DETERMINATION OF BURNING RATE OF SOLID PROPELLANT COMBUSTION

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Abstract

Propellants burn along the local normal and the linear regression rate is called burn rate. In this paper, the burning rate was determined from the combustion photography (images) taken by high speed camera. These images were processed frame by frame by writing an algorithm in MATLAB, detecting the edges in the images of the frames. Image analysis was processed by edge detection method in MATLAB. Images of solid propellant combustion of three different proportions were taken for analysis. The results found to be satisfactory. The burning rate is obtained as the slope of the linear fit from MATLAB as shown in figure. Paper explains about the types of solid propellants, propellant ingredients and its formulation.

Keywords: burn rate, solid propellant, image analysis

I. INTRODUCTION

Solid propellants are widely used in gun and rocket propulsive applications. They are very energetic and produce high temperature gaseous products on combustion. The high material density of solid propellants leads to high energy density needed for producing the required propulsive force. Propellants on board a rocket are burned in a controlled way to produce the desired thrust. A solid propellant consists of several chemical ingredients such as oxidizer, fuel, binder, plasticizer, curing agent, stabilizer, and cross-linking agent. The specific chemical composition depends on the desired combustion characteristics for a particular mission. Different chemical ingredients and their proportions result in different physical and chemical properties, combustion characteristics, and performance.

II. SOLID PROPELLANT

This is used as fuel and oxidizer in rocket launching applications. Solid propellant is a mixture of oxidizer particles and fuel, which when ignited, undergoes combustion giving large volume of low molecular weight gaseous combustion products and high heat energy release rate. Solid propellants can be classified as [1,2,7].

1. Homogeneous propellants
2. Heterogeneous propellants.

Solid propellants are further classified based on the major ingredients as

(i) Single base propellant

The main ingredient is the nitrocellulose (NC), which is available in solid form with slightly fuel rich, used as gun propellants.

(ii) Double-base propellant (DB)

Here, the main ingredients are the nitrocellulose (NC) and nitroglycerine (NG). NG is used to plasticize the high molecular weight NC to form thermoplastic. Both these are explosives in nature, with detonation velocity of 6-7 km/sec, but when compounded together in a proper manner to form a strong tough plastic, a well controlled deflagration of few mm per second can be achieved.

(iii) Triple-base propellant

In this, the main ingredients are the nitrocellulose (NC), nitroglycerine (NG) and nitro guanidine (NQ).

(iv) Composite propellant

The main ingredients are AP particles, aluminum particles and HTPB.

(v) Composite modified double-base propellant (CMDB)

The main ingredients are the nitrocellulose (NC), nitroglycerine (NG), AP particles and aluminum particles.

A. Propellant Formulation

This is very important to govern the following

(i) specific impulse energy
(ii) ballistic parameters like burn rate, temperature sensitivity

(iii) mechanical properties

(iv) ageing characteristics

B. Propellant Ingredients

Propellant Ingredient	Type
Ammonium Perchlorate (AP)	Oxidizer
Hydroxyl-terminated polybutadiene (HTPB)	Prepolymer
Di-octyl adipate (DOA)	Plasticizer
Toulene di-isocynate (TDI)	Curing agent

A propellant formulation is characterized by the following [10]

(i) Oxidizer content

(ii) Metal contents

(iii) Binder used

(iv) Oxidizer particle size distribution

(v) Metal particles

(vi) Concentration of plasticizer and curing agents

C. Preparation of Solid Propellant:

Solid propellant was prepared by mixing oxidizer particles and binder in a proper proportion thoroughly without any air gaps in a mixer as shown in Figure 1. The propellant mixture in a mixer was surrounded by hot air circulation to have better mixing, and at the top provision is made to vacuum the moisture contents present in the mixer. After mixing, the propellant slurry was put in the large cylindrical pressure vacuum casting chamber to perform casting of propellant. The propellant after casting, it was kept in a hot air oven for seven days for curing. Three different compositions of propellant were made and experiment was conducted. [9]

III. OXIDIZER

There are four salts available like ammonium perchlorate (AP), ammonium nitrate (AN), potassium perchlorate (KP) and lithium perchlorate (LP). Among these, AP is used because of good low temperature property, low cost, easy processing and quite stable. AP is a white crystalline or powdery form, takes orthorhombic structure at room temperature conditions and cubic structure at 240°C. AP is most widely used to formulate composite propellants for rockets.

A. Preparation of AP Particles:

The “as-received” AP is grinded with the help of mixie. The different particle sizes obtained with the help of sieves available in microns (like 60 μm, 75 μm, 100 μm) in the market. Sieving is done with sieving machines or physically also can be done. AP particle is affinity to moisture and it will clump together; so we can use anti-caking agent like TCP (tri calcium phosphate). The prepared AP particles are stored in a desiccators or hot air oven at temperature 60$C.

B. Size of AP Particles

The oxidizer particles (AP) are classified as

Fine size (30-80 microns),

Medium size (100-200 micron) and

Coarse size (250-450 microns).

IV. BINDER

This is the combination of pre-polymer, plasticizer and curing agents. Some few types of pre-polymers available are [10]

(i) PolySulphide (PS)

(ii) PolyUrethene (PU)

(iii) Poly-Vinyl Chloride (PVC)

(iv) Carboxy Terminated Poly Butadiene (CTPB)

(v) Hydroxy Terminated Poly Butadiene (HTPB)

HTPB is a high viscous polymeric fluid, and this is used as binder to mix the oxidizer particles (AP) together and hence this composite form is called as heterogeneous propellant or more commonly as composite propellant.

Plasticizers are low viscous organic fluid. Some of the plasticizers are DOA, DOP, etc., They are used to get propellant slurry form for better mixing and casting, and to improve elongation properties of the binder.

Curing agents are used to maintain structural integrity of a propellant grain. Some of the curing agents are isophorone diisocyanate (IDPI), Toulene di-isocynate (TDI), etc. The choice and selection of curing agents depends on what prepolymer we use. The curing agent influences the mixing process, burning rate and combustion.

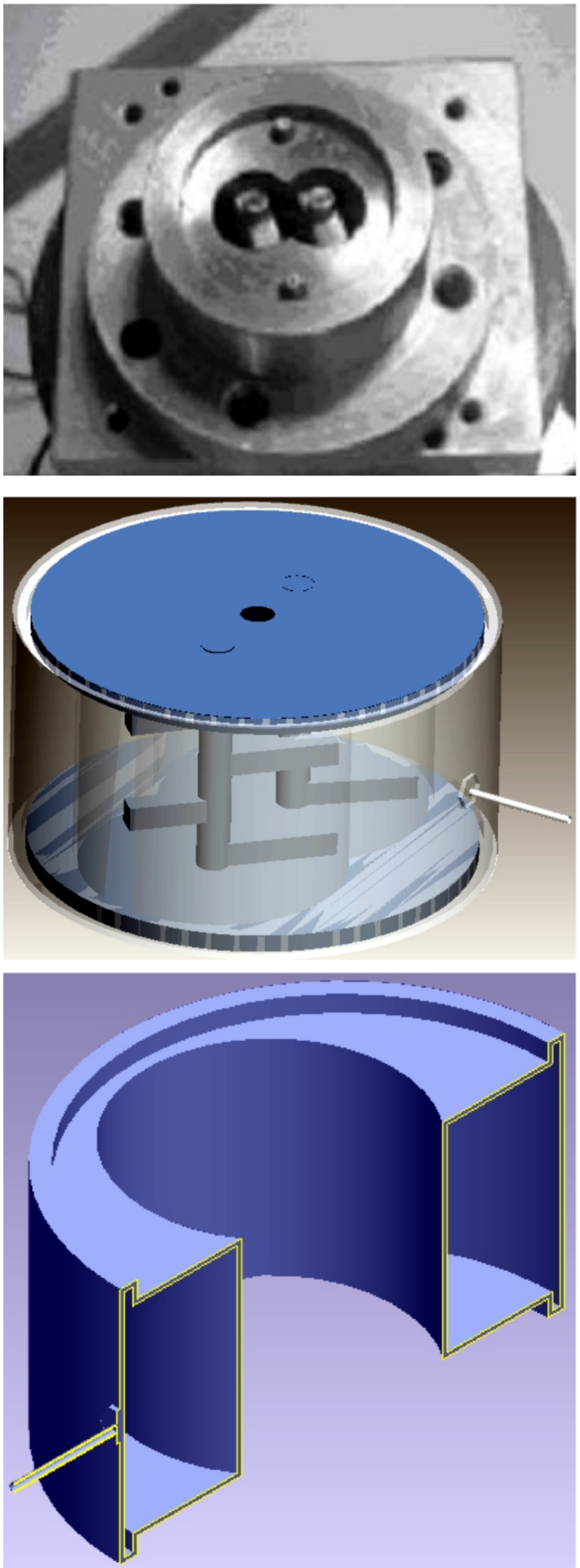


Fig. 1. A mixer

V. COMBUSTION PHOTOGRAPHY

The burning rates of the solid propellant (three samples) are determined as a result of experiments performed in an optical set-up called "window bomb" set-up[9].The combustion photography was captured by a CCD camera and recorded. The window bomb is a cylindrical pressure vessel. The schematic view of the set up is shown in figure 2. The cylindrical chamber has two windows made of toughened glass along its curved surface. The purpose of the smaller window is to facilitate the imaging of the burning process and the other window is used to provide external illumination. Using the shuttle ring control in the video cassette recorder, the recorded images can be viewed frame-by-frame for determining the burning rate of the samples. Before ignition, the chamber is flushed with nitrogen gas followed by maintaining the pressure required for combustion.

The sample is then ignited and the images were recorded. The consecutive images of the burning samples are shown in figure. The images were viewed frame-by-frame and the location of the flame front in each frame is noted. The actual position of the flame front is plotted against the time of each frame, after adjusting for the magnification of the images. The burning rate is obtained as the slope of the linear fit from MATLAB as shown in the following figures.

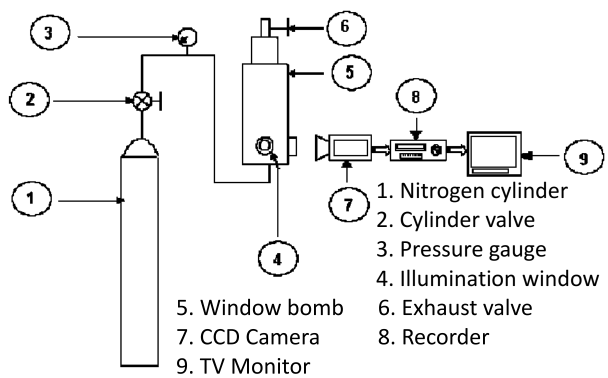
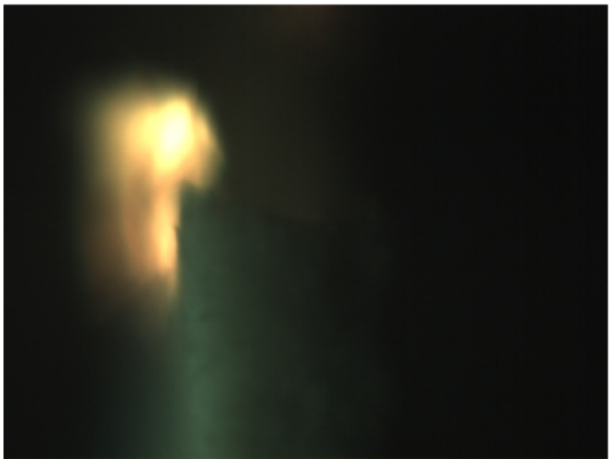


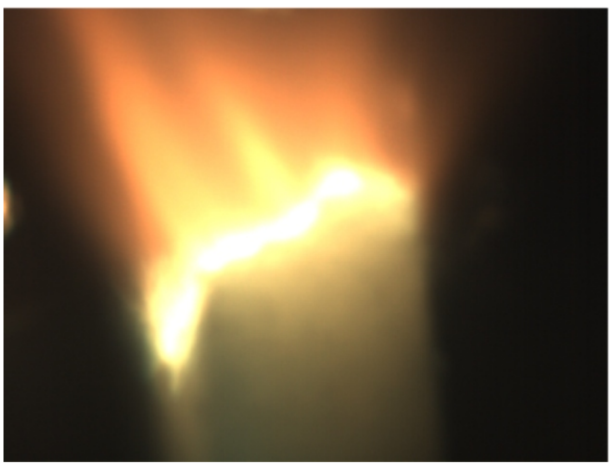
Fig. 2. A "window bomb" set-up

The following figure 3 shows images for three samples [8].

Case (i) 4% (AP), 20 bar pressure



Case (ii) 10% (AP), 20 bar pressure



Case (iii) 10% (AP), 35 bar pressure

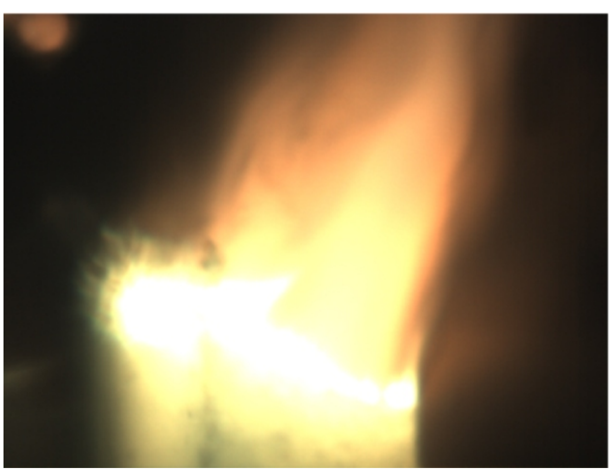


Fig. 3. Images for three cases

VI. IMAGE ANALYSIS IN MATLAB

Image analysis technique in MATLAB [9] gives information about the structure of an image. Some of the image analysis techniques are (i) Edge Detection, (ii) Boundary Tracing (iii) Quadtree Decomposition Edge Detection.

We can use the edge function to detect edges, which are those places in an image that correspond to object boundaries. To find edges, this function looks for places in the image where the intensity changes rapidly, using one of these two criteria: Places where the first derivative of the intensity is larger in magnitude than some threshold Places where the second derivative of the intensity has a zero crossing edge provides a number of derivative estimators, each of which implements one of the definitions above. The most powerful edge-detection method that edge provides is the Canny method. The Canny method differs from the other edge-detection methods in that it uses two different thresholds (to detect strong and weak edges), and includes the weak edges in the output only if they are connected to strong edges. This method is therefore less likely than the others to be fooled by noise, and more likely to detect true weak edges.

The following algorithm was developed in MATLAB to process the images, to plot a graph between pixels and frame number.

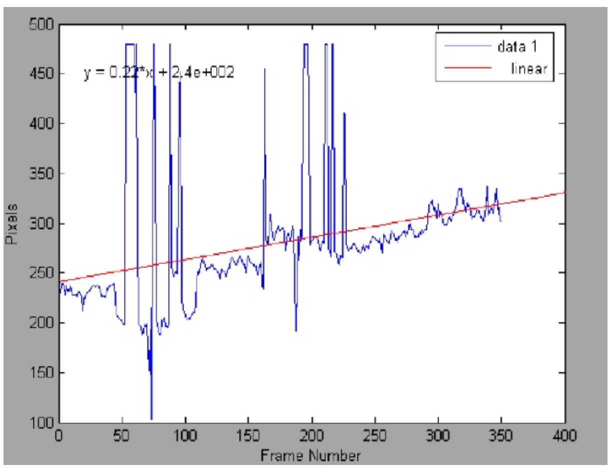
A. Matlab Code

```
clear all;
clc;
Img_nam = 'ImgA000';
H_Ind = 1;
for i = 152:171;
    ImgName = strcat(Img_nam,num2str(i),'.tiff');
    Img = rgb2gray(imread(ImgName));
    Img1 = Img(:,1:400);
    I_Blur = uint8(double(Img1)-2*mean(mean(Img1)));
    I_Val = I_Blur>1;
    I_Edge = edge(I_Val*250,'canny');
    bwAreaOpenBW = bwareaopen(I_Edge,20);
    se = strel('disk',20);
    closeBW = imclose(bwAreaOpenBW,se);
    [r c] = size(closeBW);
    for j = 1:c
      Ind = 1;
      for k = 1:r
        if closeBW(r-k+1,j)>0
          X_Ind(Ind) =k;
          break;
```

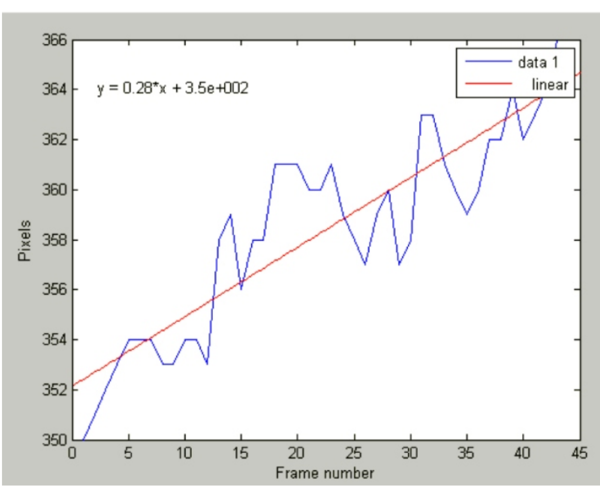
```
            end
         end
         Ind = Ind + 1;
         end
         H_Val(H_Ind) = mean(X_Ind);
         H_Ind = H_Ind + 1;
end
plot(H_Val)
xlabel('Time');
ylabel('Surface Distance');
```

The following graphs were obtained by running the algorithm in MATLAB.

Case (i) 4% (AP), 20 bar pressure



Case (ii) 10 % (AP), 20 bar pressure



Case (iii) 10 % (AP), 35 bar pressure

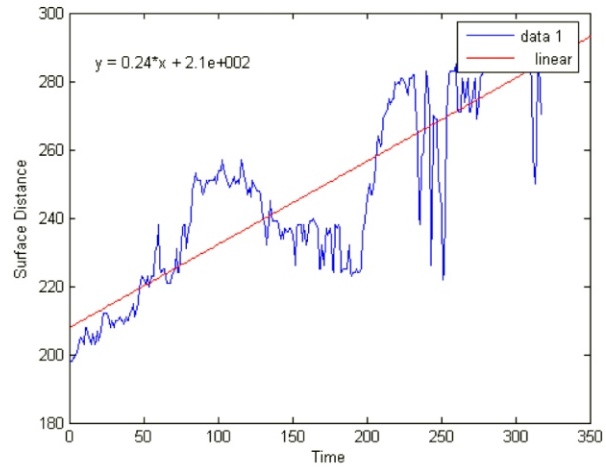


Fig. 4. Graph obtained from MATLAB for three cases.

VII. BURNING RATE CALCULATION:

By considering the number of pixels and pixel distance, and the number of frames and frame rates, slope of each case was determined, which gives the burning rate measurement for three samples in mm/sec.

$$\text{Slope} = \frac{\text{pixels}}{\text{frame number}}$$

6.5 mm = 640 pixels

1 pixel = 0.01015625mm

Frame rate = Number of frames/sec

Therefore, the unit for burning rate measurement is mm/sec.

Table 1. Shows burning rate for all three cases.

S.No	% of AP	Pressure (bar)	Burning rate (mm/sec)
1	4	20	4.915
2	10	35	5.3625
3	10	20	6.256

VIII. CONCLUSION

The burning rate for three cases was calculated by considering only the combustion photography (images) frame by frame, by writing algorithm in MATLAB and processing it. The results were appreciable. The accuracy of the burning rate value entirely depends on the clarity of the images; blurred images may not give good results. The algorithm can used by any of the research scholars to perform image analysis, make sure to get quality images.

REFERENCES

[1] Banerjee, S., and Chakravarthy, S.R., 2007, "Ammonium Perchlorate-Based Composite Solid Propellant Formulations with Plateau Burning Rate Trends", *Combustion, Explosion, and Shock Waves*, 43, 435-441.

[2] Chakravarthy, S.R., Price, E.W., and Sigman, R.K., 1995, "Binder Melt Flow Effects in the Combustion of AP-HC Composite Solid Propellants", AIAA Paper No. AIAA-95-2710.

[3] Chakravarthy, S.R., Price, E.W., and Sigman, R.K., 1997, "Mechanism of Burning Rate Enhancement of Composite Solid Propellants by Ferric Oxide", Journal of Propulsion and Power, 13, 471- 480.

[4] Chakravarthy, S.R., Price, E.W., Sigman, R.K., and Seitzman, J.M., 2003, "Plateau burning behavior of Ammonium Perchlorate Sandwiches and Propellants at Elevated Pressures", Journal of Propulsion and Power, 19, 56-64.

[5] Chakravarthy, S.R., Price, E.W., Sigman, R.K., and Seitzman, J.M., 2003, "Plateau Burning Behavior of Ammonium Perchlorate Sandwiches and Propellants at Elevated Pressures", Journal of Propulsion and Power, 19, 56-65.

[6] Chakravarthy, S.R., Seitzman, J.M., Price, E.W., and R.K. Sigman, 2004, "Intermittent burning of ammonium perchlorate–hydrocarbon binder monomodal matrixes, sandwiches, and propellants", Journal of Propulsion and Power, 20, 101-109.

[7] Srinivas, V. and Chakravarthy, S.R., 2007, "Computer Model of Aluminium Agglomeration on the Burning Surface of a Composite Solid Propellant", Journal of Propulsion and Power, 23, 728-736.

[8] Jayaraman K, 2008, "Production and characterization of Nano-Aluminium and Its Effects In Solid Propellant Combustion", PhD Thesis, IITM.

[9] MATLAB software.

[10] Course notes on “Propellants and explosive technology” conducted at IITM, Chennai, Dec 6 & 7, 1998.