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Novel blue flare tracer with enhanced color quality and luminous intensity

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ABSTRACT

Thermally stimulated light emission has a variety of applications, ranging from military signaling, rocket tracking, and illuminating devices. This study, reports on the development of novel blue flame compositions with enhanced spectral performance in terms of luminous intensity, and color quality. The light intensity and imprint spectra were measured using digital luxmeter and UV–Vis spectrometer respectively. The main giving of this study is that the light intensity of standard blue flare was increased by **459%**; the color quality was also improved by **162%**. This was achieved by means of optimizing the ratio of novel color intensifier to color source using aluminum metal fuel. Aluminum was found to maximize the formation of blue color reactive emitting species (CuCl), and to minimize the interfering incandescent emission resulted from MgO. This enhanced performance established the general rule that the color intensifier should be within 10–15 wt% of the total composition.

1. Introduction

Pyrotechnic compositions have wide range of applications including gas generator, heat, smoke, noise, delays, and colored flame compositions [1–5]. Almost all pyrotechnic compositions should contain an oxidizer, fuel, and binder [6–10]. The production of bright light, with vivid color, is the primary purpose for signaling, projectile tracking, and illuminating systems [11–14]. Certain elements and compounds when heated to high temperature have the unique property of emitting lines or narrow bands of light in the visible region (380–780 nm) [15–19]. Such elements are called the color source [20,21]. For instance, strontium (red), barium (green), copper (green or blue), and sodium (yellow) [22–25]. Strontium, barium, and copper emit color by forming their halides; this type of emission is known as molecular emission [26]. A yellow flame color is easily achieved by atomic emission from sodium atoms [22]. While atomic emission is characterized by sharp discrete wave length; molecular emission is characterized by broad band emission [27,28]. Chlorine was found to be an essential element to create different molecular emitting species [24]. Chlorine is used as color intensifier to enhance the production of colored flames in the visible band [3]. Without chlorine good colors would be difficult to be developed [29]. Magnesium metal fuel is used in many colored light formulas. In an oxidizing flame, magnesium is converted to magnesium oxide (MgO). MgO is an excellent white light emitter by incandescence [16]. This action could adversely affect the color quality [30]. The production of a vividly colored flame is a challenging problem than creating white light [22]. To develop high quality colored flame, a delicate balance between different factors is required. These factors include [31–33]:

- An atomic or molecular species that will emit the desired wavelength.
- The emitting species must be sufficiently volatile to exist in the vapor state.
- Sufficient heat should be generated to produce the excited emitter.
- The presence of incandescent solid or liquid particles can deteriorate the color quality.

Any interfering atomic and molecular emitters must be avoided or at least minimized [34–37]. The generation of an intense deep blue flame is an ultimate challenge [22]. The best flame emitter in the blue region 435: 480 nm is copper mono-chloride “CuCl”. CuCl emits a series of bands in the region 428: 452 nm, with additional peaks between 476: 488 nm [20,38]. The formation of gaseous CuCl in the flame is the main target to produce a high quality blue colored flame (Fig. 1) [10].

Increasing the temperature causes the dissociation of the CuCl molecules into neutral atoms which will emit ultra-violet light.

The atoms can combine with hydroxide radical species “OH” or oxygen atoms to form CuOH or CuO respectively [39]. The formation of CuO and CuOH must be avoided. CuOH emits in the region 525: 555 nm (green), this will overpower any blue effect. CuO will emit a series of bands in the red region, and this reddish emission is usually seen at the top of the blue flame, where sufficient oxygen from the atmosphere is present to convert CuCl to CuO [28]. Therefore the development of blue

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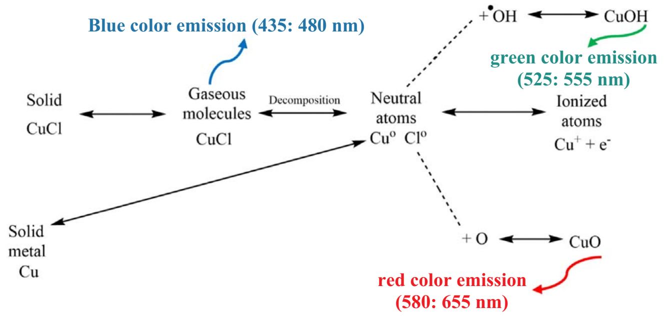

Fig. 1. Chemistry of cuprous chloride as emitters in blue flares.

color flame with high color quality requires delicate balance between these parameters to secure efficient formation of CuCl at proper flame temperature.

Shimizu had reported a good blue color performance at temperature ranged from 1660 K to 2500 K which changed the statements in the literature that the flame temperature has to be below 1500 K [40]. The main objective of this study is to maximize the formation of CuCl in the combustion flame, by optimizing blue flare constituents. Different binders, oxidizers, and color intensifier to color source ratio were investigated and optimized. Blue flares with enhanced performance, in terms of color quality and intensity were developed. It was possible to enhance light intensity, and color quality of reference flare (Shimizu high temperature blue flare) by 459% and 162% respectively. This was achieved mainly by optimizing the ratio of color intensifier poly vinyl chloride (PVC) to color source $2CuCO_3{\bullet}Cu(OH)_2$ using Al as a novel pyrotechnic fuel. Quantification of combustion gasses and combustion temperature was achieved using chemical equilibrium computer program named ICT Thermodynamic Code (Institute of Chemical Technology in Germany, virgin 2008).

2. Experimental work

2.1. Chemicals and materials

The main constituents for blue flare manufacture include: oxidizer, metal fuel, color source, binder, and color intensifier. One constituent can have a dual function, for instance NH_4ClO_4 can act as an oxidizer and color intensifier. Poly vinyl chloride (PVC) can act as a binder and color intensifier. $2CuCO_3{\bullet}Cu(OH)_2$ acts as a color source. Table 1 tabulates a list of employed chemicals in this study.

2.2. Blue flare formulation

Shimizu blue flare, which gives a good blue color, known as Shimizu high temperature blue flare was employed as a Ref. [40]. The chemical composition of such flare was 70 wt% NH_4ClO_4, 5 wt% $2CuCO_3{\bullet}Cu(OH)_2$, 15 wt% Mg, and 7 wt% shellac [41]. A systematic study to develop blue flare with enhanced spectral performance was conducted; this study includes the following main steps:

- Fuel rich / stoichiometric formulations (F_o - F_1).
- Type of binder (F_2 - F_3).
- Type of fuel (F_4).
- Fuel to color source ratio (F_5 - F_8).
- Color intensifier to color source at different fuel types (F_9 - F_{12}).

Table 2 summarizes the chemical composition of different investigated formulations.

Technology of blue flare manufacture should emphasize mixing of different ingredients to the molecular level, good homogenization, and accepted mechanical properties [3]. In this study, the blue flares were manufactured through four main steps including: sieving of solid particles to fine powder (less than 100 µm), intimate mixing of constituents, granulation to ensure homogeneity, and pressing. The employed equipment in blue flare preparation and spectral testing are scheduled in Table 3.

The employed ignition composition was (KClO3, Mg, and Carbon black).

2.3. Spectral measurements of blue flares

Photometric tunnels are widely used to measure the imprint spectra of different pyrotechnic devices including: flares, signals, tracers, and illuminating devices. The employed tunnel dimensions were 8 m (L) × 2 m (H) × 0.5 m (W). A schematic of the employed photometric dark tunnel is represented in Fig. 2.

The Miltronics DL 1076 digital luxmeter measured the illuminance (E) in lux (lx). The illuminance (E) was converted into luminous intensity (I) in candela (cd) using Eq. (1) [42].

$$\boldsymbol{I}_{(cd)} = \boldsymbol{E}_{(lx)} \times (\boldsymbol{d}_{(m)})^2 \tag{1}$$

Where: d is the distance between the light source and the detector (d). The average luminous intensity per time (cd/s) was calculated by measuring the summation of the area under the curve of the total luminous intensity (I) in candela (cd) divided by the burning time. The main disadvantage of such measurement is that it cannot offer information about color quality. In order to judge the color quality, ocean optics USB 4000 spectrometer was employed. The detector was adapted measurements over the blue band 425: 500 nm [22]. The average luminous intensity (cd/s) and spectrometer response (counts/s) were measured over the blue band (425: 500 nm) for the developed flares to reference flare [43].

3. Results and discussion

3.1. Effect of binder type

The binder type could have a significant impact on blue flare performance. The binder itself can act as color intensifier (source of chlorine). The impact of arabic gum (F_2) and PVC (F_3) on color intensity was found to be 116% and 156% respectively to that of reference binder (Shellac) (F_0) (Fig. 3).

Shellac and Arabic gum and were not effective color intensifier due to the lack of chlorine of such binders. PVC could be the recommended

Table 1
The function and structure of different used chemicals.

Chemicals	Function	Structure	Grade	Supplier
NH_4CLO_4	Oxidizer	NH_4ClO_4	Analytical grade	Alpha chemika
Copper carbonate	Color source	$CuCO_3.\ Cu(OH)_2{\cdot}H_2O$	Analytical grade	Alpha chemika
Magnesium	Fuel	Mg	98%,ribbon	Alpha chemika
Aluminum	Fuel	Al	99%,fine powder	Alpha chemika
Polyvinyl chloride	Binder & color intensifier	$(C_2H_3Cl)_n$	Analytical grade	Alpha chemika
Arabic gum	Binder	$(C_{16}H_7N_2O_3)\ _n$	Analytical grade	Alpha chemika
Shellac	Binder	$(C_{30}H_{50}O_{11})_n$	Analytical grade	Alpha chemika