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Evolution of a Detonation Wave in a Cloud of Fuel Droplets: Part I. Influence of Igniting Explosion

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A numerical investigation is presented in which the whole problem of energy release in a combustible spray-gas mixture is solved. The influence of the igniting explosion strength and energy density on the parameters of the shock waves traveling in the media is delineated. The main conclusion is that the increase of the volume of the igniting source provides better ignition characteristics.

Nomenclature

C_D = drag coefficient
D = detonation wave velocity
E_0 = energy of the igniting source
ℓ = average radius of the droplet
L = heat of evaporation
M = drag function related to the exchange of momentum between components
N = number of droplets per unit volume
Nu = Nusselt number
P = pressure
Q = thermal effect of the chemical reaction per unit mass of the fuel
r_0 = initial radius of the igniting source
r = space variable
Re = Reynolds number
t = time
T = temperature
V = mass velocity
γ = effective isentropic exponent of the gas
δ = variable proportional to the rate of size reduction of the droplet
μ = dynamic viscosity
ϕ = equivalence ratio
ρ = average density of the component
κ = heat conduction coefficient of the gas

Subscripts

Det = detonation wave
sa = shock average
0 = referring to the front of the igniting source
1 = referring to the dispersing gas
2 = referring to the droplets
∂_t = partial derivative according to time
∂_r = partial derivative according to radius

Superscript

i = initial value

I. Introduction

THE evolution of shock and detonation waves in fuel clouds is a process occurring in many burners using fuel sprays or in fuel injection combustors. Different aspects of these or related problems were investigated during the last two decades.[1-6] Detonation in fuel clouds for military purposes is also reported.[7]

Fuel clouds are formed either accidentally or by free will for special purposes. In the first case, ignition and especially detonation are highly unwanted. In the second case, ignition is usually requested, but detonation is seldom the wanted phenomenon.

In all of the cases, the questions asked and the parameters required to be estimated are the same:

1) What is the strength of the blast needed for the initiation of the detonation in the medium?

2) What are the parameters of the shock wave after the initiation, and will it become a detonation?

Some of the experimental studies[2,8,9] help in the general understanding of the basic questions related to the detonation wave propagation:

1) What are the dynamics of the transition from blast to detonation that depend on the blast and on the medium parameters?

2) What is the structure of the detonation waves in the two-phase medium?

3) What is the mechanism of reinforcement of the shock waves by energy release in the reaction zone?

4) What is the reason for the instability in the reaction zone of the two-phase detonation?

Because of the complexity of the problem, the theoretical works deal usually with only one of the preceding questions. The mathematical tools used in each case were especially adapted to the problem.

For the question of transition from blast to detonation, self-similar solutions were used.[10,11] For the question of defining the structure of the detonation waves, the model of steady-state detonation was used.[12,13] And, for the mechanism of reinforcement of the shock waves and instabilities in the reaction zone problems, rough approximations were used[14] along with self-similar solutions.[11]

Obviously, all aspects concerning two-phase detonation are connected to each other, and dealing with each aspect apart may not reveal the real phenomena.

It was the aim of this study to solve numerically, in the most general form, the whole problem of the two-phase detonation, to calculate the dissipation of energy from an explosion in a fuel cloud, and to follow the fate of this energy impulse till it causes ignition of the medium or eventually becomes a detonation.

The problems presented herein are the study of the influence of the size of the igniting source and its energy, and the way the shock wave is transformed to a detonation wave.

II. Exposition

A. Presentation of the Problem

Energy is released within a cloud of fuel droplets in an oxidizing atmosphere and causes the cloud to burn and eventually to detonate. The energy is released in a finite

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volume, and its origin can be an explosive discharge, a concentrated laser beam, etc.

After the release of the energy, there is a radiation period. The heat exchange between the high-energy zone where the energy was just released and the rest of the cloud medium is done mainly through radiation. However, it was shown that this period is very short even when the gas is completely transparent.[15,16] In our case, where the medium is a fuel droplet cloud partially opaque, this period is negligible.

The second period is the gas-dynamic evolution of the explosion. Most of the energy released is transferred to the media in its closest vicinity, and a shock wave appears that causes a detachment between the explosion volume and the rest of the undisturbed cloud. The distribution of the gas-dynamical parameters behind the shock wave depends mainly on the source of the energy. If the source is a nuclear explosion or a concentrated laser beam, the parameters can be calculated with reasonable accuracy according to the Sedov-Taylor model.[17-19]

The third period is depicted by the strong shock wave traveling within the combustible cloud. The pressure on the shock wave is usually larger by a few orders of magnitude than the atmospheric pressure of the cloud, and thus, the counterpressure can be neglected. However, the medium releases energy behind the shock wave, and this energy influences the gas-dynamic parameters behind the shock wave.[20,21]

The fourth stage will occur when the pressure on the shock front decays to two orders of magnitude larger than the counterpressure. Here, the continuation of the shock waves' trajectory is governed by the dynamics of the shattering of the fuel droplets and by the thermodynamic parameters of their combustion.

There are three possibilities for the shock wave's evolution: 1) the complete and rapid dissipation of the shock's energy (because it cannot ignite the cloud); 2) the dissipation of the shock's energy and the formation of a wave of combustion; and 3) the propagation of the shock at constant velocity where the energy dissipation, caused by the shock wave motion, is compensated by the energy release of the burning droplets. There is also an inertial influence of the droplets on the shock's propagation. The droplets acquire a high velocity on the shock's front, and therefore, they can compress the gas behind the shock's front. But, since the velocity of the gas decays faster than that of the droplets, they can cause additional compression waves.[22,23]

Since the conditions of the energy release behind the shock wave in a two-phase medium is dependent mainly on the gas-dynamic and physical parameters of the medium, the solution of the problem of formation and propagation of the detonation waves in the medium is possible in the frame of a gas-dynamic model, taking into account the thermochemistry of the cloud.

It is the authors' intention to explore the influence of the parameters of the igniting source (like the energy of the source, the energy's density, the size of the source, etc.) on the dynamics of formation of a detonation wave in a two-phase combustible mixture.

B. Mathematical Model

The detailed mathematical model is presented separately.[24,25] Here, only the basic assumptions and equations will be presented.

Basic Assumptions

We assume that the medium is composed of an oxidizing gas with fuel droplets. The assumptions about the medium properties conditions are: 1) the droplets are spherical in size; 2) the collision between the droplets can be neglected; 3) the distances where the flow parameters change drastically are much bigger than the size of a single droplet; 4) the volume occupied by the droplets is negligible when compared with the volume of the gas; 5) the density changes and heat transfer processes are relevant only in processes of phase change; 6) the heat transfer coefficient of the droplets is far bigger than the same coefficient in the gas: the temperature gradient in the droplet can be neglected; 7) the dispersed phase (droplets) behaves as a continuous medium; 8) chemical reactions occur only in the gas phase; and 9) the gas phase behaves as an ideal gas.

The theoretical justification for these assumptions can be found in Rudinger,[26] Nigmatulin,[27] Borisov et al.,[12] and Nettleton.[28]

The velocity and the temperature of the two phases can be different, and phase changes may occur without reaching equilibrium conditions.

It is known that the combustion of the fuel vapors is much faster than the speed of the droplet's shattering/vaporization.[4,5,12] This means that the rate of the energy release is determined by the droplet shattering, and the chemical kinetics of the combustion processes can be neglected.

Conservation Equations

The conservation equations are based on assumption 4 in the former section, according to which they are divided into two separate sets; conservation equations for the gas phase and separately for the liquid phase. The conservation equations for the two phases are interconnected through their right-hand sides.[22]

The conservation equations for the gas phase for a unidimensional case with a spherical symmetry with the Euler coordinates are written according to Nigmatulin[27] and Luikov[29]:

Conservation of Mass

$$\partial_t \rho_1 = -(1/r^2)\partial_r(r^2 V_1 \rho_1) + \delta\rho_2 \tag{1}$$

Conservation of Momentum

$$\partial_t(\rho_1 V_1) = -(1/r^2)\partial_r(r^2 \rho_1 V_1^2) - \partial_r P - \rho_2 M + \delta\rho_2 V_2 \tag{2}$$

Conservation of Energy

$$\partial_t\left(\frac{P}{\gamma-1} + \frac{1}{2}\rho_1 V_1^2\right) = -\frac{1}{r^2}\partial_r\left[r^2\left(\frac{P}{\gamma-1} + \frac{1}{2}\rho_1 V_1^2\right)V_1\right]$$
$$-\frac{1}{r^2}\partial_r(r^2 P V_1) - \rho_2 V_2 M + \delta\rho_2\frac{V_2^2}{2} + \rho_2\delta Q \tag{3}$$

By defining the right-hand side of Eq. (3), the temperature of the droplets during the shattering or vaporization is assumed not to change. Also, it was assumed that the heat of vaporization is negligible compared to the heat of combustion. Both assumptions are acceptable for liquid fuel. For example, for heptane, the heat of combustion is 45×10^6 J, while the heat of vaporization is 0.36×10^6 J at 50°C, which means that the heat of vaporization is less than the size of the error in the value of the heat of combustion.

The conservation equations for the liquid phase, according to Wallis[30] and Luikov,[29] are

Conservation of Mass

$$\partial_t \rho_2 = -(1/r^2)\partial_r(r^2 \rho_2 V_2) - \delta\rho_2 \tag{4}$$

Conservation of Momentum

$$\partial_t(\rho_2 V_2) = -(1/r^2)\partial_r(r^2 \rho_2 V_2^2) + \rho_2 M - \delta\rho_2 V_2 \tag{5}$$

Since the internal energy of the droplets is constant and negligible compared to the gas phase, the equation for the conservation of the amount of droplets is written as

$$\partial_t N = -(1/r^2)\partial_r(r^2 N V_2) \tag{6}$$

Shattering and Vaporization of Fuel Droplets

Two models were used. The first was the aerodynamic shattering which is dominant for droplets between 50 and 800 μm. This model was proposed and named by Engel[40] in 1958, where the droplet is shattered by scaling off the outer parts of its surface by the very fast flow of the gas. Thus, the droplet is shattered gradually while its radius diminishes constantly. The energy necessary for this process is very small compared to the heat of vaporization. This model was experimentally checked with droplets of 50-1500 μm and shock waves with Mach numbers of 1.1-3.5.[2,3,31,32]

The authors' calculations showed that this model alone is not enough to describe the behavior of the droplets, although it describes well the first steps after the drop was hit by the shock wave.

The second model used was the evaporation model, obtained from the energy balance of the droplets with the following assumptions: 1) the drop evaporates evenly on its entire surface; and 2) the temperature of the drop does not change during the evaporation. Thus, from the equation of heat balance of the droplet behind the shock wave, the rate of the droplet's evaporation is found[24]

$$\frac{d\ell}{dt} = -\frac{3\kappa Nu(T_1 - T_2)}{\pi \ell \rho_2^i L} \tag{7}$$

The aerodynamic shattering equation was taken according to Engel[40]

$$\frac{d\ell}{dt} = -\left(\frac{\rho_1\mu_1}{\rho_2^i\mu_2}\right)^{1/6}\cdot\left(\frac{\mu_2}{\rho_2^i}\right)^{1/2}(V_1 - V_2)^{1/2}\ell^{-1/2} \tag{8}$$

If the two models are combined together, the equation for the parameter δ for the rate of size reduction of the droplet is obtained[24]

$$\delta = \frac{9\kappa Nu(T_1 - T_2)}{\pi\ell^2\rho_2^i L} + 3\left(\frac{\rho_1\mu_1}{\rho_2^i\mu_2}\right)^{1/6}\left(\frac{\mu_2}{\rho_2^i}\right)^{1/2}(V_1 - V_2)^{1/2}\ell^{-3/2} \tag{9}$$

Force Acting on the Drop by the Flow

This was determined according to Borisov et al.[12]

$$M = \frac{3\rho_1 C_D}{8\rho_2^i\ell}|V_1 - V_2|(V_1 - V_2) \tag{10}$$

where C_D is dependent on the Reynolds number as follows:

$$C_D = \begin{cases} 27\,Re^{-0.84} & \text{where} \quad Re < 80 \\ 0.27\,Re^{0.21} & 80 \le Re < 10^4 \\ 2 & Re \ge 10^4 \end{cases}$$

After all of these assumptions, the equations are brought to a nondimensional form as described by Eidelman,[24] and Eidelman and Burcat.[25]

C. Boundary Conditions

The initial distribution of gasdynamic parameters behind the shock wave was calculated using the solution of the self-similar problem described elsewhere.[20,21] Thus, at $t-t_0$ in the region bordered by r_0, there are the following parametrical conditions:

$$P = \begin{cases} P(r,t_0) & r \le r_0 \\ P^i & r > r_0 \end{cases}; \quad \rho_1 = \begin{cases} \rho_1(r,t_0), & r \le r_0 \\ \rho_1^i, & r > r_0 \end{cases} \tag{11a}$$

$$V = \begin{cases} V_1(r,t_0) & r \le r_0 \\ 0 & r > r_0 \end{cases} \tag{11b}$$

The parameters for the liquid phase will be

$$\ell = \begin{cases} 0, & r \le r_0 \\ \ell^i & r > r_0 \end{cases}; \quad N = \begin{cases} 0, & r \le r_0 \\ N^i, & r > r_0 \end{cases}; \quad V_2 = \begin{cases} 0, & r \le r_0 \\ 0, & r > r_0 \end{cases} \tag{12}$$

From the mathematical point of view, our problem is a Cauchy problem for a set of hyperbolic partial differential equations. The system is solved by the flux-corrected transport (FCT) method described by Boris and Book.[33]

III. Calculations

The computer program written for the FCT method is described in detail in Refs. 24 and 25. Here, the steps along which the calculation proceeds are represented schematically. The system of the conservation equations (1-3) and (4-6) with boundary conditions (11-12) are solved numerically. The solution procedure can be outlined in terms of time loops as follows:

0) Initial value is given before the first loop for system (1-3).
1) Half-step calculation for system (1-3) (the gas component).
2) Calculation of source terms for system (4-6) (the liquid component).
3) Half-step calculation for system (4-6).
4) Calculation of source terms for system (1-3).
5) Whole-step calculation for system (1-3).
6) Calculation of source terms for system (4-6).
7) Whole-step calculation for system (4-6).
8) Calculation of source terms for system (1-3) to be used in the next loop.
9) Repeat the loop from the first step.

By examining this code on a model problem (the analytical solution of propagation of a blast wave from a strong point explosion without counter pressure), the general error of the code was determined. The phase error was less than 2% and the amplitude error was less than 3%.[25]

IV. Results

The volume of the source explosion for sources of equal energy density was changed to find its influence on the ignition of the fuel cloud. $E_0/[(4/3)\pi r_0^3] = 2.9842\times10^8$ J/m^3 was taken as the energy concentration per unit volume.

In this series, it was assumed that the parameter's distribution in the source zone suits the Sedov[18]-Taylor[17] solution.

Figure 1 represents the graph of pressure velocity and density of the gas phase vs the radius of the shock wave.

Part of the graphs in the line was drawn from the shock wave backward for 60% of its radius in order that the agglomeration of lines will not blur the picture in the first 40% of the radius. Each of the graphs belongs to a specific radius of the shock waves. The graphs for the same time are one below the other. The velocity and pressure graphs for the radii 0.2-0.5 m were drawn on a different scale than the other graphs, as mentioned in the legend.

In this case, the parameters of the two-phase medium were heptane C_7H_{16}, the liquid phase, with the parameters $\ell^i = 10^{-4}$ m; $L = 3.6\times10^5$ J/kg; $\rho_2^i = 675$ kg/m^3; and $\mu_2 = 3.7\times10^{-4}$ kg/s·m. The boiling temperature is 330 K. The gaseous phase is oxygen with the parameters $\rho_1^i = 1.3$ kg/m^3; $\mu_1 = 0.207\times10^{-4}$ kg/s·m; and $\kappa = 0.1$ W/m·°C.

The two components were taken in stoichiometric proportions. The heat of combustion of the mixture was found with the help of the Gordon and McBride[34] computer program. The effective γ was also calculated with the same program. The values found are $Q = 40\times10^6$ J/kg and $\gamma \simeq 1.17$. The radius of the igniting explosion was $r_0 = 0.2$ m

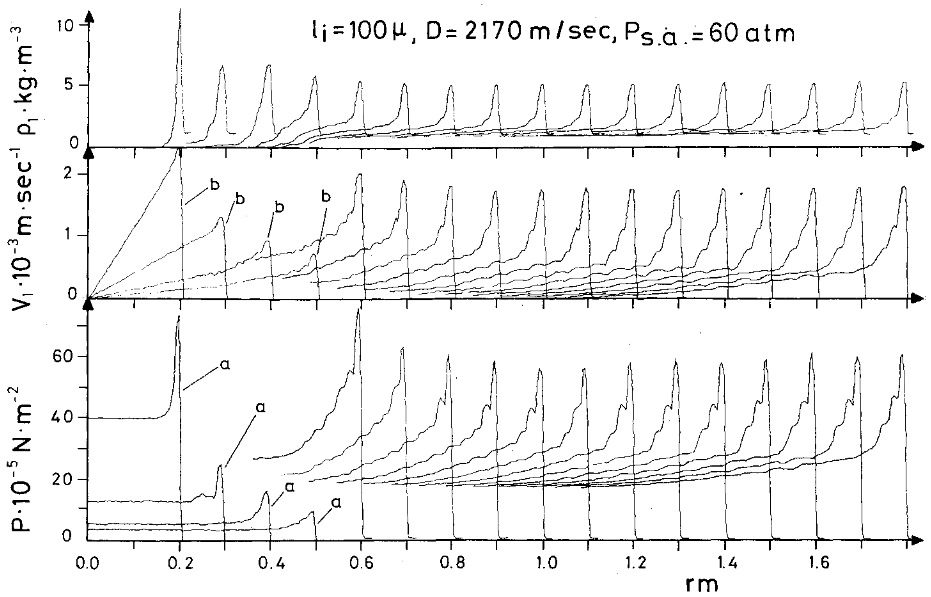

Fig. 1 Pressure, velocity, and density in the two-phase media vs the radius of the shock wave for heptane droplets in oxygen. $E_0 = 10^7$ J; $r_0 = 0.2$ m: a) $P \times 10^{-6}$ N/m^2; b) $V \times 3.29 \times 10^{-3}$ m/s.

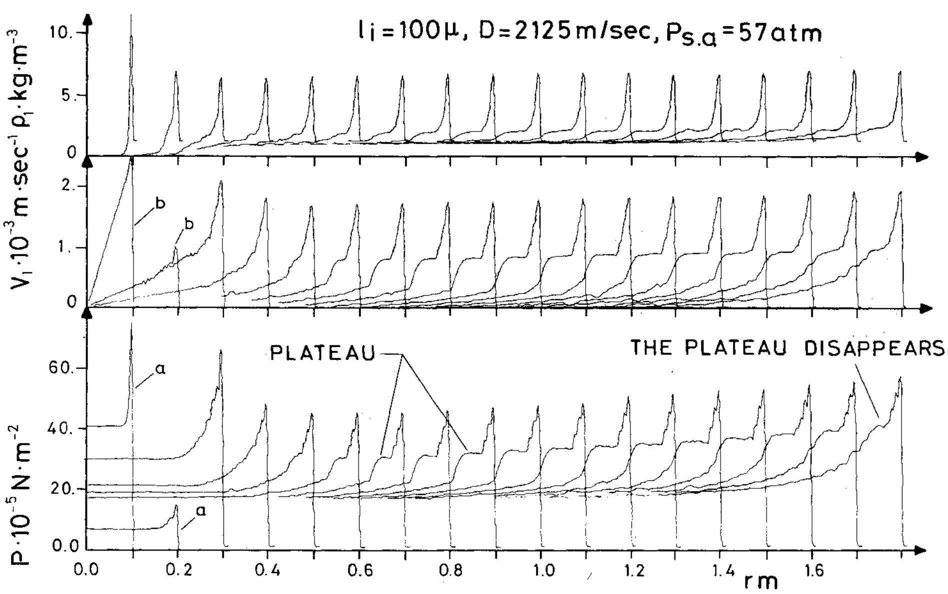

Fig. 2 Pressure, velocity, and density in the two-phase media vs the radius of the shock wave for heptane droplets in oxygen. $E_0 = 1.25 \times 10^6$ J; $r_0 = 0.1$ m: a) $P \times 10^{-6}$ N/m^2; b) $V \times 3.29 \times 10^{-3}$ m/s.

and $E_0 = 10^7$ J. Here, there is a direct transition from the explosion to detonation, and the velocity of the shock wave decays to a constant velocity close to the detonation velocity in the mixture at $r > 4.5\ r_0$. The chemical energy liberated when $r = 4.5\ r_0$ equals to $E_b = 9.5 \times 10^6$ J. Here, the transfer to detonation is in the line of Levin's[41] criterion, according to which detonation determines the shock wave parameters when $E_b \geq E_0$.

The average detonation parameters found in this computation were $P \simeq 60 \times 10^5$ N/m^2; $D \simeq 2170$ m/s; and $\rho = 6.1$ kg/m^3. These values are slightly lower than the values calculated by Borisov et al.[12] for the steady-state detonation and from the Chapman-Jouquet values calculated using the program of Gordon and McBride.[34]

In Fig. 2, the conditions are as described in Fig. 1, but the parameters of the igniting explosion were in this case $E_0 = 1.25 \times 10^6$ J and $r_0 = 0.1$ m. Here, because the total explosion energy was smaller than the former, there was no direct transition to detonation, but a minimum in the parameters is obtained at $r \simeq 0.6$ m. From this point on, the shock wave gets stronger until at $r \simeq 1.7$ m, it gets to the steady detonation parameters: $D \simeq 2125$ m/s and $P \simeq 57 \times 10^5$ N/m^2. The detonation parameters are very similar to those found in the former calculation since all the parameters of the medium are the same. The small differences appearing are calculation artifacts. Both cases were calculated on the same numerical grid size on nondimensional coordinates. But, on dimensional coordinates, the case of $r_0 = 0.1$ m causes a grid twice as dense as in the $r_0 = 0.2$ m case. Thus, the values obtained in the second case are slightly better.

The dynamics of the shock wave's propagation influences the parameters behind the front. In Fig. 2, the shock wave is weaker; therefore, it decays so the droplets shatter at a longer distance. As a consequence, a steady plateau is obtained at 0.025 m behind the shock wave. With the increase of the shock wave's force, the droplets shatter at a shorter distance and the plateau is also shortened until it disappears completely at $r = 1.8$ m. From this radius, the shock's parameters are the same as in Fig. 1.

All three parameters shown in Fig. 2 decay very abruptly from their maximal value within 2-3 cm behind the shock to a steady plateau which stays for another 4-5 cm and then decays to a minimal value. This behavior is caused by the influence of the droplet's dynamics on the gas. Since the droplets have momentum, they reach their maximum velocity in the region where the gas velocity decays, and when the gas velocity drops below that of the droplets, they act as a piston returning to the gas some of the lost kinetic energy that was transferred

Table 1 Results for five computed cases

Experiment number	r_0, m	E_0, J	D_{min}, m/s	P_{min}, N/m^2	D, m/s	P_{Det}, N/m^2	ρ_{Det}, kg/m^3
1	0.2	10^7	2125	57×10^5	2170	60×10^5	6.1
2	0.1	1.25×10^6	1900	45×10^5	2125	57×10^5	7.3
3	0.1	1.56×10^5	1750	35×10^5	2125	57×10^5	7.3
4	0.05	1.56×10^5	1675	33×10^5	2125	57×10^5	7.3
5	0.025	1.95×10^4	1440	23×10^5	a	a	a

[a]The steady detonation value not reached at the end of the calculation time.

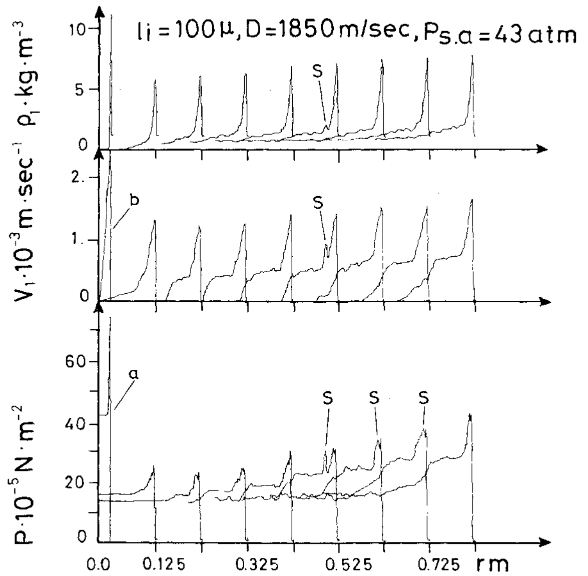

Fig. 3 Pressure, velocity and density in the two-phase media vs the radius of the shock wave for heptane droplets in oxygen. $E_0 = 1.95\times10^4$ J; $r_0 = 0.025$ m: a) $P\times10^{-6}$ N/m^2; b) $V\times3.29\times10^{-3}$, m/s; S secondary shock.

to them. As proof that this explanation is correct, the fact that the droplet's velocity in the "plateau" region is slightly higher than that of the gas is cited. The chemical energy, released in this region, is also responsible for the plateau formation.

In the case presented here, we get a behavior similar to the stationary compression waves described by Antonov.[23]

Figure 3 represents the further decrease in the energy of the igniting explosion while keeping the rest of the parameters the same, including the energy density. Here, $E_0 = 1.95\times10^4$ J and $r = 0.025$ m. The shock wave decays to its minimal value at $r = 0.18$ m ($D = 1440$ m/s; $P = 23\times10^5$ N/m^2), and from there the shock wave is reinforced by the energy liberated by the cloud. Because of the very dense grid ($\Delta h = 0.00125$ m), the calculation was not proceeded beyond $r = 0.925$ m, where the parameters attained were $D = 1850$ m/s and $P = 43\times10^5$ N/m^2. It has been observed here that the process of the shock reinforcements is done through a system of secondary waves produced by the combustion region, which can be seen distinctly on the figure. The process will be explained in further detail in Pt. II of this paper.[42] Table 1 summarizes five experiments, two of which (3 and 4) were not cited.

In Fig. 4, the results which are obtained by the numerical solution using cylindrical coordinates (the solid line) with the experimental results of Gabrijel and Nicholls are compared.[9] The parameters of two-phase media and the energy of the initiating explosion were taken exactly the same as in the experiment [Gabrijel and Nicholls,[9] p. 1057, Fig. 5]: the mixture of the kerosene drops of a 190-μm radius with the air at temperature 298 K and pressure 1 atm with equivalence ratio of $\phi = 0.753$.

In the authors' calculations, the igniting source of total energy $E_0 = 5.3\times10^6$ J/cm and radius $r_0 = 0.1$ m were used.

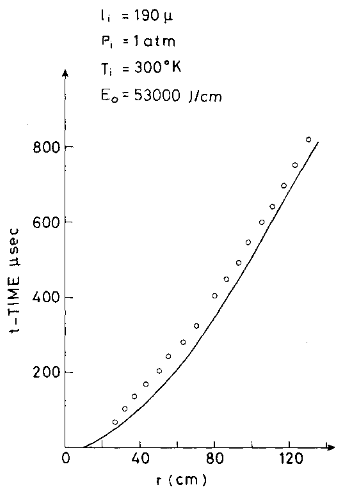

Fig. 4 Comparison between experiment (Gabrijel and Nicholls) and calculations. Time vs radius of the shock front.

The parameter's distribution in the source zone suits the Sedov[18]-Taylor[17] solution. The computed and experimental results are in good agreement and show the ability of the model presented here to describe the real process of detonation.

The slight difference between experimental and theoretical results at the small radii of the wave could be explained by differences in the igniting sources (in the Gabrijel and Nicholls[9] experiments, the initiating blast wave is produced by condensed explosives which are located in a small cylindrical cavity).

V. Discussion

In Figs. 5 and 6, we have summarized all the calculations together in order to compare them. The pressure on the shock's front vs the shock's radius is presented in Fig. 5, and the velocity of the shock's front vs the shock's radius is presented in Fig. 6.

It is clear that beyond $r = 1.2$ m, all the five graphs tend to the same values, and these values depend on the physicochemical properties of the cloud and not on the ignition conditions.

But, for the shorter distances, the main reason for the behavior towards a transition to detonation is the energy of the igniting explosion.

The cases 1, 2, and 5 are the same cases shown earlier in Figs. 1-3. The density energy of the igniting source is the same, but the size of the radius changes by a factor of 2 from experiment to experiment. This causes the energy of the igniting explosion to be larger by a factor of 8 from experiment to experiment. It is clear that with the increase of energy, the transition to detonation occurs faster with smaller minimum values from which the shock wave has to recover in order to attain the detonation parameters. In the last case, there is a direct transition to detonation with no minimal values when the source energy is big enough.

Case 3, which was not presented previously, was calculated in order to show the influence of increasing the volume while

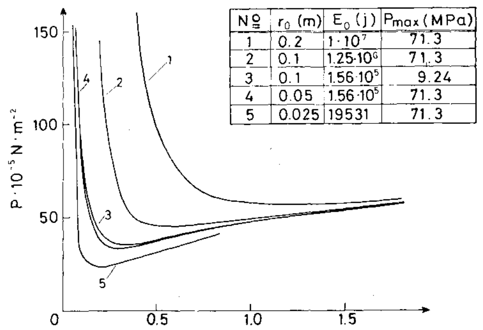

Fig. 5 Pressure on the shock front vs the radius of the shock for different volumes of igniting explosions.

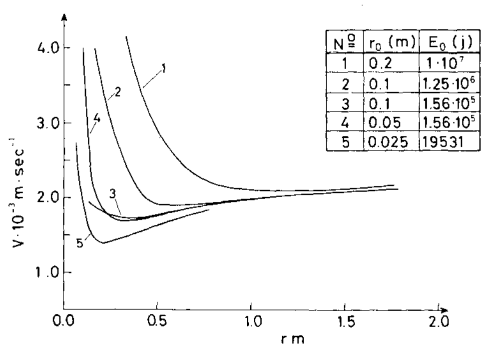

Fig. 6 Velocity of the shock front vs the radius of the shock for different volumes of igniting explosions.

the energy remains the same. Comparing cases 4 and 3, it is shown that in case 3, where the initial radius of the source is two times larger, the transition to detonation occurs faster and the minimal parameters attained by the shock front are bigger than in case 4.

Therefore, we conclude that in order to achieve a better ignition, it is wise to increase the volume of the igniting source, but the energy density still has to be big enough to ignite the medium.

Generally, it should be mentioned that the distribution of parameters behind the shock wave is very different than in adiabatic explosion.[35] The velocity of the shock decays rapidly within the first 5-10 cm *behind the front* to ⅓ of its original value, and then decays to zero value at a distance approximately 1.5 m behind the shock wave (see Figs. 1 and 2). The pressure and the density behave similarly.

It can be summarized that for a stoichiometric mixture of heptane in oxygen with droplets of 100-μm size, the transition to detonation occurs after approximately 1.2 m. The increase of the explosion volume increases the chances for a safer ignition.

This has a direct consequence on the planning of experiments in two-phase detonations. For example, Nicholls et al.[8] did not reach stable detonation in a cell 60-cm long since the detonation stabilizes only at twice this distance.

Bull et al.[36] ignited a gaseous mixture of ethylene and oxygen and received detonation 60 cm from the center of the explosion. It is therefore to be expected that a two-phase mixture will take longer to detonate.

Finally, a word about ignition criteria. Many studies have been devoted to define a theoretical or empirical criterion for a direct initiation of a detonation in gases.[10,37-39] These criteria were defined according to the ignition delay time, delay zone, or an experimental point where the ignition parameters are known. These criteria give a very crude estimation of the ignition conditions because they do not take into consideration the mutual dynamics of the shock wave and the reaction zone.[36,39]

An ignition criterion for a two-phase media is even more complicated. However, fortunately, such a criterion was not needed in our case. Since in the present study the dynamic problem of the explosion in the two-phase media was solved in a detailed manner, there was no need for an empirical ignition criterion.

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