INVESTIGATION ON PARAMETERS INFLUENCE FOR INTRINSIC INSTABILITY ANALYSIS OF SOLID PROPELLANT (AP+HTPB+TDI) USING COMPUTATIONAL IMAGE-PROCESSING TECHNIQUE

by

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The effect of the different mixture in a high volumetric concentration of oxidizer – (AP), with least percentage of binder – (HTPB+TDI), for improving the propellant burn rate was investigated. The combustion experiment is performed using a window bomb set-up and the high-speed camera is utilized to capture the flame images. An image processing approach is used to measure the burn rate and intrinsic instability of flame by discrete wavelet transform method. Region growing algorithm technique is used for image segmentation. The morphological operation is implemented with Euclidean distance measurement for the identification of flame height in configuring with dependent parameters (burning rate, diffusion flame height). The qualitative analysis (signal characterization) and quantitative analysis (mean, kurtosis, skewness, standard deviation, and frequency) were used to study the intrinsic instability characteristics of the flame diffusion. A result obtained from the analysis proves that the instability in fuel combustion occurs at higher mix and pressure level.

Key words: *solid propellant, ammonium perchlorate, burn rate, hydroxyl terminated polybutadiene, wavelet transform, statistical analysis*

Introduction

Heterogeneous solid propellant, which contains both oxidizer and fuel, are highly combustible and produce high temperature gaseous molecules by Beckstead *et al.*[1] and Rodic and Bajlovski, [2]. A fine AP particles exhibit plateau characteristics by Masafumi *et al*. [3]. A computer-assisted technique is used to obtain the burn rate and intrinsic instability of the proposed propellant formulation for fuel lean composite propellant by Williams [4]. The AP/binder ratio is shown in tab. 1. The study shows how a lean mixture of the binder into the propellant inclusion alters burn rate characteristics. Then the study carries out the intrinsic instability of flame, by depressurization of varying in cylinder pressure. The proposed architecture of the study system is shown in fig. 1.

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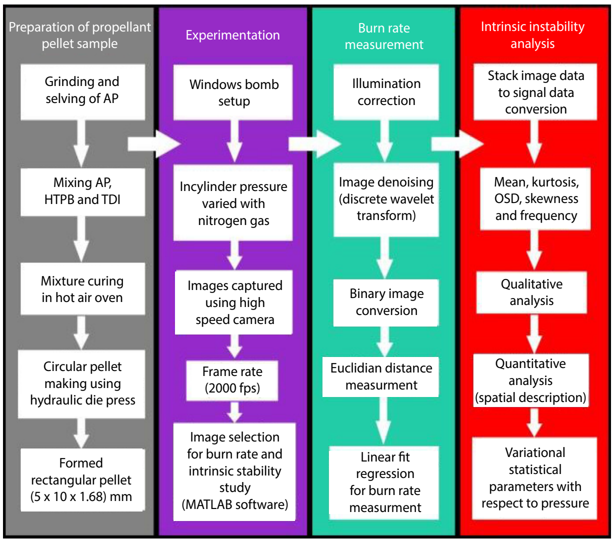

Figure 1. Proposed plan of the system for the measurement of burning rate

Origin of the problem and need for research

It is observed the previous study that combustion characteristics of the use of lean fuel mixture based on computer-assisted technique are not so well described. While the existing techniques provide insight into the combustion environment, the burning and instability characteristics of rich fuel mixture but do not provide a clear picture on a validating technique for the characterization of burn rate and intrinsic instability of the flame. Clearly, more diverse computer-assisted techniques are needed to elucidate the mechanisms of composite propellant combustion for lean fuel solid propellant mixture. In particular, direct measurements of the propellant flame structure of sample mixture could give only a drafted view of the propellant characterization. Hence, there is a need to study the solid propellant characterization based on the lean mixture with a computer assisted measurement technique.

Objective of the work

The proposed approach is to identify that, how the oxidizer influence can modify the burn rate and instability characteristics in a composite solid propellant. This is achieved by statistical validation through computational image processing method to study the effects of lean binder replacement with inclusion modified, AP/Binder (92/08, 94/06, 96/04, 98/02 and pure AP wt.%). The end effects of inclusion content, density, burning rate and an intrinsic instability of the flame are addressed to determine how lean mixture of the binder into the propellant inclusion alters the burn rate characteristics and the instability behavior. The study is to conduct a mathematical model using an image processing technique for the experimentally acquired images in high-speed camera (NX7-S2) to measure the burn rate for the different propellant mix samples and addressing intrinsic instability. The specifications of the High-speed camera is presented in tab. 1.

Table. 1 Image acquisition parameters of the high-speed camera system

Parameters	Value
Frame rate [fps]	2000
Electronic shutter [s]	1/100000
Video duration [s]	6
Total frames	12000
Pixel resolution [mm^2]	0.0978 × 0.0978
Focal length [mm]	7

Methodology

Preparation of propellant pellet

The AP (an oxidizer) of particle size 63-75 μm obtained through planetary ball mill (PULVERI SETTE 5 classic line, Germany), HTPB (fuel binder), and TDI (curing agent) of required amount as shown in tab. 2 is mixed thoroughly in a beaker and kept in an oven at 303 K for curing for 7 days. Around 1.8 gram of the mixture is taken in a stainless steel die of the circular cross-section of one-inch diameter, kept under hydraulic press at 200 bar for two hours to make pellet as shown in fig. 2. The pellet sample is prepared with the dimensions of 10 mm × 5 mm × 1.68 mm for five different compositions.

Table. 2 Composition of solid propellant samples by weight percentage

Binder [%]	Density [gcm^{-3}]	AP [%]	HTPB [%]	TDI [%]
0	1.95	100	–	–
2	1.9294	98	1.88	0.12
4	1.9088	96	3.76	0.24
6	1.8882	94	5.64	0.36
8	1.8676	92	7.52	0.48

Figure 2. Preparation of propellant pellet samples using die press

Experimentation

Figure 3 shows the set-up consisting of a cylindrical chamber pressurized with nitrogen (purge gas) and two optical windows, one for light illumination and other for capturing the combustion photography with a high-speed camera of 2000 fps, Jayaraman [5]. The sample is placed in-between the two electrodes and nichrome wire placed on the top of the pellet, then connected to two electrodes, DC power supply is used for ignition. Figure 4 shows sample images of combustion photography. The experiment conducted for five proportions at the pressure range of 20, 35, 50, 70, and 100 bar, respectively.

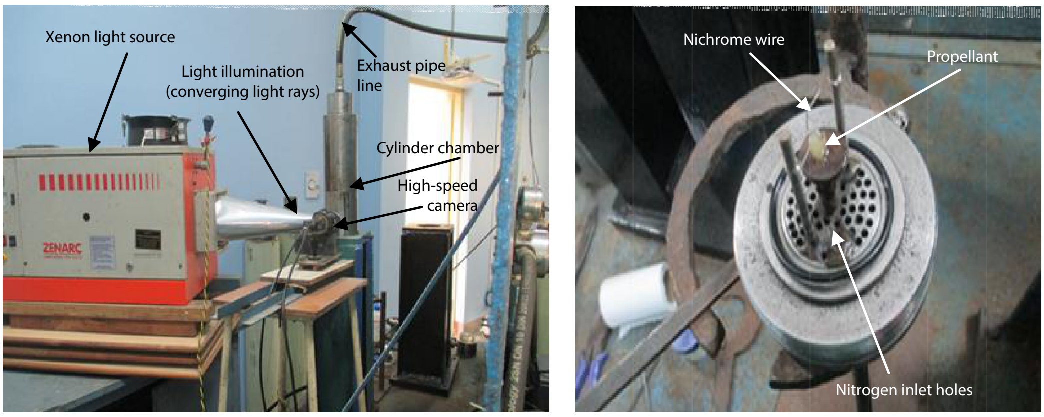

Figure 3. Experimental view of the window bomb set-up

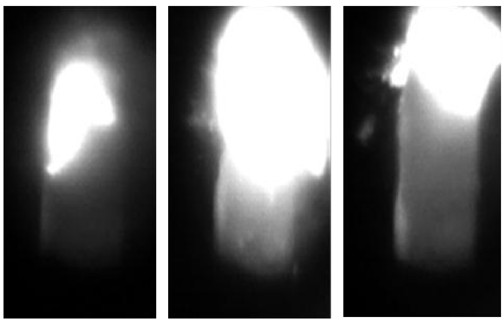

Figure 4. Sample images of combustion photography for different pressure

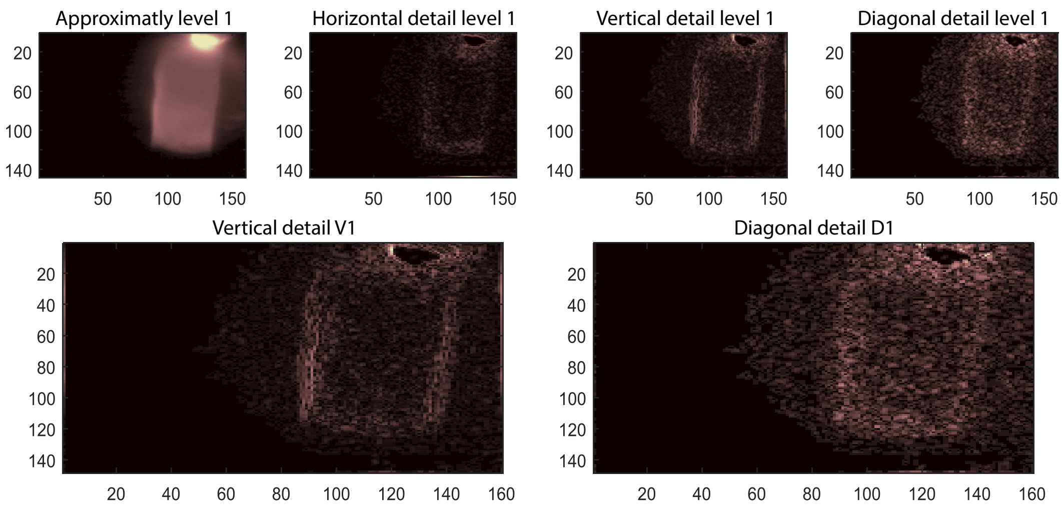

Figure 5. Image de-noising using discrete wavelet transform

Image processing approach

Figure 5 shows the image de-noising using discrete wavelet transform [6, 7]. The proposed measurement system of flame burn rate and instability initializes with contrast enhancement and stationary wavelet transform. The segmentation process is shown in fig. 6. where the region of interest (ROI) is the crucial step in the analysis of flame based propellant images. The accuracy of the segmentation depends on the region of interest (ROI) from the images. Segmentation of propellant images refers to segmenting the regions in the image that contains only the propellant samples for the burn rate measurement.

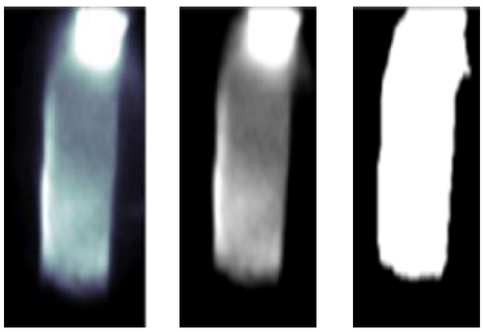

Figure 6. Segmentation process using region growing algorithm

The Euclidean distance, d, is the pixel distance between two points in Euclidean space. The analysis is carried out to predict the exact pixel distance to nominal distance of the burning propellant images. It was observed that the behavior of Euclidean distance becomes more useful with increased number of samples by Xia *et al*. [8]. In the Euclidean plane, if $p = (p_1, p_2)$ and $q = (q_1, q_2)$ then the distance is given by Reddy and Udgata [9]:

$$d(p,q) = \sqrt{(q_1 - p_1)^2 (q_2 - p_2)^2} \tag{1}$$

This method is used to detect the segmented propellant height in terms of pixel distance converted to the actual distance based on the Euclidean plane. Thus the reduction in the propellant sample with respect to the burn rate can be measured.

Intrinsic instability analysis

Intrinsic instability study details the mechanism of flame characterization to weak disturbances. Under oxidizer rich and at higher pressures say 100 bar, intrinsic instability is noticed in the type of statistical parameters derived from the combustion images for flame growth, whose position oscillates laterally about the mid fuel binder layer. Figure 7 illustrates the main parameters for the image data acquisition for the qualitative and quantitative analysis of the propellant combustion.

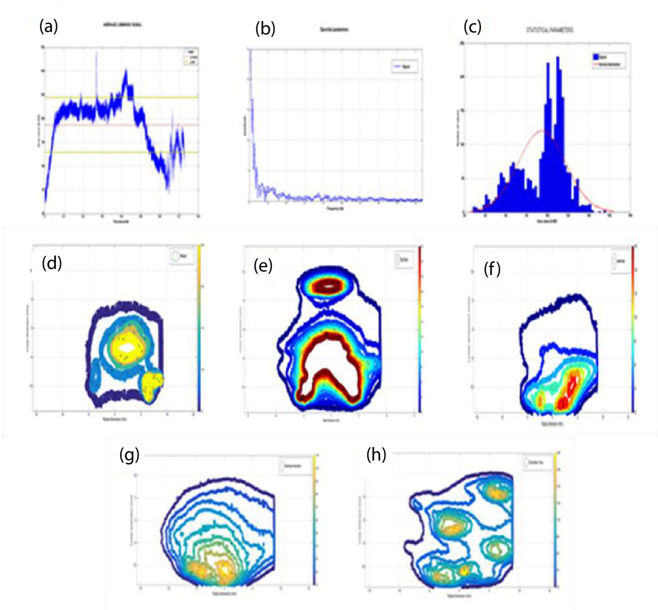

Figure 7. Qualitative and quantitative analysis of the propellant combustion extracted from the image; (a) signal characterization, (b) power spectral density, (c) histogram plot, (d) mean, (e) kurtosis, (f) skewness, (g) SD, and (h) oscillation frequency

Results and discussion

Burn rate measurement

A linear fit curve regression model has been developed using MATLAB software, where the slope equation is determined to be the burn rate value. The burn rate regression graph for varying in-cylinder pressure (20-100) bar with different binder mix samples and pure AP is shown in fig. 8.

Instability characteristics

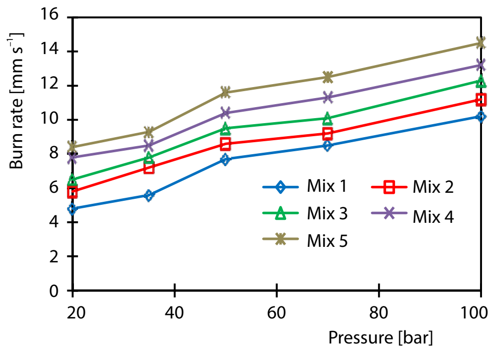

Figure 8. Burn rate *vs.* pressure

Under depressurization for various in cylinder pressure and different spectral characteristics for instability burning of flame are obtained as shown in sigs. 7(a)-7(c). and the spatial characteristics are shown in figs. 7(d)-7(h). The present study in this part is to illustrate significant differences in flames when the fuel is burnt under rapid depressurization of in-cylinder pressure. The distribution of parameters is obtained as color contour maps in order to visualize possible flame patterns. Pure AP sample is compared to the mixed binder ones taken into account underlying in cylinder pressures under rapid depressurization. The flame parameters with a statistical definition for flame brightness, fluctuation amplitude, and distribution symmetry and oscillation frequency are shown in tab. 3. The brightest area, composed of values above 180 gray units, extends and increases with fuel binder addition due to the compensative fuel mix with the oxidizer content, tab. 2. This effect has the same opinion with previous experimental results Lu *et al*. [10] and Lu *et al*. [11].

Instability of flame mostly depends on the addition of binder fuel content on the oxidizer, which causes the flame to detonate on ignition. On the depressurization condition, the flame starts to oscillate highly for the binder mixed fuels, whereas the pure AP oxidizer proves a stable burning. No important increments are observed in the pure AP and their values are

Table. 3 Combustion flame parameters with statistical definition

Signal characterization	Statistical/spectral parameter	Mathematical expression
Flame brightness	Mean value, $\bar{x}$	$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$
Fluctuation amplitude	Standard deviation, σ	$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$
Distribution symmetry	Kurtosis, (k) and skewness (s)	$y = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^m}{\sigma^m}$
Oscillation frequency	Flicker, F	$F = \frac{\sum_{k=0}^{N-1}\lvert X(f_k)\rvert f_k}{\sum_{k=0}^{N-1}\lvert X(f_k)\rvert}$

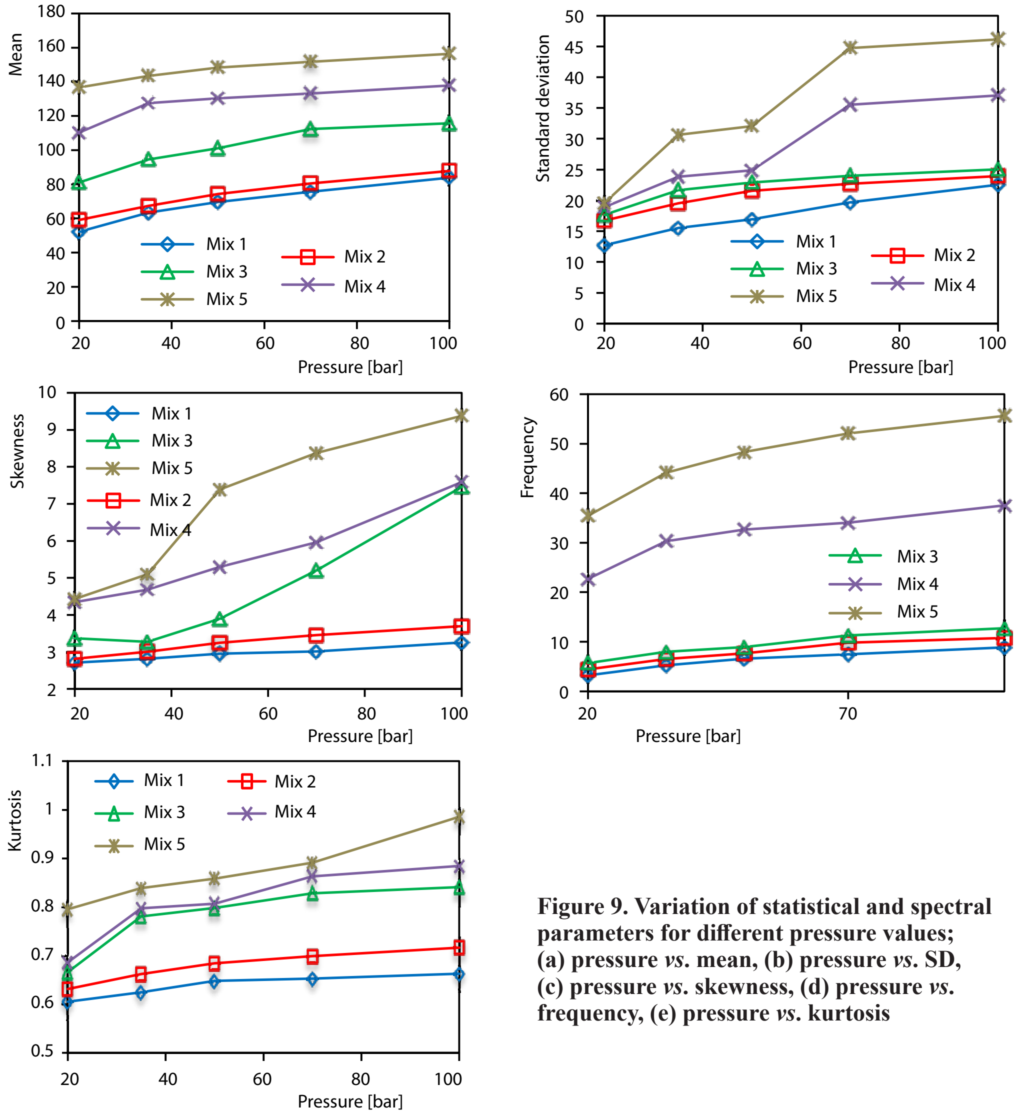

Figure 9. Variation of statistical and spectral parameters for different pressure values; (a) pressure *vs.* mean, (b) pressure *vs.* SD, (c) pressure *vs.* skewness, (d) pressure *vs.* frequency, (e) pressure *vs.* kurtosis

relatively even or even to some extent lower with flicker rise. The quantitative plots for mean, standard deviation, skewness, frequency, and kurtosis is presented in figs. 9(a)-9(e).

Conclusion

An experimental result reveals that oxidizer rich solid propellants exhibit an increase in burn rate by adding few percentages of fuel binder (HTPB). At the pressure 100 bar, mix 5-burn rate (14.5 mm/s) is higher than the burn rate mix 1-(10.2 mm/s). Intrinsic instability of flame has possessed a statistical characterization of the flame front. The physical characteristics of the flame were studied by wavelet and image processing techniques. The increase in cylinder pressure increases burn rate, also fuel binder addition shows growth in flame brightness from which statistical and spectral parameters were obtained. The quantitative and qualitative results show the flame stability which proves that the instability in fuel combustion occurs at higher mixes and pressure level.

Acronyms

AP – ammonium perchlorate
HTPB – hydroxyl terminated polybutadiene
TDI – toluene diisocyanate
SD – standard deviation
ROI – region of interest
fps – frame per second

References

[1] Beckstead, M. W., *et al*., A Model of Composite Solid-Propellant Combustion Based on Multiple Flames, *AIAA Journal*, *8* (1970), 12, pp. 2200-2207
[2] Rodic, V., Bajlovski, M., Influence of Trimodal Fraction Mixture of Ammonium Perchlorate on the Characteristics of Composite Rocket Propellants, *Sci. Technol. Rev. LVI*, (2006), 2, pp. 38-44
[3] Masafumi, T., *et al*., Intrinsic Instability of AP Composite Propellants in an Intermediate Pressure Range, *Proceedings*, 41st Aerospace Sciences Meeting and Exhibit, Reno, Nev., USA, AIAA 2003-1160
[4] Williams, F. A., *Combustion Theory*, 2nd ed., CA: The Benjamin/Cummings Publishing Company, San Francisco, Cal., USA, 1985
[5] Jayaraman, K., Production and Characterization of Nano-Aluminium and Its Effects in Solid Propellant Combustion, Ph. D. thesis, Indian Institute of Technology-Madras, Chennai, India, 2008
[6] Lu, G., *et al*., A Digital Imaging Based Multifunctional Flame Monitoring System, *IEEE Trans Instrum Meas, 53* (2004), 4, pp. 1152-1158
[7] Lu, G., *et al*., An Intelligent Vision System for Monitoring and Control of Combustion Flames, *Meas Control*, *32* (1999), July, pp.164-168
[8] Xia, S.-Y., *et al*,. Effectiveness of the Euclidean Distance in High Dimensional Spaces, *Optik International Journal for Light and Electron Optics*, *126* (2015), 24, pp. 5614-5619
[9] Reddy, B. N., Udgata. S. K., Energy Efficient Aggregation in Wireless Sensor Networks for Multiple Base Stations, *Proceedings,* Inter. Conf. on Swarm, Evolutionary, and Memetic Computing, Chennai, India, 2013
[10] Lu, G., *et al*., Monitoring of Oscillatory Characteristics of Pulverized Coal Flames through Image Processing and Spectral Analysis, *IEEE Transactions on Instrumentation and Measurement*, *55* (2006), 1, pp. 226-231
[11] Lu, G., *et al.,* Impact of Co-Firing Coal and Biomass on Flame Characteristics and Stability, *Fuel*, *87* (2008), 7, pp.1133-1140

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