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Convective Ignition of Propellant Cylinders in a Developing Flowfield

Avi Birk* and Leonard H. Caveny†
Princeton University, Princeton, N. J.

Research is directed at determing the site and mode of convective ignition of propellant cylinders in cross flow. A shock tunnel was used to provide up to 20 ms of flowing heated gas at 1-2 MPa, 1600-2100 K, 10-300 m/s. Test gases were 100% N_2, 10% O_2/90% N_2, and 50% O_2/50% N_2. Instrumentation included six radiation detectors, high-speed shadowgraph sequences, pressure probes, and heat flux gages. Ignition is a gas phase process. Compared to triple-based propellant, single- and double-based propellants ignited more rapidly in oxidizer-containing flows. Flame blow-off occurred for high Reynolds number (e.g., 16,000), low freestream oxidizer flows. The high heating rates accompanying boundary-layer development can produce submillisecond ignition. Depending on the flow conditions, first ignition can occur either at the leading edge or in the wake.

Nomenclature

A_R = pre-exponent factor of gas phase reaction rate expression
A_p = pre-exponent factor of pyrolysis rate expression
C_p = specific heat capacity
D = cylinder diameter
E_R = gas phase activation energy
E_p = pyrolysis activation energy
T = temperature
R = universal gas constant
Re_D = Reynolds number based on the cylinder diameter
U = velocity
t_f = residence time of flow around cylinder
Y = mass fraction
λ = thermal conductivity
ρ = density
μ = viscosity
θ = angle from the front stagnation point

Subscripts

B = boundary layer
e = edge of boundary layer
f = fuel
ox = oxidizer
s = separation zone
so = solid
w = wake or wall

Introduction

THE primary objective of the present work is to elucidate the behavior and ignition trends of propellant cylinders (0.5-1.5 cm in diameter) suddenly subjected to a hot, rapidly developing (or shock-induced) flow. Polymers and propellants are being studied, as well as combinations of partially inert cylinders. Ignition delay times and sites are largely influenced by the strength of the abnormally high heat fluxes associated with the compression waves and boundary-layer development around the cylinder surface at the initiation of the flow. The flowfield and zones of ignition being examined are shown in Fig. 1.

The convective heating and fluid flow around cylinders in cross flow have been studied extensively. However, heating under high-speed reactive flow conditions has received little attention. Previous experimental studies of convective ignition in carefully controlled environments were either limited to flat surfaces[1] or employed low heating rates which produced stagnation point ignition in tenths of seconds rather than in milliseconds.[2] When ignition occurs in tens of milliseconds, the influence of the transient flow conditions at the initiation of the tests is of small importance. This paper includes situations in which ignition occurs in submillisecond time and, hence, transient flow conditions are important.

The results of this research have applications to the understanding of the purposeful ignition of solid propellants as well as of the pathological situations leading to detonation of granulated propellants.

Physical Situation

As the hot gas flow impinges on a propellant cylinder, thermal and viscous boundary layers develop adjacent to the cylinder surface in a time on the order of the flow time around the cylinder (D/u, typically a fraction of a millisecond). This period of flow is generally characterized by accelerating

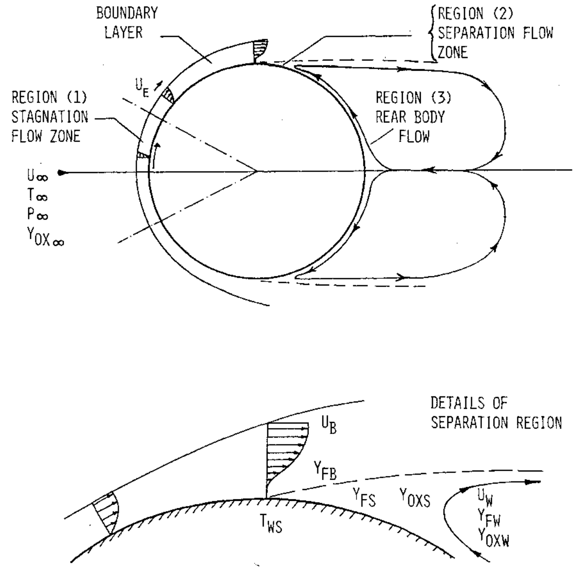

Fig. 1 Flowfield around a cylinder in cross flow showing three zones where ignition criteria are examined.

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Index categories: Combustion Stability, Ignition, and Detonation; Boundary Layers and Convective Heat Transfer – Turbulent.

*Ph.D Candidate, Mechanical and Aerospace Engineering Dept.

†Senior Member of Professional Staff, Mechanical and Aerospace Engineering Dept.; presently with Air Force Office of Scientific Research, Bolling AFB, Washington, D. C. Associate Fellow AIAA.

velocity and a steep rise in the pressure field around the cylinder. During this brief transient, the heat flux is abnormally large so that the surface temperature rises rapidly. In the Reynolds number range of interest (subcritical regime), the flow separates to form a turbulent wake region behind the propellant cylinder. Once the boundary layer and turbulent wake are established, the cylinder enters a relatively prolonged period of heat-up. Typically, for flows in the range of interest (e.g., Reynolds numbers $< 10^5$), the heat transfer coefficient is highest at the front of the cylinder (stagnation point) and at the wake region. In general, the chemical processes that follow the condensed phase decomposition do not occur in negligible time and are complexly intertwined with the gas flow around the cylinder. Ignition, if it occurs, occurs in the gaseous phase in the regions shown in Fig. 1.

Writing the reacting boundary-layer equations in nondimensional form, somewhat similar to Ref. 3, reveals the following parametric groups of importance in determining the ignition likelihood of the propellant:

Gas phase Damkohler number: ratio of residence time to reaction time

$$D_G = A_R / \rho_e t_f$$

Surface Damkohler number: ratio of residence time to fuel loading time

$$D_S = \rho_{so}^2 A_p^2 t_f / \rho_e \mu_e$$

Thermal property ratio of solid phase to gas phase

$$\epsilon = \lambda_{so} \rho_{so} C_{pso} / \lambda_e \rho_e C_{pe}$$

The gaseous products (e.g., NO_2, aldyhydes in the case of nitrocellulose-based propellants) emerging initially from the front of a cylinder enter the reacting boundary layer with its higher temperature. For the case of propellants, the reactions that begin there are those of the usual fizz zone.[4] The fate of the reactants depends upon the local temperature, concentration, velocity, etc. These effects are being interpreted in the form of the Damkohler number D_G. For $D_G \gg 1$, the reaction is faster than the flow so that the reactants emerging from the stagnation region are consumed while still in that neighborhood.

Both Damkohler numbers, D_G and D_S, determine the ignition delay time which is shorter for larger D_G and D_S values. The thermal property ϵ is of major importance. Indeed the instantaneous surface temperature of the propellant surface T_W being suddenly exposed to hot gas of a temperature T_e is given by:

$$T_W = (T_e - T_0) / (1 + \epsilon^{1/2}) + T_0$$

A sudden onset of ambient conditions is typical of shock-tunnel tests where a surface temperature jump, given by the above expression, is induced by the impinging shock wave on the cylindrical specimen. A large initial jump will shorten the ignition delay time appreciably. As the flow around the cylinder develops following the arrival of the shock wave, T_W starts to rise at a rate compatible with the convective heat-transfer mechanism.

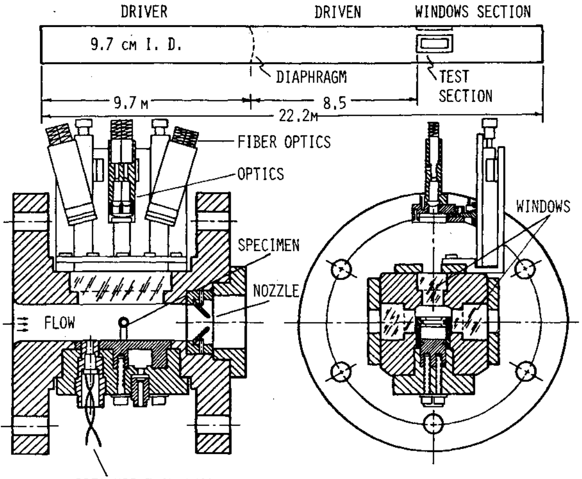


Fig. 2 Schematic diagram of shock tunnel and detail of test section.

Under specified heating conditions, the time for the surface temperature to reach a prescribed value is also proportional to $\epsilon^{1/2}$. The unsteadiness of mass flow rate $\rho_e u_e$ and pressure field P_e is very important, especially at the initiation of the flow when $\partial \rho_e u_e / \partial t$ and $\partial p_E / \partial t$ assume large values. The effects are a result of reducing the boundary-layer thickness and compression work throughout the boundary layer.

Experimental Approach

The shock-tunnel apparatus used in this research is the basic device described in Ref. 2 in which ignition data were given for constant temperature and pressure conditions where only the flow velocity and gas composition were changed. The specially developed test section for this experiment is shown in Fig. 2. The present study broadens the data to include the effects of pressure and temperature changes with a special emphasis on the role of the initial transient conditions on the subsequent ignition behavior. A series of tests was conducted with single- (M1), double- (M26, NC/TMETN), and triple-based (M30) propellants, with HMX composite and with plexiglass. The formulations are given in Table 1. The range

Table 1 Propellant formulations[a]

Nominal M26 and M30 propellants		
	M26E1	M30
Nitrocellulose (13.15% nitration)	67.3	28.4
Nitroglycerin	25.0	22.2
Nitroguanidine		47.7
Barium nitrate	0.8	
Potassium nitrate	0.7	
Ethyl centralite	6.0	
Graphite	0.2[b]	
Cryolite		0.3
Specific lot of M1 propellant		
Nitrocellulose (13.15% nitration)	82.6	
Dinitrotoluene	9.3	
Dibutylphthalate	4.9	
Diphenylamine	1.1	
K_2SO_4	2.1	
NC/TMETN propellant[c]		
Nitrocellulose (12.6% nitration)	53.9	
Trimethylolethane trinitrate	39.1	
Triethylene glycol dinitrate	7.0	
HMX/PU composite propellant		
Cyclotetramethylene tetranitramine	85.0	
Polyurethane binder	15.0	

[a] Percentages are by weight. [b] One lot of M26 did not have graphite. [c] Total ethyl centralite in propellant is 1.7%.

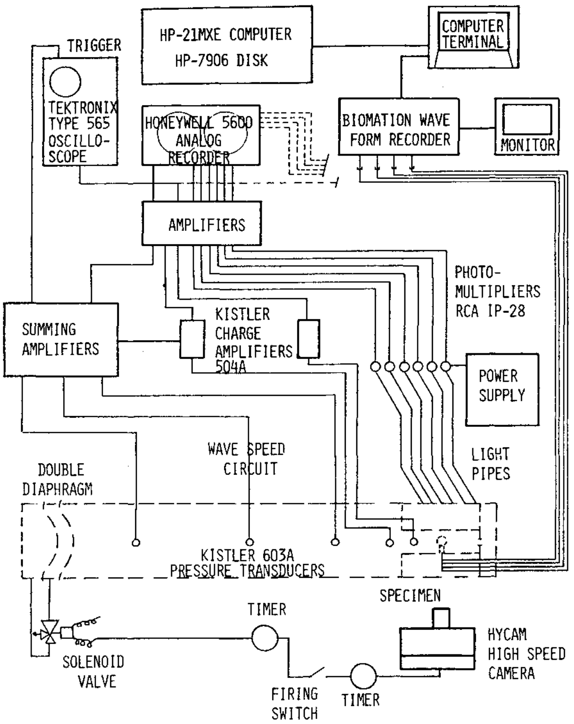


Fig. 3 Instrumentation for convective ignition experiment.

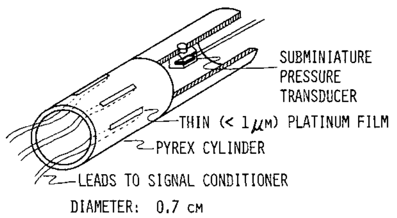


Fig. 4 Inert cylinder instrumented for heat flux and pressure measurements.

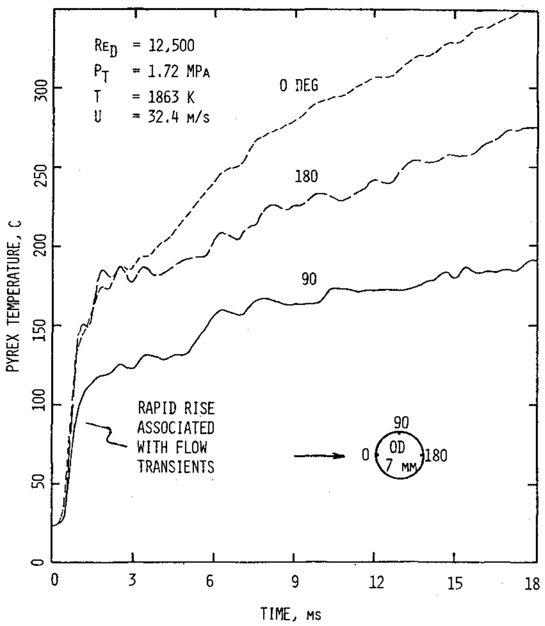


Fig. 5 Temperature transients on pyrex cylinders.

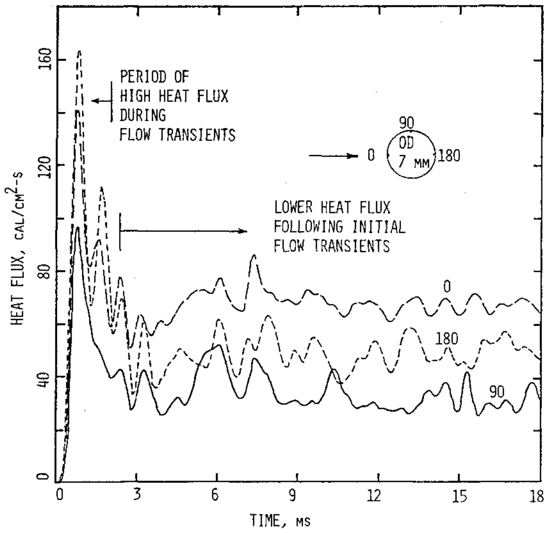


Fig. 6 Heat fluxes corresponding to Fig. 5 conditions.

of exposure conditions were: pressure 1.3-2.0 MPa, temperature 1800-2300 K, velocity up to 150 m/s. The test gases were: 100% N_2, 10% O_2/90% N_2, and 50% O_2/50% N_2.

The cylindrical test specimen (nominally 7 mm in diameter) is mounted in a 3.2×3.2 cm test section as shown in Fig. 2. The subsonic flow velocity is controlled by adjusting the variable area nozzle downstream of the specimen. Six ultraviolet detectors are used to detect ignition and flame spread. High-speed shadowgraph photography with color film using a blue monochromatic light source reveals both the flow structure and the onset of flame development by the radiation of the visible flame. The type of instrumentation used to detect and record the flow and ignition processes is shown in Fig. 3.

As illustrated in Fig. 4, an instrumented (inert) cylinder (7 mm in diameter) was devised to include three thin platinum film calorimeters and a high-frequency pressure transducer which can be rotated to measure the pressure and temperature distribution around the circumference. The measured thin-film temperature (Fig. 5) and corresponding heat fluxes (Fig. 6) revealed that the heating rates during the initial transients exceeded the heating rates during periods of steady flow by more than a factor of two and that the heating rates had significant unsteady components. This is attributed to the wave motion in the test section following the diffraction of the shock wave on the cylinder. The measured heat fluxes were used to calculate the corresponding propellant surface temperature had it been under the same flow conditions. It was found that the intense heating rates during the initial transient (<1 ms) result in a corresponding propellant surface temperature above that required for gasification, whereas approximately 5 ms are required to produce gasification at the heating rates corresponding to steady flow.

The convective-heating-rate overshoots associated with the flow development transients are sufficiently high so that, at the higher Reynolds numbers, initial gasification and contributions from the propellant decomposition occur within 1 ms. However, at the lower Reynolds numbers, the initial rapid heating rates play a less prominent role and the nearly steady-state heating provides the primary ignition stimulus. The high heating regime is of considerable practical importance and not merely a characteristic of the experimental apparatus. Indeed, the heating-rate overshoots will accompany all shock-induced flows. Pressure vs time measurements taken at $\theta = 0,90$, and 180 deg (following the location of the thin films) were found to be almost identical in shape, unlike the corresponding surface temperature vs time. The heat transfer at $\theta = 180$ deg (rear stagnation point) was found to be the most sensitive to pressure unsteadiness, while the heat transfer to the 90 deg point was found to be the least sensitive. (See Fig. 7.)

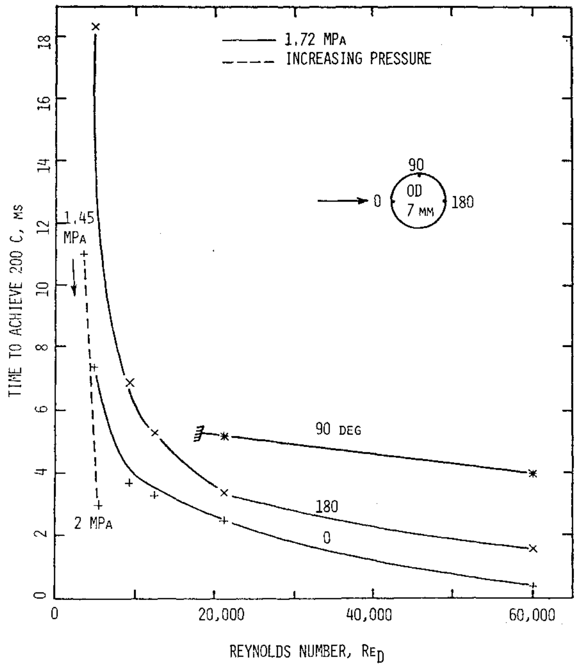


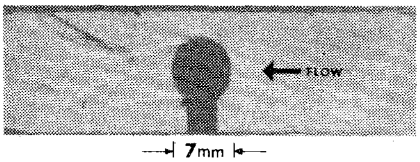
Fig. 7 Time to achieve a prescribed temperature rise is very dependent upon Re_D and pressure.

Discussion of Results

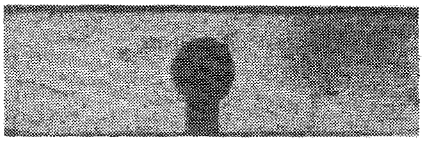
Examination of the high-speed motion pictures and ultraviolet detector data obtained for propellants heated by nitrogen reveals that the volatiles originating at the front surface are rapidly diluted and swept away prior to developing a flame. The flame and onset of ignition were more pronounced and vigorous when oxygen was present in the freestream. The flame under fully inert conditions was very thin and relatively close (0.05 mm) to the surface. Vortex formation and shedding of burning pockets of gas from the wake were apparent from the high-speed films and occurred with a regularity related to the Strouhal number of the flow.

Figure 8 is an example of a high-speed motion picture sequence of propellant igniting. Within 0.25 ms of the onset of convective heating, vapors originating at the front surface have been ignited and are burning. During the transients to full flame development, the vapors burn out and are then re-established permanently within the next 0.5 ms. After another 1 ms, the combined effects of convective heating and heat feedback from the propellant decomposition produce sustained combustion over the entire surface of the cylinder.

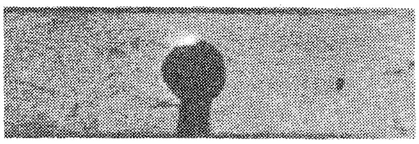
Ignition data are given here for M30 triple-based propellants for constant pressure and temperature (solid lines on Fig. 9), for constant velocity and temperature (dashed lines on Fig. 9), and for constant pressure and constant higher temperature (Fig. 10). The ignition times were calculated from the light detector data, considering the time of the shock-wave



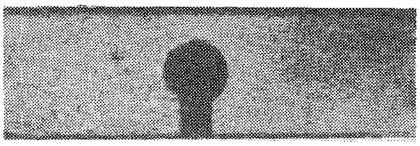
t = 0.25 ms
GASIFICATION AND FIRST
EVIDENCE OF IGNITION AT 90°



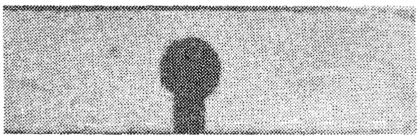
t = 0.50 ms
TRANSIENT FLAME DEVELOPMENT
AT 90° (VAPORS ORIGINATED
AT FRONT SECTION)

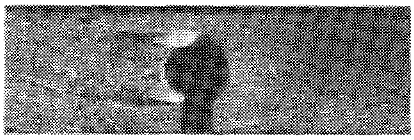


t = 0.75 ms
VAPORS BURNED OUT

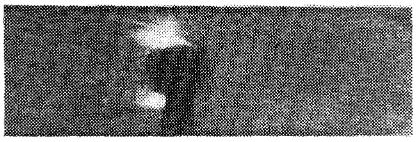


t = 1.00 ms
FLAME REDEVELOPING

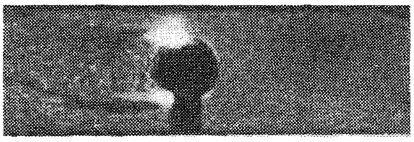




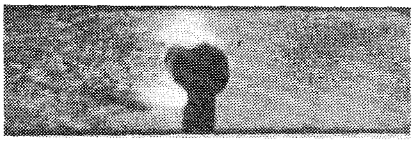
t = 1.50 ms
FLAME ESTABLISHED AT
LEADING EDGE



t = 1.75 ms
FLAME ESTABLISHED AT
LEADING EDGE



t > 5 ms
BURNING IN WAKE



t > 5 ms
BURNING IN WAKE

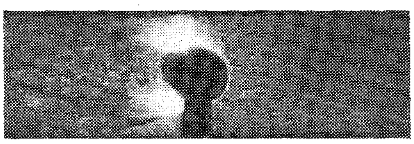


Fig. 8 Photographs showing convective ignition events (M26 propellant, 1.63 MPa, 1740 K, 140 m/s, 50% N_2/50% O_2, $Re = 55{,}000$).

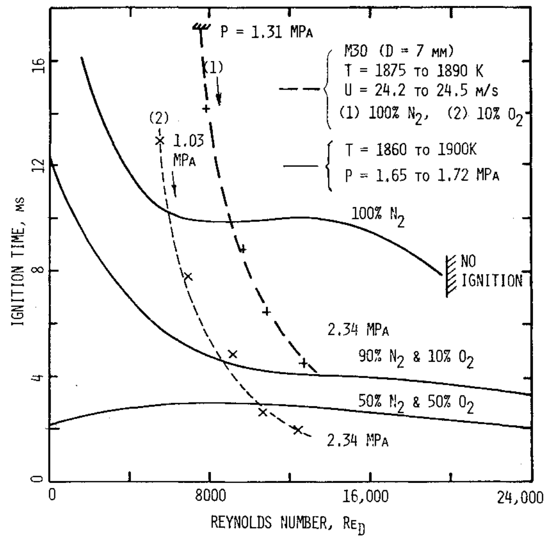


Fig. 9 Ignition data showing decreasing ignition times with increasing velocity, oxygen, and pressure (for triple-based propellant M30).

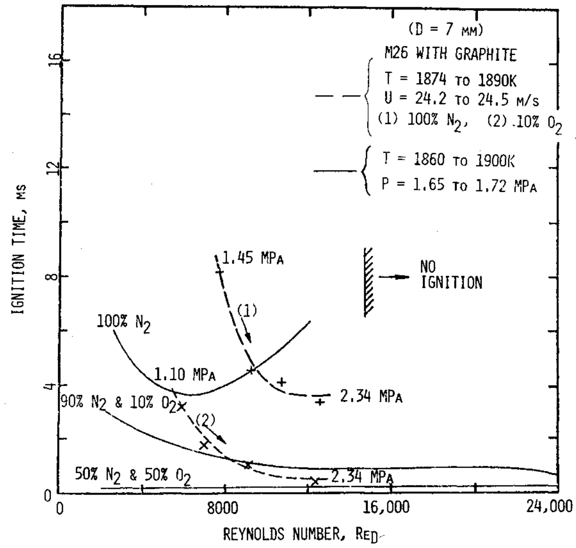


Fig. 11 Ignition data showing decreasing ignition times with increasing velocity, oxygen, and pressure (for double-based propellant M26).

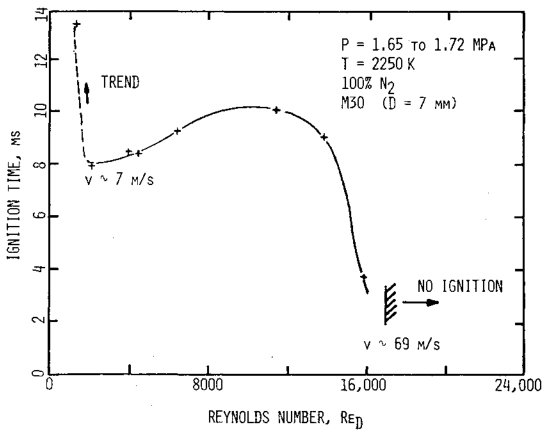


Fig. 10 Ignition data obtained under high temperature and constant pressure.

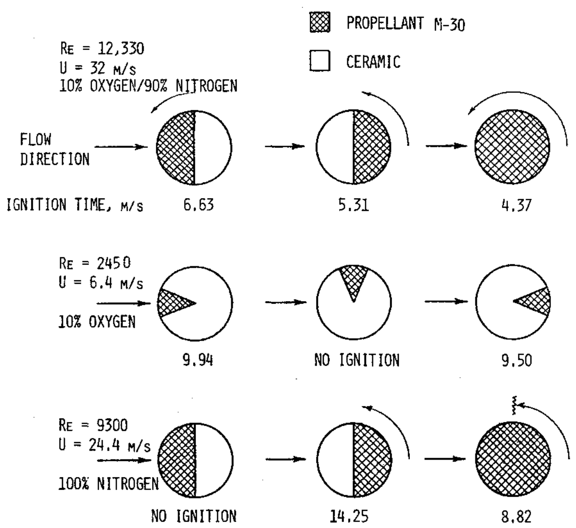


Fig. 12 Ignition trends demonstrated by a series of partially inert cylindrical specimens.

arrival as $t=0$. The shock-wave arrival was detected from its induced luminosity. In some cases, a phenomenon of a short $(t<t_f)$ sequence of ignition extinction was observed. It was attributed to evanescent flow unsteadiness at a frequency greater than $1/t_f$ that stimulates ignition by momentarily distorting the boundary-layer profiles of velocity and temperature. Therefore, somewhat arbitrarily, ignition was considered to occur when the flame established lasted for more than $3t_f$. The choice of Reynolds number as the coordinate in Figs. 9 and 10, although somewhat arbitrary, is logical since only one parameter varies along each curve, either the velocity (or t_f) or the pressure (density). Indeed the Reynolds number could have been replaced by any of the Damkohler numbers. The inert heating of the propellant during the steady-state period prior to gasification is also a function of Reynolds number only.

As shown in Fig. 11, a similar series of experiments was conducted for the double-based propellant M26 coated with graphite. Compared to M30, M26 ignites much more rapidly. Indeed, for the 10 and 50% O_2 conditions ignition occurs in submillisecond time. Effects of Damkohler number and hydrodynamic mixing on ignition times and trends are demonstrated by the results obtained from series of tests with partially inert, partially M30 propellant cylinders under various flow conditions (Fig. 12). Note, in particular, that the observed ignition time for 10% O_2 case at $\theta=0$ deg is greater than that for $\theta=180$ deg, even though the heat flux for $\theta=0$ is larger than that for $\theta=180$. Referring to Fig. 1, the flow in region 3 around $\theta=180$ deg resembles the flow around $\theta=0$ deg. However, the residence time of the former may be much greater, thus possibly the local D_G is larger than at $\theta=0$ deg and the ignition time is shorter.

The main results and trends are:

1) Compared to triple-based propellants, single- and double-based propellants ignite more rapidly in flows containing an oxidizer (see Fig. 13); only the double-based propellant (M26) that contained graphite was ignited under fully inert flow conditions (see Fig. 14). M30 is found to be less sensitive to outer flow oxidizer content. Plexiglass ignited very rapidly under 50% O_2 but did not ignite under 10% O_2.

2) The higher the oxidizer content of the outer flow, the shorter is the ignition delay time and the ignition site tends toward the front stagnation point (see Fig. 15).

3) Flame blow-off phenomena occurred for low freestream oxidizer concentration, high Reynolds number flows. In all of those cases, the flame was established only in the rear half of the cylinder.

4) In the cases of single- and double-based propellants, as well as with plexiglass, ignition under 50% O_2 flow conditions occurred many times within transient boundary-layer

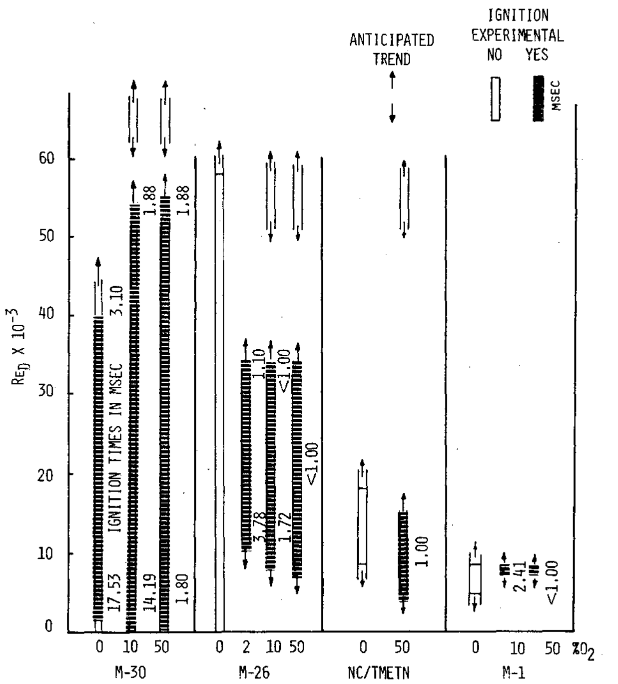


Fig. 13 Propellant ignition trends as a function of oxygen content and Reynolds number.

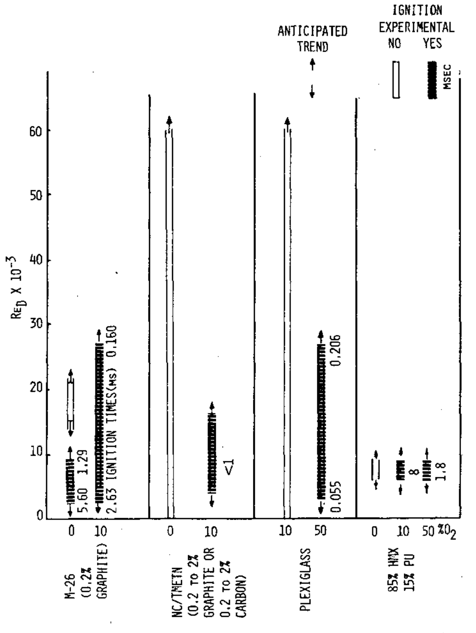


Fig. 14 Ignition trends for several special situations.

development time characterized by an almost simultaneous ignition at both the front and rear stagnation points.

5) Higher Reynolds numbers associated with higher velocities do not necessarily result in shorter ignition delay times as seen from Fig. 9 for 50% O_2 and from Fig. 10. The role of the flow Damkohler number and its competition with the heating rate is evident from these figures.

The ignition trends are partially explained by examining surface temperature data obtained from special thin-film gages under simulated flow conditions. Figure 5 shows the surface temperature transients on the pyrex cylinder. The heat fluxes corresponding to Fig. 5 are given in Fig. 6. Notice the very steep rise at the onset of the flow and the subsequent much slower rise when flow conditions start to stabilize after the boundary layer is developed. That steep initial rise was found to depend mostly upon the ambient pressure. The heating rate during the steady-flow period varied from test to test as the Re_D was changed. The large surface temperature rise during the initial flow transients results in much shorter times to reach some prescribed surface temperature, as compared to pure steady-flow case. The time to reach a surface temperature of 200°C at $\theta = 0{,}90$, and 180 deg is shown in Fig. 7 as a function of Reynolds number. The rise rate behavior is very steep and the role of the initial rapid rise of temperature (Fig. 5) is evident. The initial rates of temperature rise at the front and rear stagnation points are very similar in magnitude; and if sufficient oxidizer is present in the outer flow, ignition may occur almost simultaneously at the front and rear stagnation sites. As pressure is increased, the rate of temperature increase is higher and rapid ignition may occur even with a lower oxidizer content.

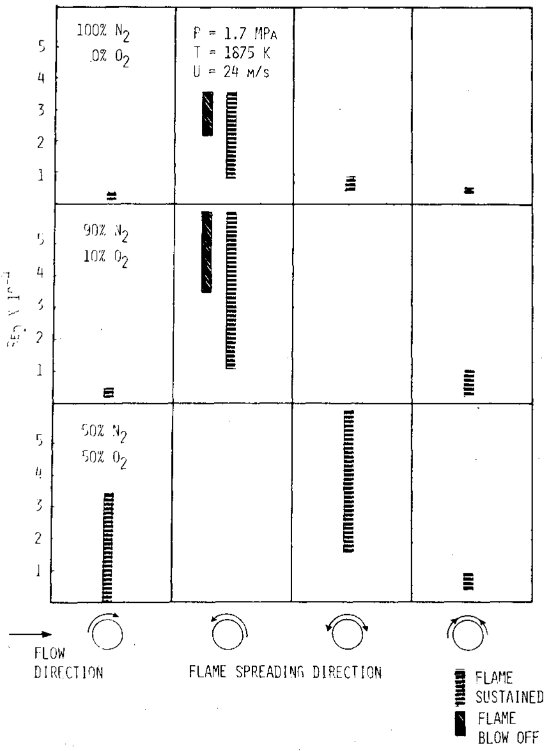


Fig. 15 Flame spreading tendencies as a function of oxygen concentration and Reynolds number.

Analytical studies similar to Ref. 3 of the flow situation based on examination of the transient boundary-layer equations in nondimensional form reveal the same trends as were found experimentally. After the transient conditions are over, when steady-state flow is obtained, the time to achieve some prescribed temperature rise is proportional to t_f, T_e, and $\epsilon^{1/2}$. The boundary-layer development time is in the same range as the time of the flow around the cylinder (t_f), typically 50-400 μs. Ignition, if it then occurs, is in submillisecond time.

The following subsections deal with possible mechanisms relating to the effects of the freestream oxidizer (O_2) and the graphite content of the propellant on ignition trends.

Sensitivity to Freestream Oxidizer

As already mentioned, no ignition was obtained under purely inert conditions with the single- and double-based propellants. In fact, even increasing the freestream temperature and pressure to values up to 2400 K and 2.1 MPa did not result in ignition in those cases. On the other hand, as seen from Fig. 13, M26 without graphite ignited even with 2% O_2 in the freestream under the nominal conditions of freestream temperature and pressure of 1875 K and 1.7 MPa, respectively. M30, the triple-based propellant, ignited under inert gas conditions and was much less sensitive to the amount of freestream oxygen. The inert heat-transfer rate to the propellant is not affected appreciably by the ratio of O_2/N_2 in the freestream during most of the ignition delay time. Thus, the contributions of the chemical reactions and flame structures of the propellants are the sources of the observed effects of O_2 and the differences in propellant type. In addition, the propellants do not differ significantly in their thermal properties, and gasification temperatures of the propellants were always obtained during the test time, as was evident from the high-speed films and from the post-test diameter measurements and surface structure examination.

The compositions of the propellants are given in Table 1. The main component of M1 is nitrocellulose (NC), (83%). The main components of M26 are NC (67%) and nitroglycerin (NG), (25%). The main components of M30 are NC, (28%), NG (22%), and nitroguanidine (NGU), (48%). Thus, NC is the major component in M1 and M26, and NGU is the major component in M30. Both M26 and M30 contain about the same amount of NG.

Although M1 is the least energetic of the propellants, it demonstrates approximately the same trends as M26 (ignition delay times being only slightly longer than the latter). Thus, it is concluded that the major difference is in the decomposition products and the flame structure of NGU vs NC.

Basically, NC is a nitro compound including nitrate esters (C - O - NO_2), and NGU is a nitro compound including nitramine (C - N - NO_2). The mechanism of double-based (nitrate esters) combustion have been widely studied (see Ref. 5 for a recent study). The major features are:

1) Decomposition products are NO_2 + CH_2O + higher hydrocarbons.

2) Flame zone temperature profile is subdivided into fizz zone, dark zone, and luminous flame zone.

The temperature gradient is the steepest in the fizz and luminous flame zones, and quite flat in the dark zone. It should be remembered, however, that this kind of profile is superimposed upon the boundary-layer profile and will be strongly affected by it. With respect to ignition, the fizz zone (being close to the surface) is the most important because ignition occurs through the bootstrapping process of gaseous phase/solid phase interactions. The dark zone temperature gradient, being relatively low, inhibits the transfer of energy from the luminous flame zone. After the boundary layer comes into existence, the stage of luminous reaction zone may not be realized, since the reactants are diluted by the convective flow away from the surface.

NO_2, a very strong oxidizer, is reduced in the fizz zone to NO and the principal fuels emerging from this zone are H_2 and CO.[6] Thus, the combustion is incomplete and only about half the energy stored in the double-based propellant is liberated there. The reasons for it are: 1) NO has large activation energy for oxidation reactions, and the temperature at the end of the fizz zone (or in the boundary layer close to the surface) is not sufficiently high; and 2) the radicals necessary to take part in the highly exothermic oxidation reactions of H_2 and CO are either depleted (H, OH), or initially nonexistent (O). Thus, any addition of H, OH, and O radicals to the fizz zone may eliminate the dark zone and cause the luminous zone to collapse to the surface resulting in a one-stage intense heat-release zone close to the surface to provide the impetus for ignition.

Addition of even small amounts of O_2 to the freestream replenishes the boundary layer with the above radicals. A possible mechanism is as follows: O_2 diffuses toward the surface where chain-branching reactions of O_2 with HCO and H (radicals which exist in the fizz zone) would supply OH radicals to the oxidation of CO, via $OH + CO \rightarrow H + CO_2$, thus liberating heat to accelerate the other reactions. Description of the above types of reactions may be found in Ref. 7.

In conclusion, the presence of O_2 in the freestream shifts the major exothermic reactions toward the surface where the residence time of the flow is larger and heat transfer to the solid phase is enhanced, thus resulting in ignition. Higher rates of heat transfer to the surface in inert freestream conditions would merely increase gasification.

In the case of M30 most of the NC is replaced by NGU which is less energetic and its decomposition routes are different than NC. The proposed decomposition products of NGU are: $H_2NCN + N_2O + H_2O$ or $NH_3 + N_2O + HNCO$ (Ref. 8). From Ref. 5, the kinetic routes follow through the decomposition of N_2O as follows:

$$N_2O + M \rightarrow N_2 + O + M \qquad \text{high activation energy}$$

$$N_2O + H \rightarrow N_2 + OH \qquad \text{lower activation energy}$$

Thus, the reactions may not form a large amount of NO, and CO is probably oxidized to CO_2 in earlier stages. It is conceivable that the energy release is more concentrated and the flame does not exhibit a multizone structure. Since there are also NC and NG decomposition products available in the gaseous phase, they supply the H radicals which facilitate faster decomposition of N_2O at the lower temperature close to the solid surface. It is also known that NO_2 reacts exothermically with NGU.[9]

There is also the possibility that carbonaceous residues formed on the surface during NGU decomposition (as was found from microscopic scanning of extinguished M30 propellants during the test series) act as flame holders since they may reach a much higher temperature. However, the authors believe that the main effects are due to gaseous phase chemistry rather than solid phase residues which may form only after ignition is obtained.

In conclusion, M30 ignites even under inert conditions due to the intense one-stage reaction zone, unlike M26 and M1. The sensitivity of O_2 in the freestream is less, because the concentration of H and CHO which start the reaction mechanism with O_2 should be lower in NGU flame than in NC flame.

Polymer Ignition

Ignition of plexiglass was obtained only under 50% O_2 and 50% N_2 conditions. This is attributed to the tendency of flame, which in this case is a pure diffusion flame, to be closer to the surface for higher freestream oxygen content. A flame of low oxygen content will tend to burn closer to the outer edge of the boundary layer, away from the surface, thus only slightly affecting heat transfer to the solid phase.

Effects of Graphite Content of Propellant

The role of carbonaceous matters in double-based propellants was addressed in conjunction with the phenomenon of super rate and platonization of the double-based propellants' burning rate.[10] One explanation is that the carbon in the condensed phase catalyzes the exothermic reactions involving the reduction of NO.[11]

The authors believe that the effects are more physical in nature. It is possible that graphite particles form local hot spots to enhance reaction rates. Thus, heat conduction to the condensed phase from the gaseous phase is enhanced through the graphite particles, a factor which may locally enhance subsurface exothermic reactions.

The effect of graphite on ignition trends was found significant only under inert conditions and even then ignition was not vigorous and the flame spread was relatively slow.

Conclusions

The convective ignition of the various propellant cylinders tested revealed the following trends:

1) The effects of the high heating rates associated with the initiation of the flow are very pronounced, particularly in short ignition delay times (submilliseconds).

2) The freestream oxygen content of the flow has a very prominent effect on ignition delay times and sites, particularly for low and moderate Reynolds numbers (up to 12,000). A higher content of oxygen in the freestream would reduce ignition delay time considerably and shift the site of ignition toward the front stagnation point.

3) Single- and double-based propellants containing nitroglycerin and/or nitrocellulose could not be ignited under inert conditions. (Only one propellant containing graphite ignited.) They ignited, however, when even small amounts of oxygen were present in the freestream. The triple-based propellant containing nitroguanidine as a major component ignited under inert conditions and was less sensitive to the oxygen content of the flow compared to the other propellants.

4) Compared to the triple-based propellant, single- and double-based propellants ignited more rapidly in flows containing an oxidizer.

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