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Ignition Studies on Aluminised Propellant

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ABSTRACT

An experimental investigation on the ignition of metallised propellants (AP/HTPB/*Al*) has been carried out to determine the ignition delay, minimum ignition energy and corresponding heat flux, threshold heat flux for ignition and minimum ignition temperature. Ignition experiments were conducted using a shock tube under convective heating conditions similar to those prevailing in a rocket motor. Heat flux at propellant location was measured by thin film heat flux gauge and also calculated from a ribbon thermocouple output under similar test conditions. The igntion delay was measured as the time lag between the arrival of hot gas at the propellant and the light emission due to actual ignition of the propellant. The experimental results indicate that the ignition delay characteristics are independent of pressure. The minimum energy for ignition obtained for the propellant is 1100 J/m^2 corresponding to the heat flux range of 80-120 W/cm^2 for a gas velocity of 110 m/s. The threshold heat flux required to ignite the propellant was 40 W/cm^2 at a velocity of 110 m/s. Heat flux corresponding to minimum ignition energy and the threshold heat flux increase with gas velocity. The threshold ignition temperature of the propellant was found to be 600 ± 20 K

1. INTRODUCTION

A large number of experimental studies are reported on the ignition of solid propellants under radiative and conductive heating of the propellant. Based on these studies it is now known that the process of ignition of the propellant under radiative or conductive heating is a gas phase phenomenon. In most practical situations, as in the solid propellant motor, heating of the propellant is predominantly by convective heating. In open literature, only very few studies have been reported on the convective ignition of the propellant.

Ignition studies on propellant by convective hot gas have been done by Bear[1] in a shock tube. The propellant sample (AP based) was mounted flush with the wall of a constant area test section attached to the end of the shock tube. The propellant was ignited by the flow of hot gas generated behind the reflected shock, over the propellant surface. The results were in agreement with the thermal ignition theory of the propellant. Kellar *et al.*[2] made a similar study on AP/PBAA propellant and confirmed the above results.

Kashiwagi *et al.*[3] studied the ignition and flame spread on a solid polymeric fuel in a hot oxidising stream. The experiments were done in a shock tunnel with a flat plate fuel specimen placed parallel to the hot oxidising stream. Results were also compared with the predicted results. Experimental results confirmed that ignition is a gas phase process. Ritchie *et al.*[4] conducted experimental studies on ignition of nitramine-based, low vulnerability ammunition (LOVA) propellants by convective heating in a shock tunnel. Cylindrical propellant sample was mounted in the test section

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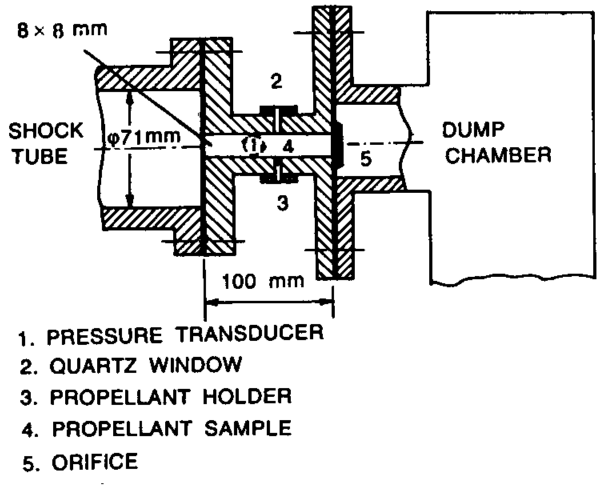

Figure 1. Test section details and dimensions.

perpendicular to the directionof the flow and the ignition was observed in the flow separation point of the cylindrical sample. No ignition was observed in the stagnation point where the heat flux is the highest. This indicates the significance of the gas phase reaction responsible for ignition.

For most of the experimental investigations reported so far, only unmetallised propellants were used. Studies on the performance of the solid propellants had established that the presence of the metal powder in the composite propellant can improve the burning properties considerably.[5,6] On the other hand, metal powder can cause increased ignition resistance due to the increased thermal conductivity and the higher ignition temperature. It can also cause reduction in the evaporation rate of the fuel and oxidiser components due to its shielding effect causing further resistance.

The purpose of the present study is to experimentally investigate the ignition delay and ignition temperature of aluminised propellant (AP-HTPB-*Al*) subjected to convective heating. A new experimental technique to measure ignition temperature is utilised for the present investigation so that the measurements can be made during the convective ignition of the propellant simulating the case of an actual rocket motor. The experimental data for various convective parameters like pressure, temperature and test gas velocity can be of use in analysing the ignition process of an aluminised propellant.

2. EXPERIMENTAL DETAILS

In the present study, shock tube technique is adopted to produce high temperature gas which convectively heats the propellant to ignition. Details of the test section are shown in Fig. 1. A 10 cm long test section with 8 x 8 mm square internal dimensions has been connected to the shock tube end flange which opens into the test section through a bell mouthed opening. The test section exhausts into a dump chamber through an orifice. Velocity of hot gas through the test section was controlled by using appropriate orifices-connected exit station. The propellant specimen (10 mm x 8 mm x 5 mm) kept flush with the inside of test section channel gets heated up by the convective flow of hot gas over the surface and ignited after the induction time. Hydrogen was used as the driver gas and air was used as test gas.

Shock velocity was measured with the help of four piezo-electric pressure transducers [PCB Piezotronics, USA, Model A22] and microsecond electronic counters using time-distance method. Shocked gas properties were calculated from the measured shock speed, taking real gas effects into consideration.

Thin film heat transfer gauges making use of quartz substrate mounted flush with the test section interior were used for measuring the heat flux. The heat transfer gauge may be considered to be consisting of a number of small strips or slabs of backing material, each strip similar to a capacitor and a resistor. An electrical model with continuous variation of capacitance and resistance can be approximated with a network of lumped constants. The applied voltage to the network is proportional to the surface temperature and the corresponding current in the network is proportional to the heat transfer rate. An analogue network on these lines was fabricated and used for heat flux measurements. Temperature history recorded by a ribbon thermocouple kept flush with the test section was also used to calculate the heat flux under similar test conditions and found to agree within 15 per cent of the measured value obtained using thin film gauge.

The heat transfer coefficient to the propellant from the hot gas is also calculated by the correlation expressed in terms of Nusselt number for flat plate[7] explained below. Since the thickness of the boundary layer at the propellant location is very small compared to the test section cross section, the flow over the propellant surface can be approximated as flow over a

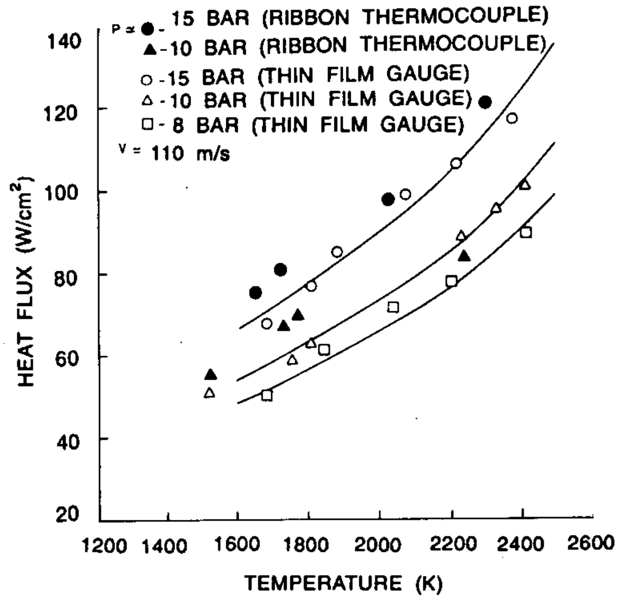

Figure 2. Comparison of measured and computed heat flux.

flat plate for which Nusselt number (Nu) can be written in terms of Reynolds (Re) and Prandtl numbers (Pr) as;

$$Nux = 0.453\ Rex^{0.5}\ Pr^{0.33}$$

Heat flux is computed by multiplying heat transfer coefficient with difference of the free stream temperature and initial surface temperature of the propellant. The variation of the measured heat flux with temperature for a flow velocity of 110 m/s is compared with the heat flux computed using the correlation of heat transfer to a flat plate in Fig. 2. The measured values of heat flux agree well with the values calculated using the correlation.

For ignition time measurements, the arrival of hot gas at the propellant was detected by sensing the pressure rise through a piezoelectric pressure transducer mounted close to the propellant in the test section. The ignition was detected by sensing the light emission on a photomultiplier. The two signals were fed to a CRO and the time difference between them was reckoned as ignition delay.

In most of the investigations reported in literature regarding the measurement of ignition temperature of a propellant, radiative heating was used as the ignition source. Since the dependence of ignition temperature on nature of heat flux cannot be ruled out, knowledge of ignition temperature under conditions similar to those obtained in the actual rocket motor is important. A new method to measure the minimum ignition temperature under convective heating conditions using a shock tube was utilised in the present investigation. The advantage of this technique over other methods is that the ignition source is convective as in a rocket motor. The effect of environmental parameters such as temperature, pressure, velocity and environmental composition on ignition temperature also can be investigated by this technique

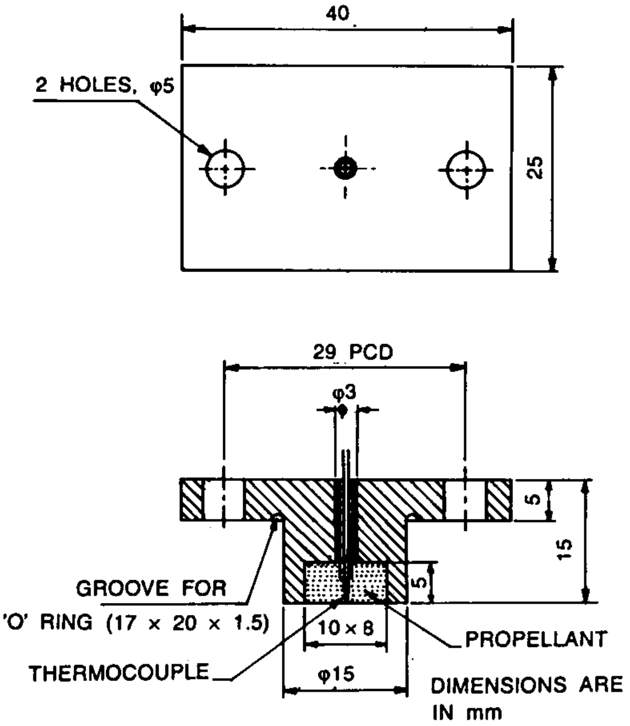

Figure 3. Propellant holder with thermocouple.

In the experimental set-up for ignition delay measurements a minor modification is made in the propellant holder, to fix the thermocouple. Fig. 3 shows the details of the propellant holder with the thermocouple. The propellant holder carrying the propellant with the thermocouple embedded just below the surface is inserted into the test section so that the surface of the propellant is flush with the inside of the test section. The thermocouples used in present investigation were chromel-alumel thermocouple of 200 µm and platinum-platinum-rhodium (13 per cent) thermocouple of 30 µm size. When the propellant is ignited by the convective heat flux, output from the thermocouple is suitably amplified and stored in a CRO. The temperature history recorded in the CRO forms the basis for deducing the ignition temperature. A change in slope of the temperature signal was taken as the ignition point. A typical temperature profile recorded by 200 µm chromel-alumel thermocouple is shown in Fig. 4.

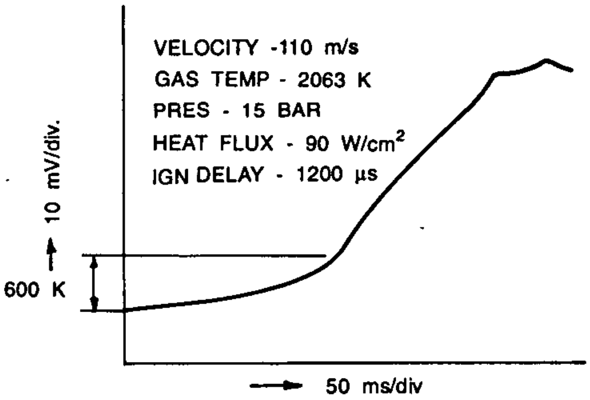

Figure 4. Temperature profile recorded by the thermocouple.

Experiments were conducted to measure the ignition delay for a wide range of pressure, temperature and velocity of test gas (air). The required pressure and the temperature range of 5-16 bar and 1500-2500 K respectively were obtained by varying the initial test gas conditions of the shock tube, and the diaphrgm thickness. The average flow velocities of 75 and 340 m/s were obtained by using different orifices in the test section.

The ignition temperatures were measured in different environmental conditions. The test details are shown in Table 1.

Table 1. Ignition temperature of metallised propellants

Experiment No.	Test condition Flow Vel. (m/s)	 Pressure (bar)	Ignition temp.as indicated by thermocouple (K)
1	340	15	600
2	340	15	620
3	340	15	600
4	340	15	600
5	Open atmosphere		570
6	Open atmosphere		600
7	Open atmosphere		600
8	110	15	600
9	110	15	620
10	110	15	600
11	110	15	570
12	110	15	620
13	110	15	610
14	110	15	585
15	110	15	585
16	110	15	600
17	110	15	600
18	110	15	610
19	110	15	600
20	110	15	600

Ignition temperature of propellant = 600 ± 20 K

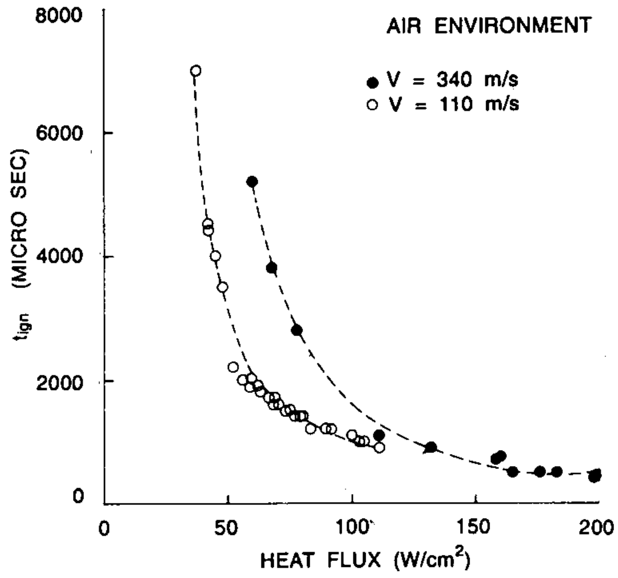

Figure 5. Ignition delay variation with heat flux.

3. RESULTS AND DISCUSSION

Study of ignition of a propellant under convective heat flux is complicated because of the large number of parameters involved in the process. Some of the major factors which control the ignition are the rate of supply of the external energy or the heat flux and the time of exposure to the heat flux. External heat flux to the propellant in convective heating depends on pressure, temperature and velocity of the igniting medium. Apart from contributing for the overall heat flux to the propellant surface, each of these parameters may have independent effect on controlling the ignition process.

Figure 5 is the representation of the variation of ignition delay with externally applied heat flux in air environment. It is quite natural that the ignition time or the time of exposure of the propellant surface to the input energy to achieve ignition reduces with increased rate of energy input. The two sets of data points in the plot correspond to two different velocities (110 m/s and 340 m/s). The variation of heat flux for these two velocities are obtained by varying the temperature and pressure of the hot gas.

In the ignition delay plot (Fig. 5), it can be observed that at lower heat flux the ignition delay increases sharply, which indicates the requirement of a threshold energy input rate to attain ignition. Below this threshold heat flux, ignition cannot be achieved. Since in the shock tube experiments the maximum observation time is limited to a few milliseconds, it was not possible to obtain the exact value of the threshold heat flux.

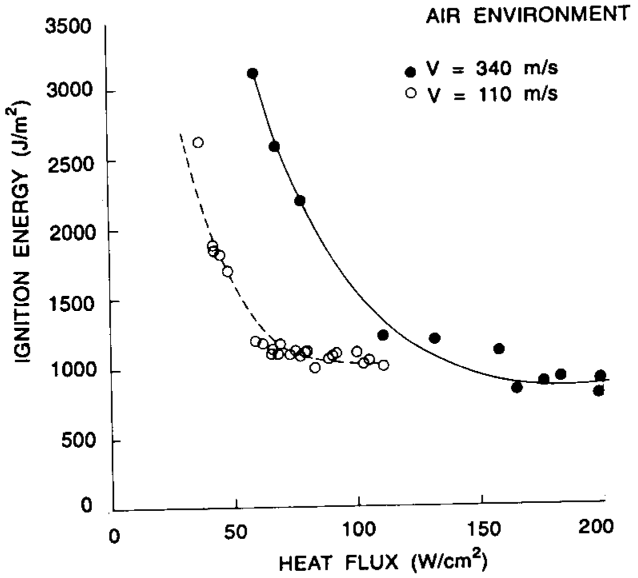

Figure 6. Ignition energy variation with heat flux.

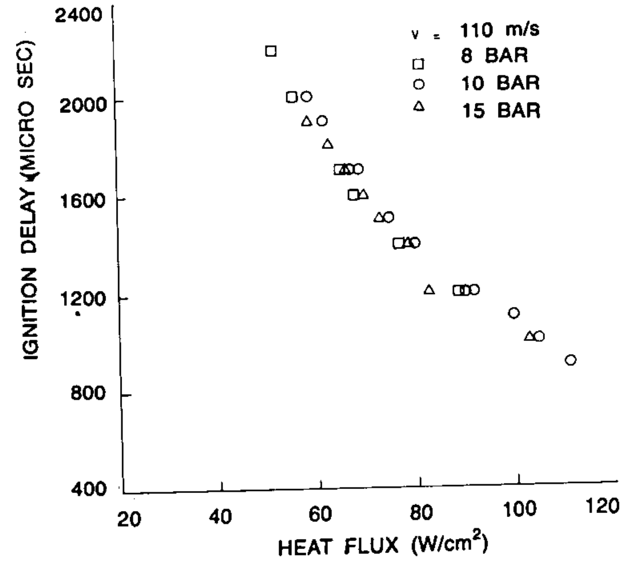

Figure 7. Ignition delay variation with heat flux for different gas pressures.

Moreover, it varies with the velocity as can be seen from the plot. But from the nature of the variation of the ignition delay, we can see that the threshold value of heat flux is approximately 40 W/cm^2 for a gas velocity of 110 m/s. This value of threshold heat flux is only a representative one, which is system dependent and may vary depending on the oxidiser concentration of the environment, heating source, propellant geometry, surface nature, etc. of the propellant. The plot also shows that at high heat flux the ignition delay tends to a constant minimum value. This tendency can be explained by the existence of a minimum ignition time for ignition reaction, which depends on the kinetic rate parameters of the propellant.

A more detailed information on the relationship between ignition and energy input rate (heat flux) can be obtained from the ignition energy plot shown in Fig. 6. It can be seen from the plot that the minimum ignition energy is 1100 J/m^2 and the energy required to ignite the propellant shoots up at very low input rate. This shows that the most effective utilisation of the energy occurs above a particular heat flux, which depends on velocity. For a gas velocity of 110 m/s the heat flux corresponding to minimum ignition energy is 60 to 120 W/cm^2 with a higher range for higher velocity. The reduced effect at lower heat flux may be due to the thermal conduction within the propellant. At low heat flux the heat lost by conduction to the propellant is a considerable fraction of the applied heat flux. This may be the reason for the sharp increase of ignition delay and energy at low heat flux. At very high heat flux, the conduction loss will be an insignificant part of the applied heat flux. Fig. 7 represents the ignition delay variation with heat flux for different pressure conditions. It can be seen from the plot that the effect of pressure on ignition delay chracteristics is insignificant for the present range of investigation.

The ignition temperatures measured under different environmental conditions tabulated in Table 1 indicate that the ignition temperature of the propellant is 600 ± 20 K and it is independent of the environmental conditions.

4. CONCLUSIONS

1. The ignition delay mainly depends on the applied heat flux. For a constant heat flux, ignition delay increases with flow velocity. Effect of pressure appears to be insignificant.

2. The threshold heat flux to ignite the propellant under test is 40 W/cm^2 for a velocity of 110 m/s in irenvironment and increases with the velocity.

3. The minimum ignition energy for the propellant is 1100 J/m^2 in air environment.

4. The dependence of ignition delay on flow velocity and the increase of threshold heat flux with velocity indicate

that the gas phase reactions are responsible for the ignition of solid propellant.

5. The minimum ignition temperature of the propellant is 600 ± 20 K.

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