Flame Analysis Of Micro And Nano Flash Powder For Firework Applications

A. Azhagurajan[a*], N. Selvakumar[b] and Sriram Jeyakumar[c]
[a] Assistant Professor, Department of Mechanical Engineering, Mepco Schlenk Engineering College, Sivakasi – 626 005, Tamilnadu, India.
Tel: +91 4562-235000, +91 9486288214; fax: +91 4562-235111; email: a_azhagu@yahoo.co.in
[b] Professor, Department of Mechanical Engineering, Mepco Schlenk Engineering College, Sivakasi – 626 005, Tamilnadu, India. Email: nsk2966@yahoo.co.in
[c] Safety Engineer, L&T ECC, Metallurgical & Material Handling Division, EHS Department, Kolkatta, India.
Email: sree_8620@yahoo.co.in

Abstract: *Flame height and width of flash powder used in firework manufacturing were observed as a function of their particle size. Mass consumption and flame propagation velocity were also calculated. Particles of 250, 150 and 75 micron size as well as nano-sized particles were used in the study. In addition, the performance analysis of the flash powder compositions was checked by manufacturing firecrackers. The noise level during bursting was measured and checked for correlation with the flame parameters.*

Keywords: *Fireworks, flash powder, nano, noise level*

1. Introduction

Flash powder is a pyrotechnic chemical, and contains a mixture of oxidizer and metallic fuel which burns quickly and if confined produces a loud noise. In fireworks, a flash powder composition consisting of potassium nitrate, sulphur and aluminium particles has long been employed as the main ingredient.[1]

The chemical reaction involved during the combustion of flash powder is

$$2\,KNO_3 + 4\,Al + S \rightarrow K_2S + N_2 + 2Al_2O_3$$

In firework cracker manufacturing, chemicals in different ratios are taken and sieved separately to remove the impurities and mixed thoroughly on a non-conducting surface. The mixture is again sieved 4 or 5 times to make it homogeneous and free from grit. The shell cases are filled with the chemical mixture, then thin foil papers are used to cover the shells which are then sealed. After some time, gum coated jute string is wound around it tightly, then the fuse wire is inserted.[2] The effectiveness of firecrackers depends not only on the composition of the mixture, but also on factors such as particle size and shape, choice of fuel and oxidizer, fuel to oxidizer ratio, degree of mixing, moisture content, physical form, packing density, presence of additives, local pressure, degree of confinement, degree of consolidation, crystal effects and purity of the chemicals. Firework chemical compositions have a wide range of applications involving the production of light, heat, sound, smoke, gas and a combination of such effects.[3] Chemicals used as additives even in small quantities to improve the mechanical properties can alter the combustion process and thus reduce the ignition temperature.

Most pyrotechnics and low explosives operate by combustion processes, in which a fuel combines with oxygen to release heat, light, smoke, gas and a combination of such effects. A fuse is lit by a match and this fuse burns rapidly into the core of the cracker where it ignites the flash powder walls of the interior core. The three oxygen atoms from the potassium nitrate provide the "air" that the fuse and the cracker use to burn the

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other two ingredients, aluminium and sulphur. Thus potassium nitrate forms the oxidizer in the chemical reaction by easily releasing oxygen. The core is quickly filled with flames and thus the necessary heat to ignite, continue and spread the reaction. The burning rate is also affected by the homogeneity of the mixture. Fine powders burn faster than coarse grains.

The bursting of firecrackers produces a short intense impulse noise which is mainly influenced by the quantity, purity, particle size, quality and formulation of the chemical mixture, dimensions of the cracker, packing, bulk density of composition and compaction.[4] In this paper, particle size is taken as a variable to study the reactivity of the chemicals. However, in order to gain a better understanding of its combustion properties, the reaction of flash powder particles in close contact area needs further investigation. When a pile of flash powder is ignited in the open atmosphere, a flame front spreads across the surface. Previous flame spread studies of solid fuels have provided a controlled manner to study the roles of fuel and oxidizer during a combustion event.

Nano-metallic particles have lower ignition temperature, faster burning rate and shorter burning time because of their high specific surface area compared with micron or larger-sized particles.[5,6]

Most previous work has focused on micron and nano-sized particles for propellants. In addition, particle diameter plays a significant role in determining combustion mechanisms through its influence on the characteristic transport (diffusion) time relative to the chemical kinetic time. The study of combustion of particle-laden flows is critical in the design and optimization of combustors for explosives systems using particulates.

At present, micro-sized flash powders are used to prepare firework crackers. But due to this, enormous amounts of gas and smoke are released when they are fired. This has a major environmental impact by polluting the air in the atmosphere with various toxic gases and smoke. To reduce this pollution, a smaller amount of chemicals with high reactivity should be used inside the crackers. There are many methods to improve the reactivity of flash powders like changing the composition, addition of other chemicals, substitution and reducing the particle size. In case of nano flash powders, the quantity of the powder required to make the crackers has been reduced and thus the release of gas and smoke will be reduced also. Thus the environmental pollution will be greatly reduced. In this paper, nanotechnology is applied in the field of pyrotechnics to improve the reactivity of flash powders as well as to reduce the environmental impact due to existing firework products.

2. Literature review

Goroshin *et al.* [7]conducted measurements of flame propagation of aluminium dust in various oxidizer environments in a vertical Pyrex tube. The Sauter particle diameter (d_{32}) was around 5.4 µm. The flame propagation speed obtained from these tube experiments might not properly represent the actual burning velocity due to difficulties in defining the flame shape and particle velocity upstream of the flame. Goroshin *et al.*[8] later established another experimental apparatus capable of producing Bunsen-type premixed dust flames. The burning velocity was shown to be a weak function of dust concentration for rich aluminium mixtures, a phenomenon that can be attributed to a weak dependence on the particle burning rate at the flame temperature in the diffusive regime. Shoshin and Dreizin[9] developed a lifted-flame aerosol burner for measuring laminar flame speeds of metal–air aerosols over the wide range of particle mass concentrations of 0.4–1.4 kg m^{-3}. Two different powder sizes (d_{32} of 11 and 20 µm) were examined in their experiments. A decrease in the flame speed at very high mass concentration was observed. In both the above works, micron-sized particles were used.

Risha *et al.*[10] examined the flame characteristics of combustion of nano-aluminium and liquid water. To measure the enhancement of reactivity of nano-sized Metastable Intermolecular Composites (MIC), the open channel burn test was used to determine the flame propagation velocity. A new nano-aluminium (nAl) bed setup model was developed to examine the fingering flame spread of a bed of nAl powder.[11] The fingering flame spread was observed and characterized for various particle sizes to gain a better understanding of the reaction mechanism associated with the combustion of nano-particles in close contact. An experimental investigation on the combustion behaviour of nAl and liquid water has been conducted. The combustion of bimodal nano- and micron-sized aluminium particle/air laden flows using a Bunsen-burner type apparatus, similar to the experiment of Goroshin *et al.*, was studied both analytically and experimentally. The particle compositions ranged from 100% micron-sized particles to mixtures with 30% nano-particles (100 nm) by mass. Tests indicated that an increase in percentage of nano-particles within the mixture enhanced its flame speed. The flame thickness of bimodal-particle–air mixtures, however, was much wider than that of a micron-sized particle–air mixture. [12,13]

In this paper, the author conducted an open channel burn test to measure the flame height and width for micron- and nano-sized flash powder. Also the flame parameters are correlated with the performance of firework crackers. Previous work has been carried out for aluminium dust but not for mixtures like flash powder. So, this study will be useful for understanding the combustion inside the crackers.

3. Experiment

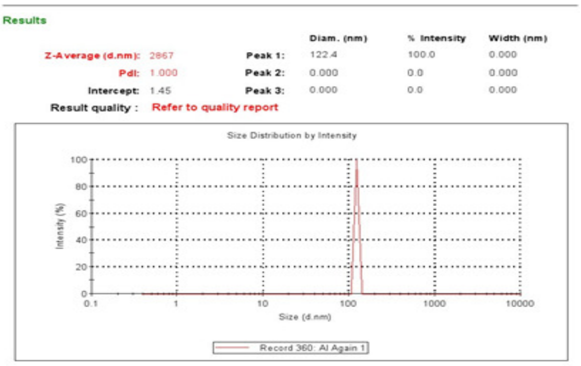
3.1 Composition preparation

The flash powder chemicals were procured from Sivakasi, Tamilnadu, India. The purity of the aluminium metal powder is 85% and the remainder is aluminium oxide. The purities of KNO_3 and S were 97.6% and 99.9% respectively. There are four sets of mixtures of Al, KNO_3 and S used in this study. Three sets have particle sizes of ≤250 µm, ≤150 µm and ≤75 µm. This means that the flash powder particles pass through the corresponding sieve/particle size number of 250, 150, 75 µm respectively and hence can be denoted as ≤250, ≤150, ≤75 µm. One set has the three flash powder chemicals with particle sizes at the nano level.

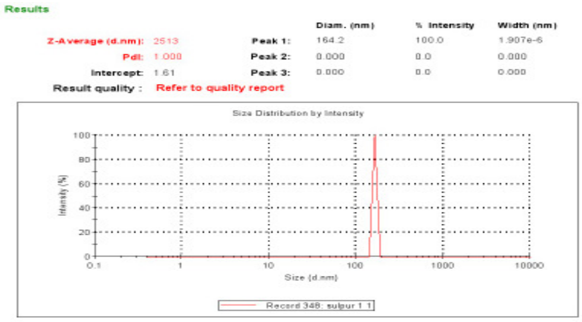
The compositions are prepared according to Table 1 for 10 samples of each of the four sets and hence the total number of samples is 40.

In the present study, a Fritsch GmbH 'Pulverisette 6' planetary mono mill was used for preparing different particle sizes of the nano-sized chemicals. After grinding µm chemicals for 8 hours in the ball mill, the particle sizes of the output powder are measured by a particle size analyser (Make: Zetasizer Nano ZS).

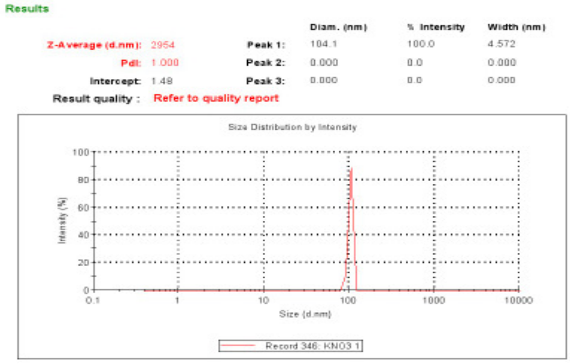
Figure 1(a–c) confirms the particle size of the various chemicals which are used in firework crackers. The flash powder compositions are prepared at different ratios by using Design Of Experiments software (Make: Stat-Ease, Inc., Minneapolis). Table 1 shows the various compositions of the flash powder.



(a) Aluminium by ball mill (122 nm)



(b) Sulphur (164 nm)



(c) Potassium Nitrate (104 nm)

Figure 1. *Particle size of various chemicals.*

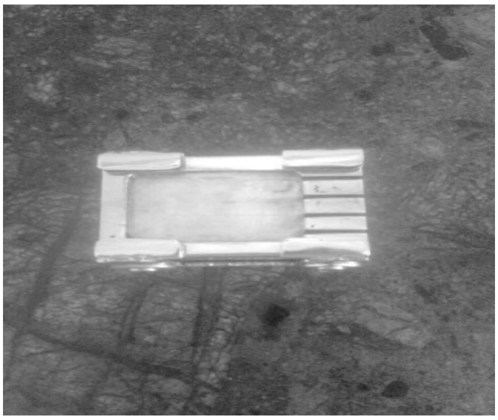
Table 1. *Compositions of flash powders.*

Sample no.	KNO_3 (%)	S (%)	Al (%)
1	50	5	45
2	65	5	30
3	50	20	30
4	50	12.5	37.5
5	57.5	12.5	30
6	57.5	5	37.5
7	60	7.5	32.5
8	52.5	7.5	40
9	52.5	15	32.5
10	55	10	35

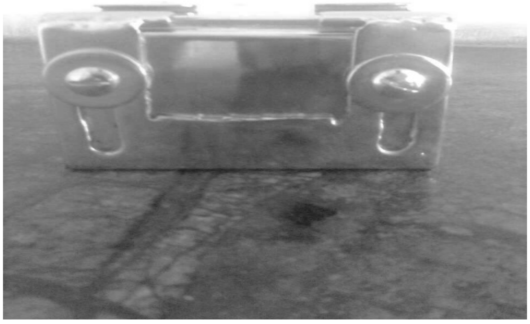
3.2 Flame spread bed setup

The experimental setup consists of a copper bottom plate, copper gas diffuser and an aluminium bracket which holds the top plate. For visualization, a quartz window is used as the top plate. To prevent lateral flow over the bed, copper shims were placed along the sides. The top plate rests on the shims, thus, the height of the shims also determines the height of the top plate. Bed shims with a thickness of 0.08 cm were also created to adjust the thickness of the bed. The length of the top plate and bottom plate is 10 cm. The height of the bottom plate is 6 cm. In the bottom plate there will be an inner bed of which the dimensions are 7 × 4 × 1 cm. The gas diffuser has oxidizer inlets on both ends and a row of twenty-four 0.08 cm diameter holes on the exit face are used to distribute the flow across the width of the channel and assure uniform flow development. A nichrome wire is placed through holes at the opposite end of the bottom plate and resistively heated by a DC power supply to serve as an ignition source. The different views of the setup are shown in Figure 2(a–b).

A high pixel camera of 30 frames per second with a shutter time of 1/30 second per frame is used to capture the video of the flame. The recorded videos and frames can be visually checked. A Sony C905 camera is used in this study. The average x-location and the time between each frame were used to calculate an average velocity of the front (v_f). Depending on the experimental conditions, an appropriate aperture was chosen to capture enough light without saturation. After recording the videos and frames, it is imported into 'Image processing toolbox 7.0' which is one of the features of the MATLAB software. The videos from the high pixel camera are imported into this software by means of 'Image Acquisition Toolbox'. By analysing the flame height and width, the reactivity difference can be compared between the nano and micron flash powders.



(a) Top view of the bed



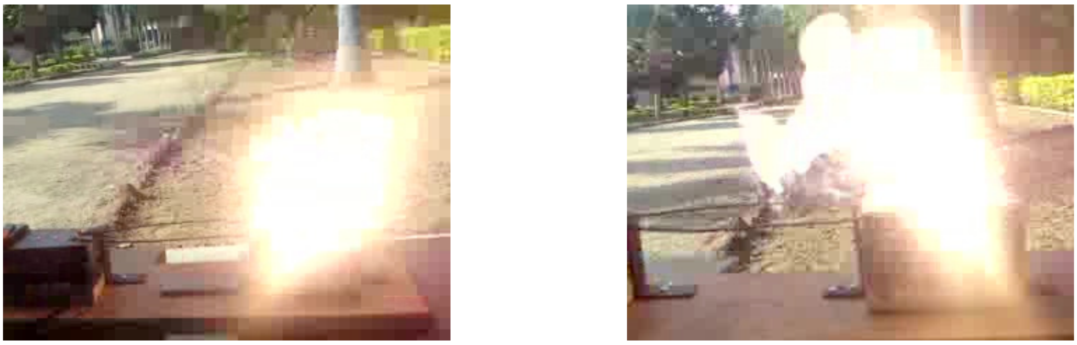
(b) Lateral view of the bed

Figure 2. *Flame spread bed setup.*

A pre-measured mass of 0.5 g of flash powder was placed in the bed and distributed uniformly. To create a smooth top surface, a glass surface was used to lightly press the powder into the bed.

3.3 Image analysis

The images of the recorded flames for both micron and nano samples are given by the Image processing toolbox in which the peak flame height



(a) 250 µm (b) 150 µm

(c) 75 µm (d) nano powder

Figure 3. *Flame height for Sample 1 for different particle sizes.*

and maximum widths are taken. The images for sample 1 are shown in Figures 3(a–d) and 4(a–d).

The flame heights and widths are calculated using Image J software. Image J is a public domain, Java-based image processing program. Custom acquisition, analysis and processing plug ins can be developed using Image J’s built-in editor and a Java compiler. User-written plug ins make it possible to solve many image processing and analysis problems, from three-dimensional live-cell imaging, to radiological image processing, and multiple imaging system data comparisons to automated hematology systems.

3.4 Firework manufacturing

In order to find the correlation between flame parameters and actual performance of the crackers during bursting, one of the sound emitting firework products, i.e. a cake bomb, was manufactured using the same composition. The inner shell volume and the quantity of the chemical filled inside the crackers were taken to be constant. Figure 5 shows a photograph of the drying of the crackers.

The performance of the fireworks is decided by the sound level it produces. As per the Govt. of India notification, the cracker sound level should not exceed 125 dB(AI) or 145 dB(Cpk) at 4 m distance from the point of bursting.

Noise level testing was carried out as per the rules of notification of PESO (Petroleum and Explosives Safety Organisation), formerly known as the ‘Department of Explosives’, Govt. of India. The noise level was measured by three noise level monitors using Model No.824L obtained from Larson & Davis, USA and the average value of the readings was taken as the sound level. The noise level was measured at 1.2 m elevation from

(a) 250 μm

(b) 150 μm

(c) 75 μm

(d) nano powder

Figure 4. *Flame width for Sample 1 for different particle sizes.*

the ground level burst at 4 m distance. The meters were placed at three points and the angle between each of them is 120°. A hard concrete surface of 5 m diameter was the site for the explosion, with no obstacle to carry out the noise level test. Figure 6 shows the sound level testing.

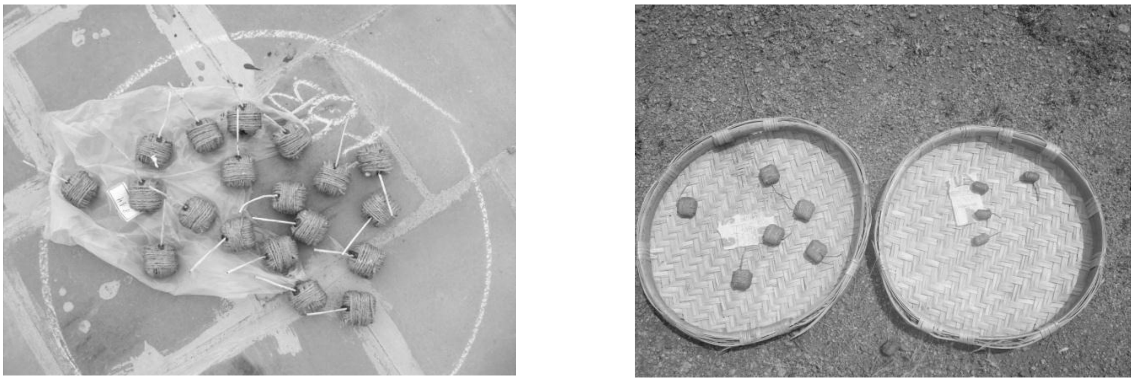


Figure 5. *Drying of cake bombs of different grades.*

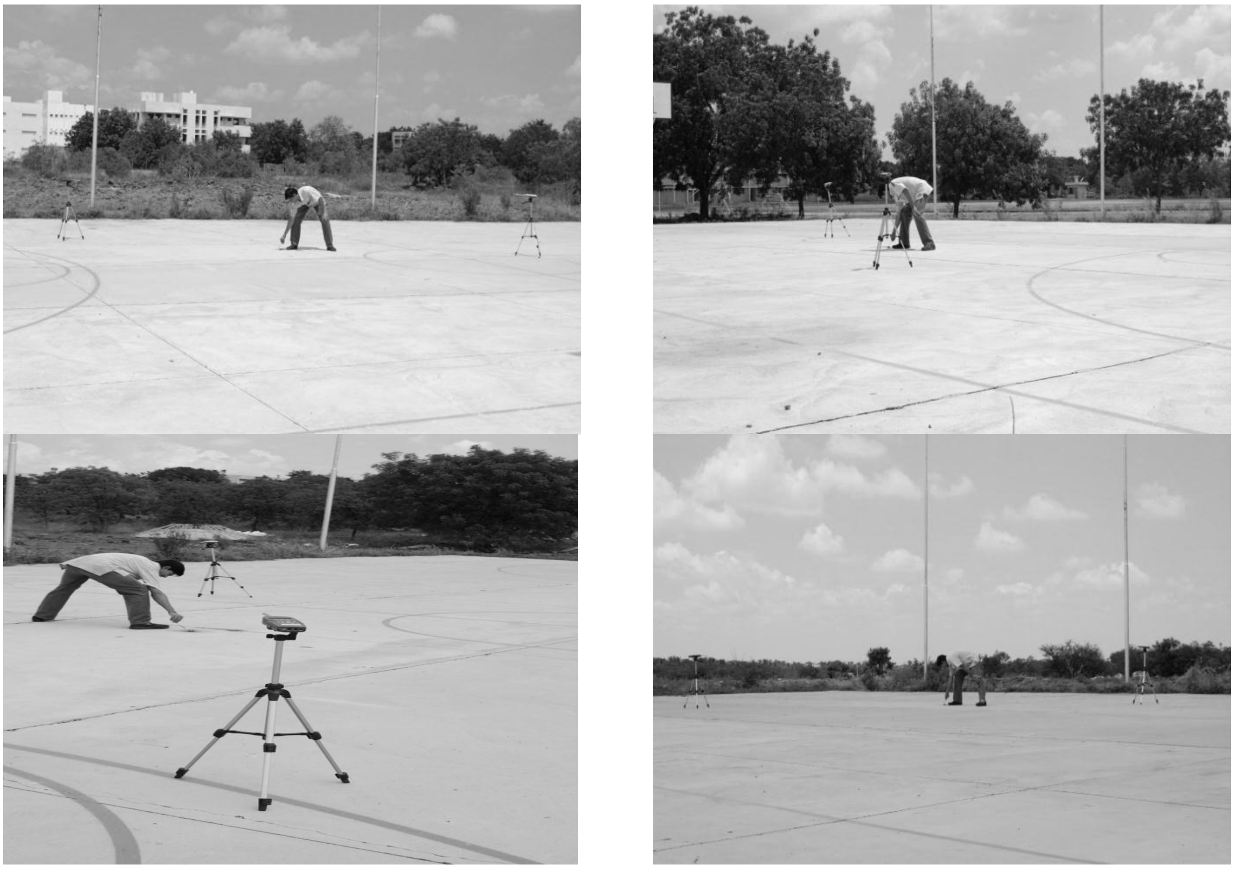


Figure 6. *Different views of sound level testing.*

4. Results

4.1 Flame height and width

From Table 2, it can be clearly seen that changing the constituents in the flash powder has a great influence on the flame parameters.

4.2 Conservation of mass

By using the stoichiometric coefficient, the mass consumption rate per unit area of the fuel can be found by using the formula:[12]

$$\Gamma_{\mathrm{FP}} = \mu_{\mathrm{stoic}}\,\Gamma \mathrm{o}_{2,} \qquad (1)$$

where Γ_{FP} is the mass consumption rate of flash powder (g cm^{-2} s^{-1}), μ_{stoic} is the stoichiometric coefficient, $\Gamma \mathrm{o}_2$ is the mass consumption rate of oxygen per unit area (g cm^{-2} s^{-1}).

Generally, $\Gamma \mathrm{o}_2$ of O_2 is 0.21 g cm^{-2} s^{-1} and μ_{stoic} of O_2 is 2 from the following chemical equation:

$2\,KNO_3 + 4\,Al + S \rightarrow K_2S + N_2 + 2Al_2O_3$

By substituting the above values in equation (1), the mass consumption rate of flash powder (Γ_{FP}) is calculated as 0.42 g cm^{-2} s^{-1}.

4.3 Flame propagation velocity

The flame propagation velocity, v_{f} can be found by using the formula:[12]

$$\Gamma_{\mathrm{FP}} = f_{\mathrm{b}}\rho_{\mathrm{bed}}v_{\mathrm{f}}\delta_{\mathrm{b}} \qquad (2)$$

where f_{b} is the fraction of the surface area burned, ρ_{bed} is the packing density of the flash powders in the bed, and δ_{b} is the non-dimensional depth of burn in the bed. It can be found from equation (3).

$$\delta_{\mathrm{b}} = d_{\mathrm{p}}/d_{\mathrm{ref}} \qquad (3)$$

The fraction of surface area burned is taken as 1, since the surface area of the bed is 4 cm^2 and both micro and nano powders are completely burned during ignition.

d_{p} is the particle size of the flash powder sample and d_{ref} is taken as 50 nm, a typical nano-particle size for nano-sized flash powders from Malchi *et*

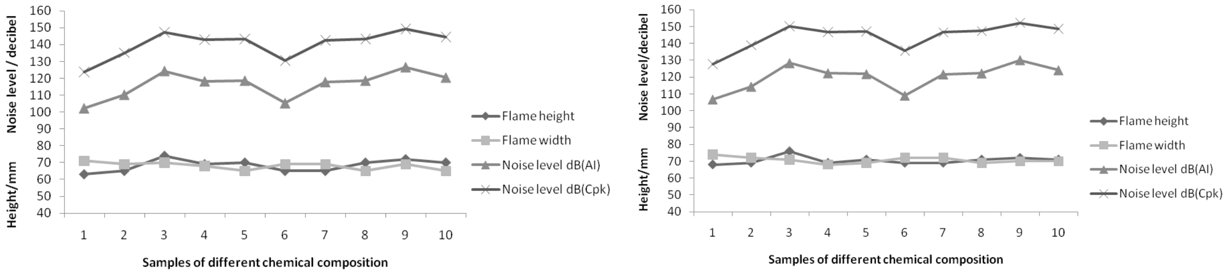
Table 2. *Flame height & width for different samples.*

Set of particle size	Set I ≤250 µm		Set II ≤150 µm		Set III ≤75 µm		Set IV Nano	
Composition sample no.	Flame height (mm)	Flame width (mm)	Flame height (mm)	Flame width (mm)	Flame height (mm)	Flame width (mm)	Flame height (mm)	Flame width (mm)
1	63	71	68	74	68	78	83	90
2	65	69	69	72	74	72	78	76
3	74	70	76	71	77	80	100	95
4	69	68	69	68	74	72	85	79
5	70	65	71	69	77	68	91	92
6	65	69	69	72	73	72	80	81
7	65	69	69	72	74	72	82	79
8	70	65	71	69	77	68	88	86
9	72	69	72	70	79	74	96	92
10	70	65	71	70	78	69	97	93

al.[12]

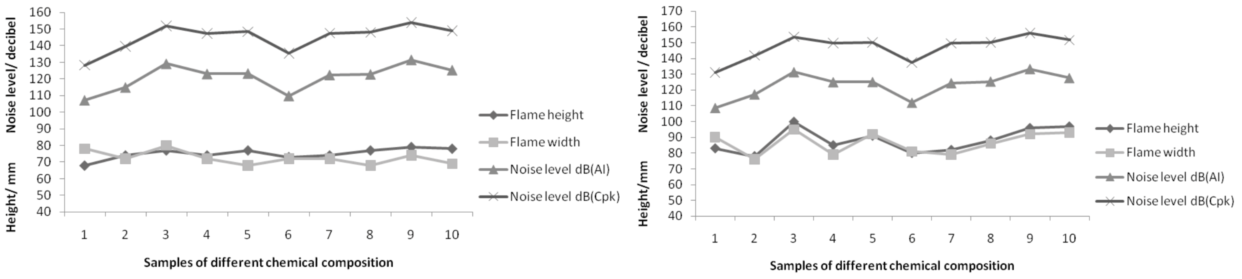
Thus the flame propagation velocities for three different micron-sized flash powders and nano-sized samples are tabulated in Table 3.

The above results show that the smaller sized particles have a higher specific surface area, and the burn rate increases which should lead to faster front velocities.



(a) ≤250 µm

(b) ≤150 µm



(c) ≤75 µm

(d) Nano-particles

Figure 7. *Pattern of flame parameters and performance analysis of firework crackers.*

Table 3. *Flame propagation velocities for micron and nano flash powders.*

Sample set number	Particle size d_p (µm)	Depth of burn δ_b	Packing density ρ (g cm^{-3})	Flame propagation velocity v_f (µm s^{-1})
1.	250	5000	0.40	2.1
2.	150	3000	0.36	3.89
3.	75	1500	0.31	9.03
4.	Nano size	2.45	0.25	6857

4.4 Noise level analysis and correlation analysis

In order to find the correlation between the flame parameters and performance analysis of the crackers, both readings are plotted. Figure 7(a–d) shows that better coincidence is obtained between the flame parameters and cracker noise level.

5. Discussion

Figure 8 shows the flame parameters for the different flash powder compositions. From Table 2 and Figure 8, it is observed that the finer particles have higher flame height and flame width than the coarser ones. As is known in general, smaller particles give higher reaction rates and energetic materials are no exception. The nano-sized sample has greater flame height and width compared to the micron-sized samples. For example the flame height for sample 1 is increased to 83 mm from 63 mm. In general, the reaction rate of nano-scale materials is several orders of magnitude larger than those of micron-scale materials and the much larger surface area can significantly change combustion behaviour.

Table 2 also emphasizes that sulphur addition has increased the height of the flame. For instance, Sample 3 has a greater flame height (74 mm) compared to sample 1 (63 mm). Fuel and oxidizer rich samples have shown significant differences in flame parameters.

Table 3 clearly indicates that decreasing particle size increases the propagation velocity and widens the flame. The increased propagation velocity is due to the higher specific surface area of the particles.

From Table 4, it is found that particle size plays a vital role in the performance of the crackers. If the particle size is reduced, the sound level of the crackers during bursting also increases.

All the above parts of Figure 7(a–d) show that there is a higher positive correlation between the flame parameter pattern and performance of fire crackers (noise level during bursting). This emphasizes that better flame height and thus high reactivity produces the fastest reaction. This leads to the high noise level.

From Figure 9 another conclusion is that if the

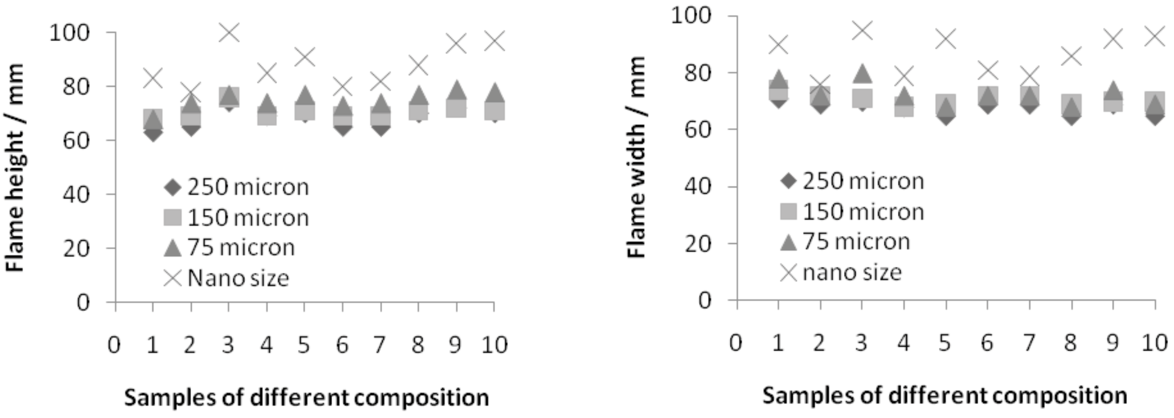


Figure 8. *Experimentally observed flame parameters as function of particle size.*

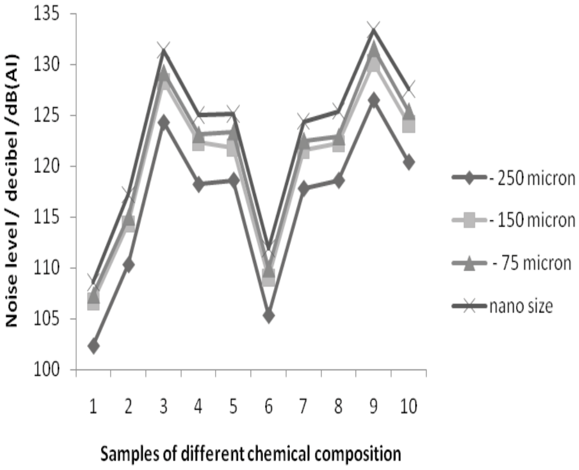


Figure 9. *Noise level for micron and nano-sized samples.*

particle size has been reduced, a high noise level is obtained for the same quantity of chemicals. So, for nano-sized chemicals, a smaller quantity of the chemical will be sufficient to produce the noise level of 125 dB(AI) and 145 dB(Cpk) compared to micron-sized chemicals.

During the bursting of firecrackers, noxious gases emitted in the atmosphere will be reduced for each cracker and hence the atmosphere does not become polluted by means of nano flash powders when they are ignited.

6. Conclusions

The flame propagation velocity can be greatly increased if the particle size of the flash powders is reduced to nano-size. As the particle size decreases from 250 μm to 104 nm, the flame heights and widths also increase from 63 mm and 65 mm to 100 mm and 95 mm respectively. Thus the maximum flame propagation velocity reached for a sample of nano flash powder is 6857 $\mu m\ s^{-1}$ whereas for the micro sample it is 11.2 $\mu m\ s^{-1}$. By using the flame height, width, and flame propagation velocity, the reactivity enhancement for the flash powders is clearly known, if the particle size is decreased. Thus, the nano flash powders can be used to enhance the reactivity and produce higher performance in firecrackers even with smaller quantities compared to micron flash powder and hence can help to reduce the gases and smoke in the environment.

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