreement with experimental results with margins of error about 10 to 15 %. It can be noticed that, for large inner openings, the theoretical maximum pressures merge together in both compartments, whereas this effect is not yet experimentally observed. This phenomenon may be explained by a molecular transfer towards the adjacent compartment, which modifies the concentrations in the reactive mixture and therefore, the maximum pressures reached. Then, the reactive system is likened to a single compartment and the pressure evolution should be the same in both parts of the vessel.

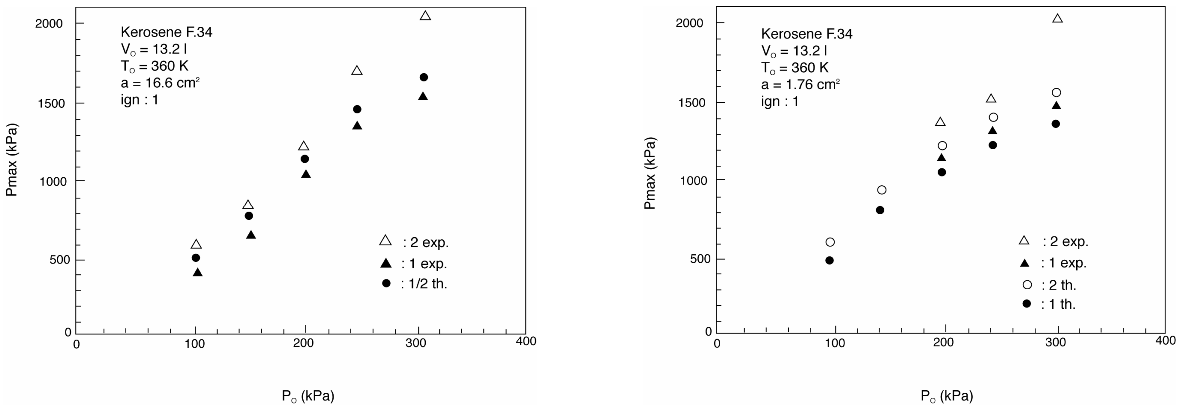


Fig 2 Maximum pressure as a function of the initial pressure in both compartments for different inner openings.

However, the calculated maximum pressure remains quite compatible with the mean pressure deduced from both experimental values.

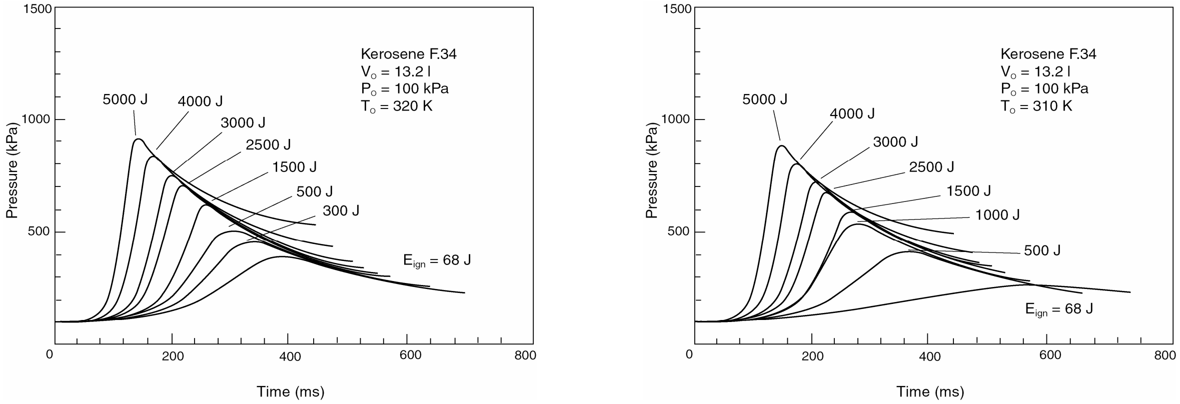
For small inner openings, the model also predicts an overpressure in the second compartment. For intermediate initial pressures (200 – 250 kPa) the theoretical difference of pressure ΔP = 150 kPa is very near the experimental value ΔP = 200 kPa . We can notice again, a slight gap about 10 to 15 % between the absolute values of theoretical and experimental pressures in each compartment.

These first results seem to show a good adaptation of the model to the description of kerosene explosions in a closed two-compartment vessel.

Influence of a single ignition :

It is interesting now to study the influence of the ignition energy on the kerosene explosions for ambient temperatures comprised between 290 and 320 K and an initial atmospheric pressure. For higher temperatures, ignition is obtained without difficulty, even with very weak energies.

Figure 3 shows the calculated time evolution of the absolute pressure for the chosen temperatures and a wide range of ignition energies between 68 and 5000 J. The effective nominal energy represents 10% of these values. The reactions expand in a single closed compartment with a volume $V_o = 13.2\ l$ and a pressure $P_o = 100$ kPa.



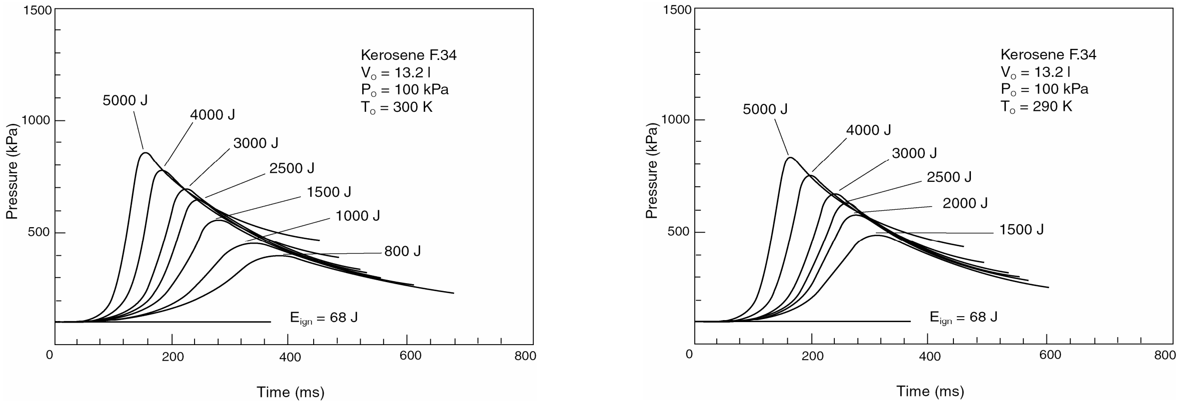


Fig 3 Pressure vs time for different ignition energies.

The essential result is the feasibility to initiate the reaction in all the studied cases. It can be noticed that for low temperatures, the ignition energy must be strongly increased (700 to 800 J). These values may be obtained for instance by the means of projectile impacts .Furthermore, we observe that the reference ignition energy E_{ign} = 68 J is not sufficient to initiate the reaction for temperatures lower than 300 K. In all cases, the increase of the ignition energy classically corresponds to a progressive increase of the maximum pressure reached and to strongly reduced rise times. These evolutions seem to be in accordance with experimental trends (Sochet,1998). Similar results are obtained in vented vessels with much more reduced maximum pressures. The previous study may be generalised to partitioned vessels. Then, the evolution of the reaction depends a lot on the location of the ignition area. In this part, ignition will be considered only in one compartment.

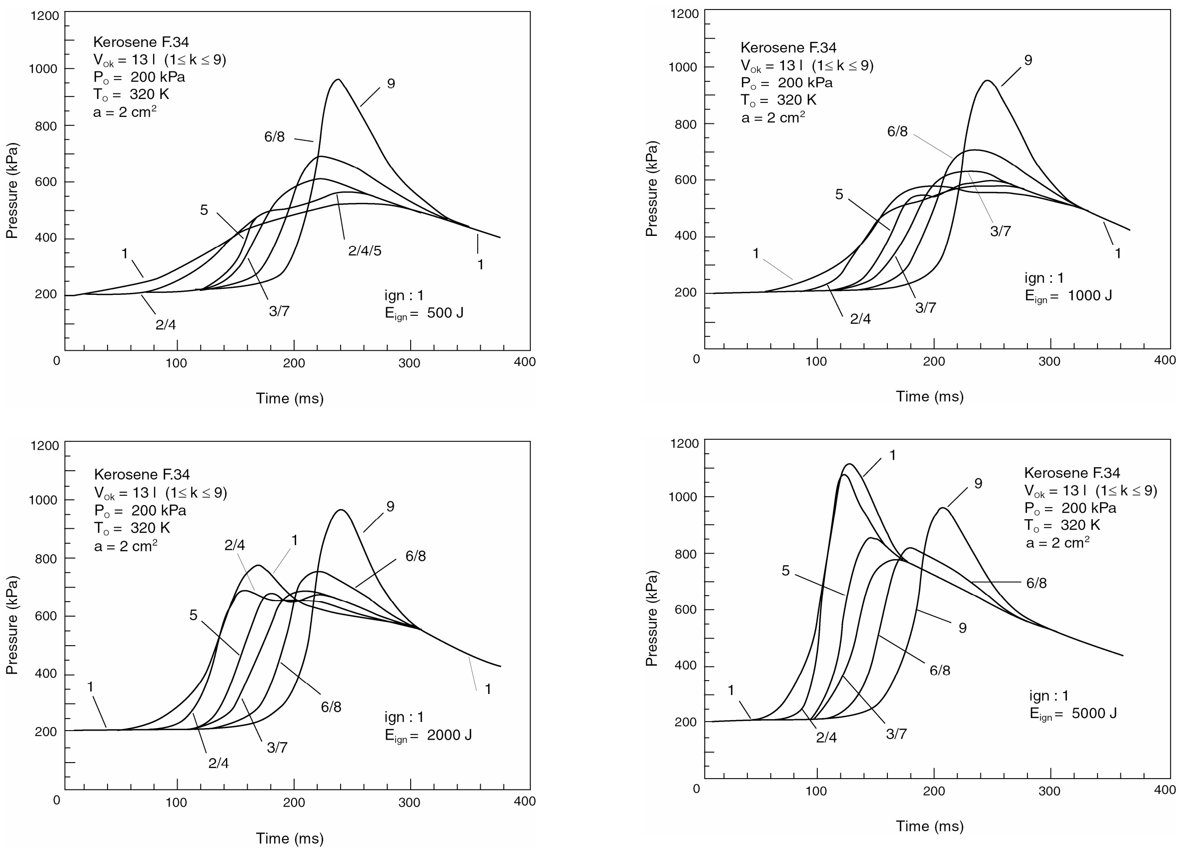


Fig 4 Pressures vs time for a side ignition and different ignition energies.

Figure 4 shows the time evolution of the pressure in each compartment of a vessel composed of nine identical compartments (3x3) such as $V_{ok} = 13\ l$ and $1 \leq k \leq 9$, for initial conditions near the stoichiometry. All the adjoining compartments are connected by a small inner opening $a = 2\ cm^2$.

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 and very important 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 220 and 250 ms. The pressure is the same in the symmetrical compartments in comparison with the ignition compartment. The maximum of pressure reached varies between 500 kPa in the first compartment, and 950 kPa in the furthest compartment, which is consistent with the previous results (Fairweather,1998).

The other parts of the figure are obtained in the same conditions, but for much higher ignition energies such as E_{ign} = 1000, 2000 or 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.

This effect is particularly evident for E_{ign} = 5000 J where the maximum pressure varies between 800 and 1100 kPa and the rise times decline from 220 to 120 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 slight overpressure about 120 kPa exists between the corners of the structure and the central compartment for rise times in the region of 200 ms.

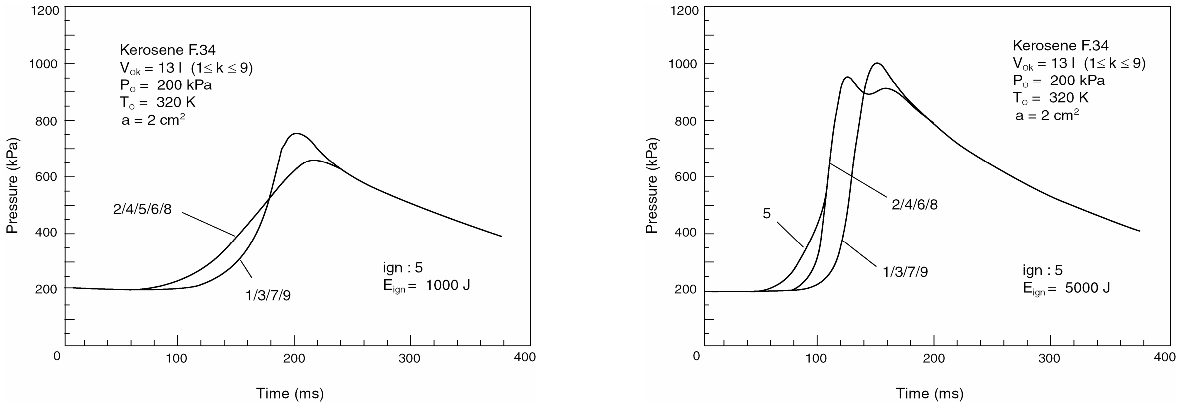


Fig 5 Pressures vs time for a central ignition and different ignition energies.

The second part of the figure shows a similar evolution with higher pressures and quicker rise times. The overpressure observed is only about 60 kPa. In both cases, the pressure evolution is relatively homogeneous in the different compartments of the structure. The overpressure observed remains very limited and is practically independent of the ignition energy. It appears therefore interesting to study the influence of a multisource- ignition on the pressure evolution.

Influence of a multi-source ignition :

Figure 6 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 first part of the figure corresponds to an intermediate ignition energy E_{ign} = 1000 J. The reaction expands around the ignition areas and leads to the formation of a progressive overpressure. The maximum of pressure reached varies between 550 kPa in the corners and 850 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, but the overpressure observed is reduced of about 30% around 300 kPa.

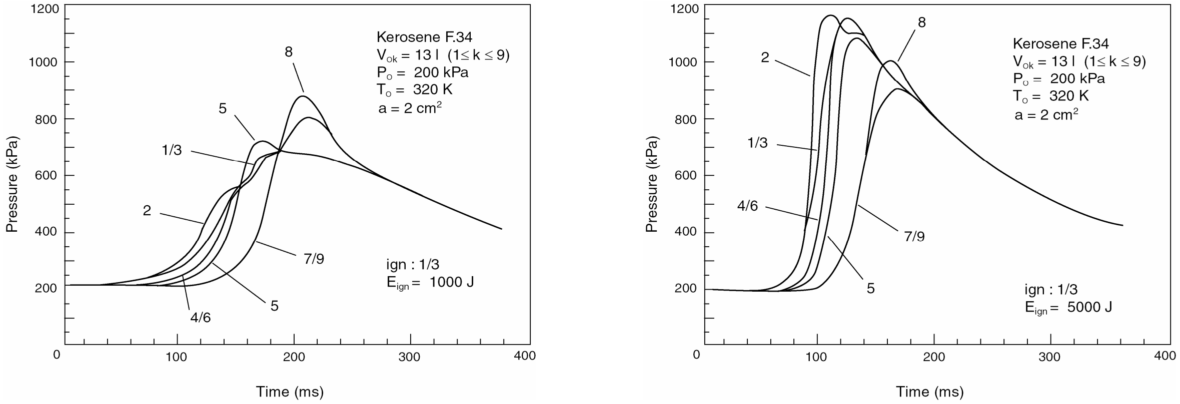


Fig 6 Pressures vs time for different locations and ignition energies.

The second part of the figure corresponds to a strong ignition energy E_{ign} = 5000 J. A decrease of the rise times and a marked strengthening of the maximum pressure close to 1150 kPa may be noticed in and around the ignition compartments. As previously, for a high ignition energy, the pressure pilling phenomenon is completely mitigated in the furthest part of the structure.

Figure 7 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 700 kPa in the corners and 900 kPa in the furthest symmetric area corresponding to compartment 9. The main result is the reduction of the overpressure when the number of ignition sources located in various points of the structure increases.

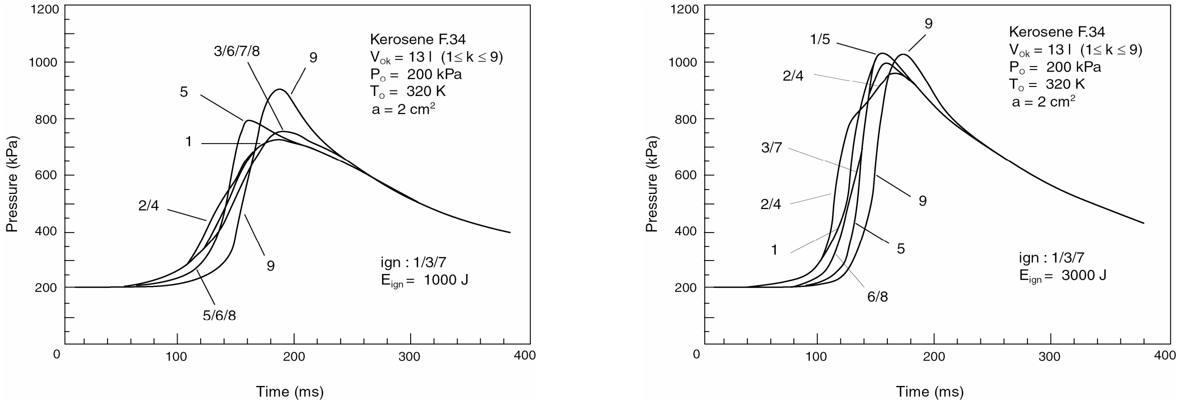


Fig 7 Pressures vs time for different locations and ignition energies.

The second part of the figure corresponds to a strong ignition energy E_{ign} = 3000 J. The pressure evolution is practically homogeneous in the different compartments and close to the evolution obtained in the global compartment corresponding to the same conditions and for a global ignition energy E_{ign} = 9000 J.

Figure 8 shows the time evolution of the pressure for a same four-source ignition in compartments 1,2,4 and 5 localised 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 800 kPa in the ignition area and 900 kPa in the furthest part corresponding also to compartment 9.

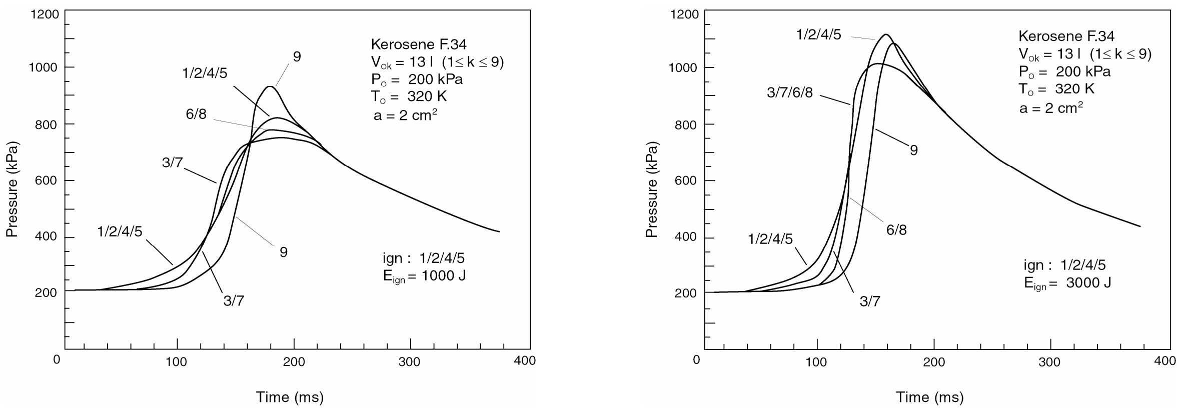


Fig 8 Pressures vs time for different locations and ignition energies.

Despite a relatively confined initiation, the scattering of the sources leads to a limited overpressure around 100 to 200 kPa and approximately constant rise times near 180 ms.

The second part of the figure corresponds to a strong ignition energy E_{ign} = 3000 J. The evolution observed is practically homogeneous without overpressure in compartment 9. It appears therefore that a scattered ignition creates favourable conditions to get homogeneous pressures in each compartment even for weaker ignition energies. This evolution may be verified for all polydispersed ignitions, in particular in the case of compartments 1,3,7 and 9. The location of the ignition energy considerably influences the thermodynamical evolution of the mixture and the possible destruction of the structure.

Similar results may be observed if the ignition compartments are fitted with vents, but the pressures obtained are reduced. In conclusion, all the cases observed indicate two kinds of situations :

- in the course of a central or a scattered multi-source ignition, 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 confined multi-source ignition located in a side compartment and for low ignition energies, a very important overpressure progressively forms with a maximum in the furthest part of the structure. The overpressure mitigates for higher ignition energies.

CONCLUSION

The previous results show a good adaptation of the model to the description of closed or vented kerosene explosions inside a two-compartment vessel. More generally, the proposed development allows the study of a multi-source ignition in a partitioned tank. The initial energy supply to the internal energy and the calculation of the hot flow by the means of the standard orifice equations through the inner openings seems to be representative of real simple cases. Experimental and theoretical results show that in all cases, an overpressure appears in the adjoining areas to the ignition compartment which may lead to a pressure pilling phenomenon. According to this work, this evolution is strongly reduced in the case of a central or a scattered multi-source ignition.

It is possible with the model to calculate the time evolution of the pressure and to localise its effects in each part of the structure which can be used to adapt protection conditions in the different fields concerned and particularly in Aeronautics. The model may be used in a rich or a rich mixture and seems to be representative of varied conditions such as the thermodynamical conditions, the location of the ignition energy or the venting effects. The validation will have to be precised by studying experimentally more complex multi-partitioned structures.

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