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Ultrasonically dispersed dyed water mists as a substitute for colored powders

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ABSTRACT

Colored powders such as colored corn starch are used in events such as The Color Run to blanket the air and surroundings with decorative color. Their use, however, presents a risk of dust explosion. The fact that such powders are used at events drawing large crowds makes any fire or explosion likely to result in a mass casualty incident. For instance, the Formosa Fun Coast explosion on June 27, 2015, resulted in multiple deaths and injuries. Development of alternatives to flammable/explosive colored powders would eliminate this hazard. We demonstrate as a proof-of-concept that an ultrasonically driven water mist can produce effects similar to those created by colored powders. Food coloring was dissolved in water, and the colored water was subsequently dispersed from various ultrasonic devices and photographed. Colored clouds were formed from the colored water. Colored clouds were visible under various conditions, and color combinations were possible. Possible risks of colored corn starch and water mists are discussed. An ultrasonic misting system is capable of safely replacing colored powders with regard to appearance.

1. Introduction

Various colored powders have been used to cover areas with color as part of festivals, events, and parties, with an example of such a scene illustrated in Fig. 1. Note how a variety of colors are present in the air due to the dispersion of colored powder. The photograph was taken by Mats Hagwall, "Party at the Big Stage," and reused under a Creative Commons 2.0 (CC BY 2.0) license.

The events have typically proceeded without mishap; however on June 27, 2015, a dust explosion and fire occurred at Formosa Fun Coast during the "Color Play Asia" event [1]. The disaster killed 15 [2], and injured 498 [3]. Subsequently, the government in Taiwan [4] has banned the use of flammable powders in such events. Shanghai and Shenyang subsequently cancelled their color runs, while the run planned in Singapore proceeded with additional precautions such as a prohibition on both smoking and machine dispersion of powder [5]. An excellent review [6] on dustiness notes that the behavior of dust/air mixtures is complex, and is not fully understood. Various investigators are studying dustiness as a metric for estimating the likelihood of an explosion occurring. However, progress in this area has resulted in the publication of standard NFPA

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Fig. 1. Photograph at the end of The Color Run at Lund, Skane, Sweden.

Table 1
Dyes used and concentrations (M – molar or equivalently mol/L).

Color	Dye name	Alternative name	Concentration (M)
Red	Red #6	New coccine	0.066
Yellow	Yellow #4	tartrazine	0.187
Blue	Blue #1	brilliant blue FCF	0.0189

Numbered dye names are provided by the manufacturer, and numbering schemes are country-specific (the same dye may be given different numbers depending on country).

(National Fire Protection Association) 652 [7], in an attempt to produce a single standard for flammable dusts across various industries [8].

The development of alternatives to colored powders would eliminate such hazards of fire and explosion. The use of approved food dyes for coloring water, rather than solid powder, provides an alternative to current approaches. Such water mists are not flammable, and are not prone to explosion. In fact, by increasing ambient humidity, they reduce explosion risk arising from other causes. They also provide a separate beneficial cooling effect [9] during warm weather. Here, we present data indicating that ultrasonically dispersed, dyed water mists can produce effects similar to that produced by previously used colored powders. Subsequently, the advantages and drawbacks of colored water mists in comparison to colored powders are discussed.

2. Experimental methods

Dyed water was prepared by dissolving the following food-grade dyes (Daiwa Dyestuff Mfg. Co. Ltd, Saitama, Japan) into separate water containers in the following concentrations (Table 1), producing water that was dyed red, yellow, and blue.

Shown in Fig. 2 is a chamber with restricted airflow constructed using an aluminum frame and clear plastic wrap. The chamber was used to test system performance in a restricted volume and had approximate dimensions of $25 \times 25 \times 50$ cm. The chamber was open at the top, and contained cutouts for nebulizer openings.

Two types of ultrasonic diffusers were used to generate water mist. The MUJI Nebulizer (Brisk Aroma Diffuser, Guangdong, China) operated at a fixed frequency of 1.7 MHz. It has a capacity of 500 mL, and was originally designed to be used as a room humidifier as well as a system for dispersing scented oils. It produces mist by dispersing water at a rate of 90–100 mL/h, at a mean particle size of 2 μm. The Mesh nebulizer WB-16A (Whirl Best International Co. Ltd, Taoyuan, Taiwan) operated at 104 ± 5 kHz, and disperses water at an adjustable rate between 30 and 120 mL/h, with a mean particle size of 7.5 μm. (All specifications obtained from manufacturers' documentation.) In the experiments performed, the maximum rate of 120 mL/h was used throughout. Colored mists were dispersed indoors and outdoors using both devices. Photographs and video recordings were obtained of the results using a camera-equipped mobile phone. Dispersion was performed both inside and outside of the restricted airflow chamber.

Fig. 2. Restricted airflow chamber with adjacent MUJI nebulizer.

3. Results

3.1. MUJI nebulizer

Fig. 3 shows a top-view photograph of the restricted airflow chamber, prior to the introduction of any water mist along with photographs of the same chamber after 25 s of mist introduction of colored mist for comparison. Photograph descriptions are as follows: (top row) Chamber prior to mist introduction, (center left) undyed water generating a white mist,

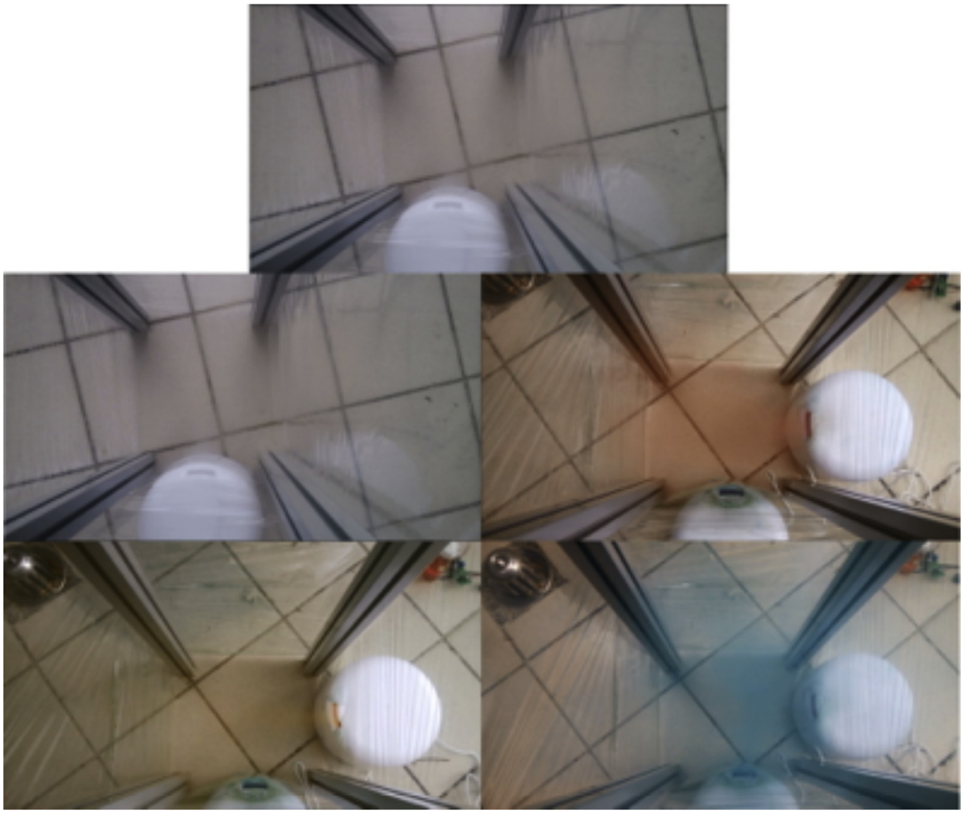

Fig. 3. Single MUJI nebulizer delivery of colored mist.

(center right) red mist, (lower left) yellow mist, and (lower right) blue mist. Center and lower row photographs depict results 25 s after starting nebulizer. The colored mist addition is clearly visible with the introduction of 0.6–0.7 mL of mist, especially in the blue case.

The combination of two MUJI nebulizers, with each dispensing a different colored mist, results in the combination of the colors present. Fig. 4 shows the results of all possible 2 nebulizer combinations. From top to bottom, they are respectively as follows: red and yellow, yellow and blue, and red and blue. The combination of two different colors creates additional colors, which are orange, green, and purple. The total mist quantity present is double that of Fig. 3. It is also possible to premix dyes before mist generation to produce desired colors to be dispensed with a single nebulizer.

The effect of present wind was examined by removing the airflow chamber and results displayed in Fig. 5. The experiment was conducted outdoors with a slight breeze present. No accumulation of mist was observed with the passage of time; wind dispersed the mist produced. It should be noted that the rate of mist production was the same as before, and that a sufficient rate of production should produce more dramatic effects and overcome the dispersal arising from wind.

3.2. Mesh nebulizer

Fig. 6 shows, from left to right, the simultaneous delivery of blue, red, and yellow mist from mesh nebulizers outdoors. The mist was continually dispersed by the wind present. The Mesh nebulizer dispensed mist at a rate similar to that of the MUJI nebulizer, although the ultrasonic frequency used was very different.

Within the restricted airflow chamber, mist accumulated as expected based on results from the MUJI nebulizer. Combinations of various colors were generated by combining water mists dyed different colors and the results shown in Fig. 7. Descriptions are as follows: (top) undyed, (center left) red and yellow, (center right) yellow and blue, (bottom left) red and blue, (bottom right) red, yellow, and blue. Combinations produced partial volumes of orange (center left), green (center right), purple (bottom left), and brown (bottom right) mists. (Where multiple nebulizers were present, a delay was present between starting the first and last devices.)

Due to the short amount of elapsed time, mixing of the various colored mists was incomplete and thereby additional colors only partially appear within the chamber. As with the MUJI nebulizer, different colors can be also produced by pre-mixing dyes prior to their dispersal.

Fig. 4. Combination of two nebulizers dispensing different colored mists after 25 s.

4. Discussion

Both colored corn starch and colored water mists have known and possible hazards (Table 2). The key advantage of using water mist is avoiding the possibility of fire and/or explosion. Nonetheless, some hazards potentially remain.

Risks from colored corn starch, besides the fire and explosion risk, include the possibility that dust exposure could lead to health problems [10]. Exposures to airborne undyed corn starch powder used in powdered gloves at 5.9 mg/m^3 was shown to cause asymptomatic lung inflammation [11]. A sample of four individuals running in the Brisbane, Australia ColorRun showed dust exposures of 0.8, 1.5, 14.2, and 14.7 mg/m^3 [12], while Safe Work Australia lists 4 mg/m^3 as the time weighted

Fig. 5. MUJI nebulizers dispensing red (left) and blue (right) mist outdoors in a slight breeze. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. Mesh nebulizers dispensing blue, red, and yellow mist outdoors with a slight breeze present. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

average workplace exposure limit for grain dust [13], suggesting that corn starch exposure may exceed safety limits, especially for workers at such events as opposed to occasional participants.

Nonflammable powders such as sodium bicarbonate have been suggested as another alternative to corn starch powder. A patent [14] exists for food-colored sodium bicarbonate being used for freshening upholstery. Such formulations would also avoid explosion hazards. Sodium bicarbonate can also be combined with corn starch in sufficient inerting concentrations such that the corn starch is rendered safe from explosion [15]. As with any solid dust, there are inhalation risks involved, and therefore inhalation of sodium bicarbonate is not advised [16]. Mixtures of corn starch and inerting sodium bicarbonate are expected to share their individual hazards.

Exposure to water mists has two known potential risks. First is the possibility of triggering bronchospasm in susceptible individuals. Inhalation of 20 mL of distilled water mist triggered positive asthma tests in 7/22 asthma patients [17]. Visits to hospital emergency departments by asthmatic children are correlated with levels of fog, which is a natural water mist [18,19]. The second risk is water contamination, with various bacteria or their endotoxins [20]. The best known bacterial

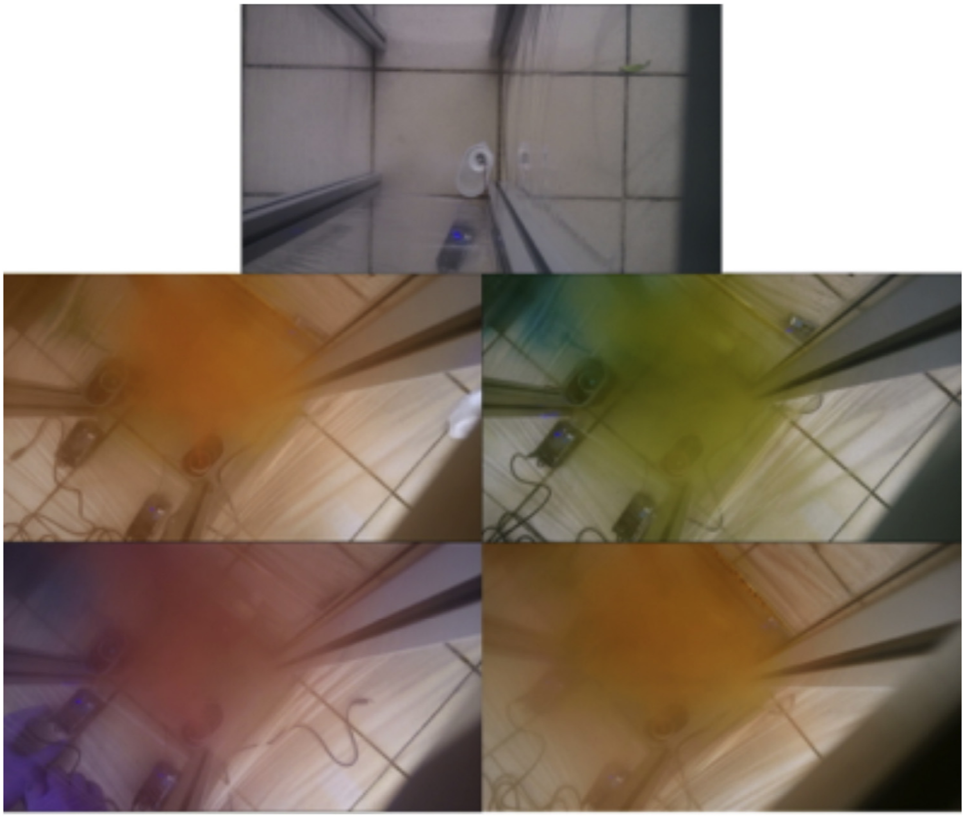

Fig. 7. Mesh nebulizer results within the restricted airflow chamber 10 s after start of last nebulizer.

Table 2
Possible hazards of colored corn starch and colored water mists.

	fire/explosion	Other possible hazards
Corn starch	Yes	Pneumoconiosis (lung disease caused by dust inhalation)
Water mist	No	bronchospasm bacterial contamination

contaminant is Legionella, of which there are 25 known pathogenic species [21]. Two outbreaks [22,23] of Legionnaires' disease were traced to grocery store misting machines contaminated with bacteria. Inhalation of contaminated mist causes disease [24,25]. Bacterial contamination can occur even with treated water. For instance, even with residual chlorine levels above 0.1 mg/L, Brevundimonas bacteria were found dispersed from water mist equipment, with a hose being the contamination source [26]. Misting systems can dispense bacterial loads as high as 3×10^8 microorganisms/mL, with contamination arising from poor system cleaning [27].

5. Conclusions and future research

Dyed water produced by dissolving food colorings into water, can be dispersed using ultrasonically-based nebulizers. Such devices produce colored mists, which create an effect similar to that produced by colored powders while avoiding dust explosion hazards. Wind presence causes dispersal of mist, and presumably requires additional mist generation to overcome. Further work is required to optimize nebulizer based mist production and to characterize optical properties of generated mists given various parameters such as dye concentration, mist particle size and velocity, and volume of water dispensed.

Mist particle size also affects its safety and settling properties. It is known that mist particle sizes less than 10 μm tend to persist in the air, as opposed to settling from gravity [28]. Such particle sizes can be breathed into the lungs, as opposed to larger droplets, which are generally filtered out by the body. Due to evaporation, larger mist particle sizes can shrink to sizes less than 10 μm and nevertheless become respirable. However, particle sizes greater than 50 μm can be ignored for mist exposure purposes in high humidity environments, despite some shrinkage arising from evaporation [28]. A potential limitation on the use of water mists is their limited throw distance from their sources, which has been previously examined in detail [29]. Throw distances exceeding a meter are rare in existing commercial systems, although exceptions exist [30]. For a given event venue, such would mean that more mist dispersal nozzles are required for adequate coverage relative to solid particle based systems. Nozzles can be mounted above crowds and colored mists allowed to drift downward.

Methods such as laser-based particle image velocimetry and sizing (PIVS) [31] would be used to characterize mists with varying parameters. Resulting mists generated would then be compared to clouds of colored powders and their optical effects. Colored water mists would not be susceptible to dust explosion or fire. Properly scaled up, colored water mists can be a substitute for colored powders in outdoor displays. Tests of such scaled up systems will be necessary in order to verify that they are capable of delivering the quantities of mist needed. An analysis of colored water mist properties indicates that their hazards (bacterial contamination and bronchospasm) are known and can be avoided through proper cleaning and avoidance of such mists by susceptible people.

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