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Improved electrospray design for aerosol generation and flame propagation analysis

Yan-Ru Lin, Hao Chen, Chad Mashuga, M. Sam Mannan*

Mary Kay O'Connor Process Safety Center, Artie McFerrin Department of Chemical Engineering, Texas A&M University System, College Station, TX 77843-3122, USA

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ABSTRACT

Although the hazards of aerosol fires and explosions have been studied for decades the data for aerosol flame propagation is still scarce. Additionally there is a lack of standard techniques and measurement apparatus, which impedes the development of optimal aerosol hazard mitigation measures. The focus of this study is development of an improved aerosol electrospray device for the generation of high quality aerosol data. The goal is achieved through higher nozzle packing, precise nozzle and mesh hole alignment and adding two ground meshes. In addition to a flat ground mesh, the utilization of a cylindrical ground mesh demonstrated improved confinement and guidance of droplets. Duratherm 600, heat transfer fluid, was examined to demonstrate the modified electrospray device capabilities as compared to previous design. Results show the modified electrospray can produce more uniform droplets, more even test chamber dispersion, smaller droplet size and higher concentration aerosol, which is essential to study aerosol flame propagation. Accordingly, the results of aerosol flame speed tests for the improved design were more reproducible. Moreover, it was found that a traditional propane pilot flame was unable to ignite the smaller aerosol droplet size due to the strong turbulence generated by the open flame. However, by careful modification of the pilot flame length, the turbulence decreased dramatically and the small droplet size aerosol can be tested.

1. Introduction

Fire and explosion hazards of a liquid are often classified by the liquid's flash point. A liquid is defined as flammable if the flash point of which is under 37.8 °C as in NFPA 30 standard (National Fire Protection Association, 2012), or under 60 °C in GHS standard (United Nations, 2011). For flash points above these values, it is called "combustible liquid," and attention to the liquid is usually less than that of a "flammable liquid." However, the real hazard depends on the properties and the operating condition of liquid, not solely on the flash point. For combustible liquids including higher flash point liquids, its flammability can be drastically increased when it is operated under high pressure and temperature, which is common in the processes in industries. When a liquid is released under such circumstances, an aerosol/mist often forms. Once an aerosol forms, its properties are significantly different from the bulk liquid or vapor. Since the droplet size is much smaller than the bulk liquid, the surface area will be much higher and evaporation rate will also increase dramatically, which would facilitate the ignition process and combustion. Furthermore, the probability of reaching an ignition source is also increased due to the aerosol dispersion.

For example, heat transfer fluids (HTFs), a group of high flash point liquids widely used in industry, have been involved in many incidents. Factory Mutual Engineering and Research (FME&R) reported there were 54 HTFs-related fires and explosions in a ten-year period and caused $150 million in loss (Febo and Valiulis, 1996). Moreover, more than 200 incidents involving HTFs have been reported in the past 20 years (Huang et al., 2013b).

One industrial scenario for mist formation is superheated liquid flashovers, in which the liquid vaporizes, expands and cools down to form fine liquid droplets. Another scenario is a liquid stream breaks down into coarse droplets due to friction force between the liquid surface and air, as demonstrated in previous work (Krishna et al., 2003; Sukmarg et al., 2002). Although it is well known aerosols pose great threat to the process industries and have been

* Corresponding author. Present address: 3122 TAMU, 246 BRWN, College Station, TX 77843-3122, USA.
E-mail address: mannan@tamu.edu (M.S. Mannan).

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studied for decades, their flammable behavior and mechanism are not well understood. Vapor and dust have consensus standard apparatus. However, no consensus standard has been established to study aerosol flammability, and hence aerosol data are much less prevalent than vapor or dust.

Flame speed is an important factor in the hazard evaluation of a material. It is generally understood that flame speed increases as aerosol size decreases. However, there is no systematic way to investigate aerosol flame speed. In a previous study, only 83–89 μm droplets of a heat transfer fluid were studied, which may not be sufficient to reveal a clear flame speed pattern (Lian et al., 2011). Therefore, it is critical to utilize a reliable device capable of producing high quality droplets to study fundamental aerosol behavior. There are three major approaches for aerosol generation. First, similar to real scenarios in the process industry, the aerosol is generated from a pressurized orifice, or sprayed from a fuel injector or sprayer (Ballal and Lefebvre, 1981; Nunome et al., 2002; Sullivan et al., 1947). This is one conventional way to generate aerosols and is widely used by aerosol injectors for internal combustion engines. However, these aerosols may be poly-dispersed and not suitable for fundamental study. The aerosol size measured at different distances is also different due to the injected formation mechanism (Krishna et al., 2003).

Another traditional way to generate aerosols is by cloud chamber (Burgoyne and Cohen, 1954; Chan and Jou, 1988; Hayashi et al., 1977), and the generated aerosols are mono-dispersed. These are based on the condensation of superheated vapor as the chamber is quickly cooled down during sudden expansion. However, the resulted atmosphere is hard to control to achieve desired droplet size at 1 atm and room temperature.

Finally, fine droplets can be generated by applying a high voltage field to break down the liquid stream through an electrospray device. It can generate mono-dispersed aerosols for fundamental study and is relatively easy to control droplet size (Tang and Gomez, 1996). However, in previous studies (Huang et al., 2013a; Lian et al., 2010; Lian et al., 2011), the generated aerosols are not sufficiently small enough for a wider range of flammability study. Also the aerosol tended to be too poly-dispersed and not uniform, and a lower concentration. In order to further investigate aerosol flammability, it is critical to improve the capability of the device to examine a more complete range of aerosol flammability fundamentals. In this study, the design of the electrospray device was improved, and the results of aerosol generation and flame propagation validate the improvement of the apparatus.

2. Experimental setup and methodology

2.1. Aerosols generation by electrospray

Duratherm 600 (D-600), a commercial HTF, is used in this study to demonstrate the capability of the improved electrospray device. Its properties are listed in Table 1. Since it is a mixture of highly hydrotreated and hydrocracked hydrocarbons, its electric conductivity is very low. As a result, an additive is needed to increase its electric conductivity for electrospray operation. The additive is Stadis 450 and its properties are shown in Table 2. The amount used in D-600 is only 1 wt% or 2 wt%. It has been shown that small amounts of additive can increase the electric conductivity drastically without significantly changing other properties of the liquid (Tang and Gomez, 1996).

Fig. 1 shows the schematic view of electrospray setup. The concept and operating procedure are similar to previous research (Huang et al., 2013a; Lian et al., 2010; Lian et al., 2011). Test fluid is contained in ten 2.5×10^{-6} m^3 syringes, and dispensed with a syringe pump (KDS 220). Ten stainless steel nozzles (2.54×10^{-4} m i.d. and 5.08×10^{-4} m o.d.) were assembled on a small metal plate, which is connected to a high voltage source (HV1). A metal mesh positioned right beneath the metal plate is connected to a second high voltage source (HV2) and serves as a relative ground. Ten 5.08×10^{-4} m i.d. plastic capillaries connect the syringes to the nozzles to transport the test fluid. The high voltages are generated by the function generators (Stanford Research System, DS-345) and then amplified to the desired levels by high voltage amplifiers (Trek Inc. 610E). The voltage difference between HV1 and HV2 is maintained at several kilovolts to energize the test fluid. As liquid stream with sufficient electric conductivity passes through the nozzles, the liquid meniscus takes a conical shape (cone-jet) and fine droplets are generated.

Table 1
Properties of the heat transfer fluid (D-600).

Duratherm 600 (D-600)	Properties
Appearance	Slight yellow, transparent liquid
Composition	Hydrotreated mineral oil
Average molecular weight	372 (kg/kmol)
Flash point	224 °C
Fire point	240 °C
Boiling point	>298 °C
Density	852.3 kg/m^3 (25 °C)
Dynamic viscosity	0.0659 Pa s (25 °C)
Kinematic viscosity	77.27×10^{-6} m^2/s (25 °C)
n[a]	1.5
k[a]	0.1

[a] n is the real part of refractive index, and k is the imaginary part of refractive index.

Table 2
Properties of the additive (Stadis 450).

Stadis 450	Properties
Appearance	Amber, transparent liquid
Composition	Toluene: 30–60%
	Naphtha: 10–30%
	Dinonylnaphthlysulphonic acid: 10–30%
	Polymer containing Sulphur: 10–30%
	Polymer containing Nitrogen: 5–10%
	Propan-2-ol: 1–5%
	Naphthalene: 1–5%
Flash point	6 °C
Boiling point	90 °C
Density	920 kg/m^3 (15 °C)
Kinematic viscosity	7×10^{-6} m^2/s (40 °C)

In our aerosol flammability study, some desired physical properties are higher concentrations, small mean droplet size, mono-dispersed droplets, stable spray and even droplet dispersion in the test chamber. Attention to equipment details are required to achieve the desired aerosol conditions. First, every nozzle should be positioned at the center of the metal mesh hole to create a uniform electric field. If the electric field is not uniform, the resulting droplet size distribution will be poly-dispersed. The comparison between improved design and previous electrospray setup is shown in Fig. 2. In addition, the distance between nozzles and metal mesh was greatly reduced so that the voltage difference between HV1 and HV2 can be set around 2–3 kV instead of 7–10 kV in previous electrospray. Lower voltages are safer and easier to achieve by the equipment.

Though electrospray is relatively easy to generate with sufficiently uniform size distribution, the major drawback is that the concentration of generated aerosols is low, which is unfavorable for reaching a lower flammability limit. In order to increase the aerosol concentration for a variety of test liquids, a multi-nozzle system can be applied. By using microfabrication and etching technology,