INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 8 (2024) 291-299
https://publisher.uthm.edu.my/ojs/index.php/ijie

Flare Synthesis Using Charcoal as a Fuel and Colour Enhancer

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DOI: https://doi.org/10.30880/ijie.2024.16.08.029

Article Info

Received: 3 July 2024
Accepted: 24 October 2024
Available online: 30 December 2024

Keywords

Pyrotechnic, flare, charcoal, bomb calorimeter

Abstract

Pyrotechnics have many applications in military and civilian systems, such as signal flares and distress flares. It is mostly used as parachutes or hand-held signal flares to mark particular positions, provide large-area illumination, and provide illumination during emergencies like accidents or for a lost person to attract searchers attention to them. Pyrotechnic flare consists of fuel, oxidizer, and colorant. In this paper, a comparison of the performance and energy output of flares with and without the addition of charcoal is made to determine whether charcoal improves flare efficiency and calorific value as measured by a bomb calorimeter. The composition of flare composition A (FCA) testing number 4 without addition of charcoal that gave the optimum result in terms of flare brightness and ignition time is 73.2 wt% of $Sr(NO_3)_2$, 4.9 wt% of NH_4ClO_4, 12.2 wt% of sulphur, and 9.7 wt% of sawdust. A further analysis of flare composition, with the addition of 0.5 wt% of charcoal, produces brighter red light and a high-intensity flame, including a longer burning time of 90 seconds. Charcoal can not only act as fuel but also improve the red flame colour in flares. A bomb calorimeter is used to measure the heat of combustion for both flares. The heat of combustion of FCA-4 is 798.29 cal/g, while FCB is 664.23 cal/g. Charcoal is successful as a fuel and colour enhancer for flare.

1. Introduction

Flare is a type of pyrotechnic device that has many applications in both military and civilian settings. These pyrotechnic compositions emitted electromagnetic radiation that provided illumination during emergencies like accidents or during the rescue of a lost person [1]. In the military itself, red flares were used in real combat and military training for signaling allied personnel and aircraft [2]. This distress flare was also a crucial device in the military act as a decoy against infrared guided missiles [3]. According to U.S. Navy which had in-service yellow flare perchlorate-containing composition which consists of approximately 30.3% Granulation 18 magnesium fuel, approximately 19.8% sodium oxalate, approximately 20% barium nitrate, approximately 21% potassium perchlorate, approximately 4% asphaltum, and approximately 5% binder. The binder is in the range of nearly 70% to nearly 80% Epon™ Resin 813 epoxy and within the range of approximately 20% to approximately 30% Versamid 140 curing agent. These compositions are the starting point in the new perchlorate-free yellow signal flare formulations.

Chemically, flares were made by mixing several chemicals that have the properties of oxidizer, fuel, and binder. The fuel properties in flares are usually made of metals like aluminum or magnesium and non-metals like sulfur or carbon [4]. Sulfur was used in early 1947 to increase the light intensity of flare composition since it reacts effectively with oxygen [5]. As for the oxidizer, it is used to supply oxygen, and examples are perchlorates, chlorates, peroxide, chromates, and nitrates [4]. The most used oxidizers in flare composition are perchlorates and nitrates [18]. Strontium nitrate is the main flare composition that provides the red brick appearance and has the properties of an oxidizer [6]. The intensity of the light emitted by the pyrotechnic composition depends on the presence of certain components in the burning mixture [7]. They emitted light through molecular emission and atomic emission [6]. This pyrotechnical flare composition was designed to burn at a constant rate, being optimized to emit radiation in either the IR spectrum or visible light [8].

As time goes by, flare devices have increased in popularity in rescue events, typically at night [2] pointed out the importance of red burning pyrotechnic flares for distress and tactical signals in both civilian and military environments. As typically the chemical compounds that were used to make a flare are strontium nitrate, ammonium perchlorate, and sulfur, developing and improving the quality of the flare along with the time of ignition was done in this paper by adding charcoal that has the properties of a color enhancer and oxidizer. The reaction of charcoal and sulfur with the help of oxygen forms sulfur dioxide and carbon dioxide, controlling the rate of ignition, which significantly helps to make the flare composition ignite longer [9]. In order to do so, an optimized formulation of the typical flare formulation was done first to obtain an ignition time that was long enough with a brighter red color observed by the naked eye. The chemical composition of the pyrotechnic substance can be modified to produce colored light, illumination, or infrared radiation depending on the desired outcome [10].

To further observe the thermal characteristic, namely the heat of combustion of the optimized formulation, alongside the addition of charcoal, as it is one of the important factors in the evaluation of flare composition performance [10], The basic law of conservation of energy comes from the bomb calorimeter, in which the energy released from the sample raises the temperature of the oxygen bomb itself and its surrounding medium, and in which the combustion heat of the samples can be measured. The medium temperature changes in value before, after, and during burning time [11].

Hence, the objectives of the paper are to investigate the effect on the heat of combustion and observe whether adding charcoal enhances the flare's overall brightness. This investigation will provide insight into the efficiency of charcoal as a luminance enhancer in flare applications, with possible effects on safety and visual observation. A bomb calorimeter will also be used to analyze the flare composition's energy release characteristics.

2. Methodology

2.1 Chemical Preparation

The chemicals used in this experiment are strontium nitrate ($Sr(NO_3)_2$) (Analytical Reagent Grade), ammonium perchlorate (NH_4ClO_4), sulfur (S), sawdust, and charcoal. The apparatus needed is a blender, weighing scale, plastic container with lid, and heat-resistant container.

NH_4ClO_4, S, and sawdust are ground by using a blender until they become smaller particles. Next, all the required chemicals for flare are weighed using a weighing scale. The flare compositions were then mixed well in a closed container and shaken for 2 minutes. Finally, the composition is transferred into a flare casing and ready to be tested.

Four different compositions of flare (FCA, Flare Composition A) that no charcoal presented were tested to obtain the optimal formulation as illustrated in Table 1.

2.2 Visual Observation

The flare composition is placed inside a darkly lit container. The flare was observed at 120 cm using a Samsung A31 phone camera. Once the flare composition has burned, the intensity and brightness of the flare are noted. The time taken from the start of the flare composition burning and emitting red light until the flare is extinguished completely is recorded. The optimized formulation will be tested three times to validate the composition. The procedure was then repeated with the addition of charcoal to the formula (FCB, Flare Composition B).

Int. Journal of Integrated Engineering Vol. 16 No. 8 (2024) p. 291-299

Table 1 *Flares composition in weight percent (%)*

Chemicals	FCA-1	FCA-2	FCA-3	FCA-4
Strontium Nitrate, Sr $(NO_3)_2$	71.9	72.5	72.8	73.2
Ammonium Perchlorate, NH_4ClO_4	4.2	4.5	4.9	4.9
Sulphur, S	13.5	13	12.7	12.2
Sawdust	10.4	10	9.6	9.7

2.3 Bomb Calorimeter Analysis

The flare composition is grinded until it becomes a fine powder. Then the composition is placed inside a crucible and weighed before being made into a pallet by using a compressor. The flare pallet is placed inside the bomb of the Parr Instrument, Model 6200 Isoperibol Calorimeter. The fuse wire is threaded inside the bomb to be in contact with the pallet, and the bomb is tightly sealed. The instrument is flushed with purified oxygen gas twice before it is filled with 25 atm of the same purified gas. After placing the bomb inside the calorimeter, 2000 mL of water is filled and sealed. The stirrer is turned on, and after waiting for a certain temperature, the sample is ignited. The reading of the bomb calorimeter is recorded.

3. Result and Discussion

3.1 Physical Analysis of Flare Composition

Theoretically, oxidizer and fuel are two mixtures that are illuminating mixtures, in which the addition of other chemicals helps in modifying the burn rate, radiant output, and safety of the pyrotechnics [12]. The flare was made of fuel (sulphur and sawdust), oxidizer (Sr $(NO_3)_2$ and NH_4ClO_4), and colorant (Sr $(NO_3)_2$) [6]. In order to find the maximum output of flare with the longest time ignition, several tests with several alterations of formulation were done throughout the testing, with the result of time ignition as illustrated in Table 2. All the testing period of FCA will be provided in 30 seconds, as this is the optimal illustration of the red color from flare.

Table 2 *Ignition time of flare composition A, without present of charcoal (FCA)*

	FCA-1	FCA-2	FCA-3	FCA-4
Ignition Time (Seconds)	52	54	65	70

The FCA-1 formulation has the lowest quality of color output, as illustrated in Fig. 1, with only 52 seconds of ignition time.

Another alternation of composition had been done in which increasing oxidizer, red colourant chemical and sawdust while reducing the amount of Sulphur used. As a result, bright red colour can be seen clearer, however, there is fire present of fire throughout the testing period for FCA-3 in Fig. 2.

Fig. 1 *FCA-1 testing at 30 seconds flare emission*

Fig. 2 *FCA-2 testing at 30 seconds flare emission*

Lowering the amount of fuel as in sawdust and sulfur was further done in FCA-3 to remove the presence of fire while keeping constant or improving the brightness of the flare; hence, the strontium nitrate increased slightly by 0.3% from FCA-2. As a result, it gave a brighter red color, as observed in Fig. 3, with longer time taken; however, there were fires present at the beginning of the testing.

As for composition FCA-4, sulfur that has the tendency to increase the burning rate was reduced by 0.5% from FCA-3. It can be observed that the optimum result of time ignition was 70 seconds with the brightest visual observation and no fire was present during the testing period, as shown in Fig. 4.

After analyzing four different compositions of flare, it is possible to deduce that by reducing the amount of fuel used, it helps to reduce the heat temperature of the flare, from which the fire present during testing could be removed. Not only that, from the observation, the addition of strontium nitrate, which gave the properties of a red colorant, gave a brighter output by controlling the amount of fuel-oxidizer. The fuel-oxidizer ratio has a significant impact on flame temperatures [13]. The temperature of the flame increased as the amount of oxidizer increased, and the ratio of fuel decreased [13].

Fig. 3 *FCA-3 testing at 30 seconds flare emission*

Fig. 4 *FCA-4 testing at 30 seconds flare emission*

3.2 Validation of Flare Composition

A validation of FCA-4 composition by repeating the process three times showed that the formulation gave the same result in more or less time. This is to make sure the formulation is validated before adding other chemicals to it.

Table 3 *Validation of FCA-4 composition*

Formulation FCA-4	1	2	3
Ignition Time (Seconds)	70	71	71

The calculated mean time of the analysis is 70.6, which is close enough as tested in a formulation of FCA-4 to be 70 seconds. The visual observation also showed a decent result, in which a bright red colour can be seen with no fire present in the analysis.

3.3 Addition of Charcoal to The Formulation

The optimum flare composition is further observed by the changes in brightness of the flare when ignited by the addition of 0.5% charcoal to the composition, as illustrated in Table 4. The result showed that the brightness of the flare, along with the time of ignition, is much longer, at 90 seconds.

Table 4 *FCB composition in weight percent (%)*

Chemicals	FCB (%)
Strontium Nitrate, $Sr(NO_3)_2$	71.9
Ammonium Perchlorate, NH_4ClO_4	4.2
Sulphur, S	13.5
Sawdust	10.4
Charcoal	0.5

The colour and intensity of optimum FCA (FCA-3) and FCB are affected by the presence of charcoal. This can be seen with the visual observation of FCA-3, which produced red-orange light, while FCB produced red light [14]. The visualization of both compositions as portraits is shown in Table 5. A red-coloured flame is desired for the purpose of better visualization [1]. In FCA, only sulphur and sawdust were used as fuel, which enhanced the output time of the flare. The addition of charcoal to FCB acted as a solid fuel, making the ignition time longer [15]. Longer burn time is better to use as a signal flare.

Sulphur, with the addition of charcoal, had the properties of a reducing agent. The reaction of these chemicals with oxygen from the oxidizer produces hot gases [9]. The general chemical reaction of this chemical is illustrated in Eq. (1) and Eq. (2), respectively.

$$S + O_2 \rightarrow SO_2 \quad (1)$$

$$C + O_2 \rightarrow CO_2 \quad (2)$$

Table 5 *The digital photograph of FCA-3 and FCB in 15s interval*

Time (s)	FCA-3	FCB
15		
30		
45		
60		

Int. Journal of Integrated Engineering Vol. 16 No. 8 (2024) p. 291-299

3.4 Heat of Combustion

A further analysis of the composition was further analyzed on their heat of combustion by using the bomb calorimeter instrument. Th Based on the result as attached in Table 6, FCB with the addition of charcoal has a lower heat of combustion with an average of 664.23 cal/g compared to FCA-4, which has an average heat of combustion of 798.29 cal/g.

Table 6 *Bomb calorimeter for FCA-3 and FCB*

Sample Name	FCA-4		FCB	
Sample / Test	Weight of sample (g)	Heat of combustion (cal/g)	Weight of sample (g)	Heat of combustion (cal/g)
1	0.5362	737.16	1.0290	738.65
2	0.5280	859.43	1.0311	589.81
Average	0.5321	798.29	1.0301	664.23

The result shows that the heat of energy released from the burning fuels attached to the heat of combustion and produced a higher reading in the bomb calorimeter [16]. By increasing the fuel percentage weight in FCB, the heat of combustion might be increased. Steinhauser et al. [7] stated that reactions between the particles emit light in the visible region at temperatures above 500 °C, and the reaction is exothermic. At temperatures above 500 °C, the mixtures will start to decompose and form an unstable compound that will emit light. According to Ritche [17], even after complete combustion of the charcoal as a colour enhancer in an oxygen-rich environment, sulphur continues to play a role, particularly in its molten state, where it is known to lower the activation energy of combustion.

The relaxation of excited electrons from the compound caused the emission of photons with 400 nm to 700 nm wavelengths in the visible spectrum [7]. This can be further visualized in the graph illustrated in Fig. 5.

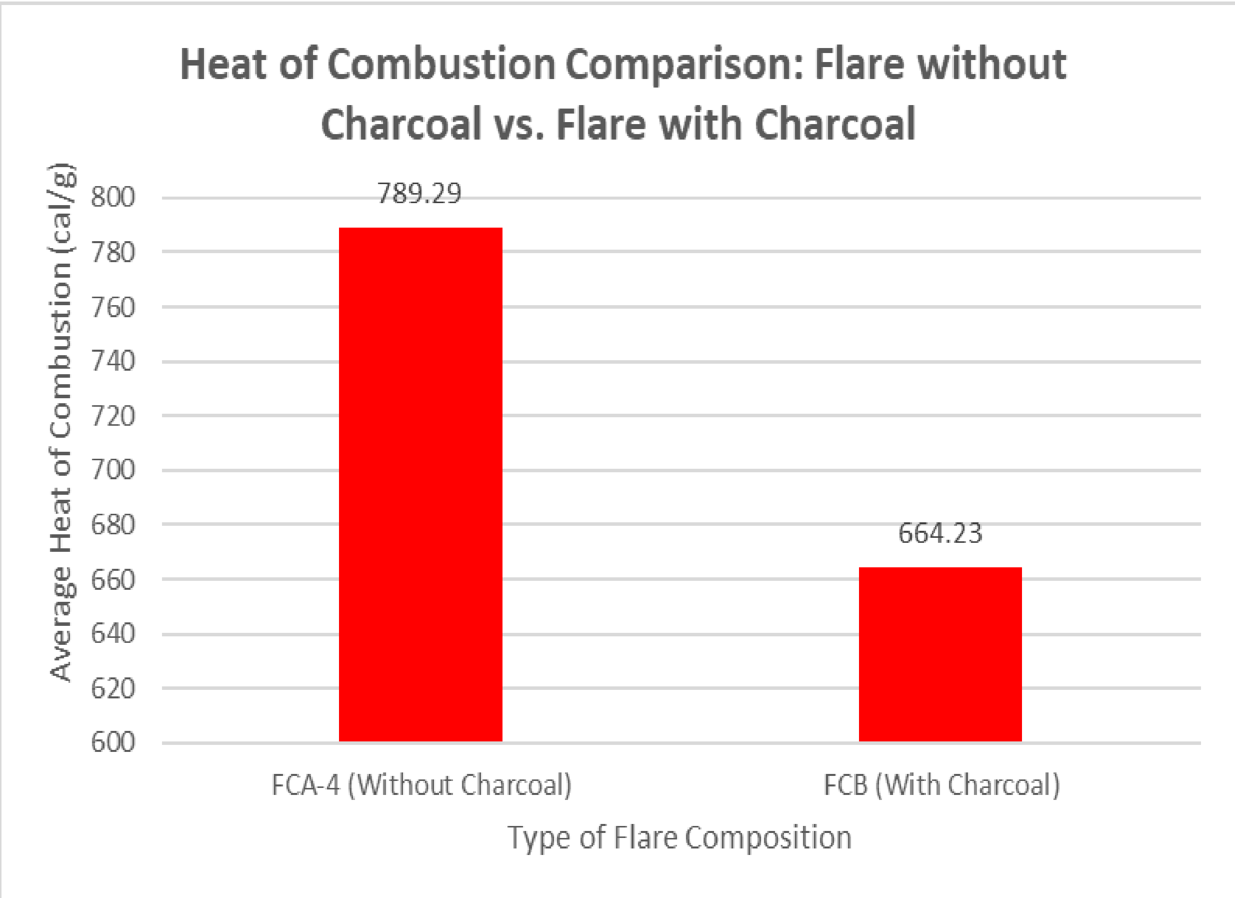

Fig. 5 *Type of formulation versus heat of combustion*

The higher emissions of heat from the FCA formulation compared to the FCB formulation showed that the flaring systems designed help to burn off waste gases and may reduce the risk of uncontrolled combustion in any explosions. Having a lower heat of combustion also leads to a longer duration of flare combustion. This can be overstated because FCB had a longer time to ignition compared to FCA-3.

4. Conclusion

In conclusion, FCB with 73.2 wt% of $Sr(NO_3)_2$, 4.9 wt% of NH_4ClO_4, 12.2 wt% of sulfur, and 9.7 wt% of sawdust and 0.5 wt% of charcoal gives a higher intensity and brightness than FCA. The addition of charcoal increased the red colour intensity in the flare. Charcoal was also successful as a fuel because it made the burning time longer. This can be seen by how the burning time for FCB (90 seconds) was longer than Flare 1 (70 seconds). For the bomb calorimeter, the heat of combustion for FCB (664.23 cal/g) is lower than that for FCA (798.29 cal/g), hence the ignition of flare could be longer. Hence, FCB is a suggested composition since it has a longer burn time and gives intense red colour and brightness, which are desired characteristics of red flare. In the future, the composition of flares can be further analysed based on their thermal characteristics.

Acknowledgement

This publication was supported by the Fundamental Research Grant Scheme (FRGS) (FRGS/1/2023/TK04/UITM/02/1) funded by Ministry of Higher Education (MOHE) and Micro-Industry Hub (MIH) Program (MIH-(005/2020), a programme funded by Universiti Teknologi MARA and MTC Engineering Sdn Bhd. The authors also acknowledge the financial support given by the College of Engineering, UiTM.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Ahmad Hussein Abdul Hamid, Zuraidah Salleh;* ***data collection:*** *Noor Farahana Abdul Rahman;* ***analysis and interpretation of results:*** *Noor Farahana Abdul Rahman, Istikamah Subuki, Nurnadia Andenan, Ahmad Hussein Abdul Hamid, Zuraidah Salleh;* ***draft manuscript preparation:*** *Istikamah Subuki. Nurnadia Andenan. All authors reviewed the results and approved the final version of the manuscript.*

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