A Continuous, Monodisperse Propellant Microdroplet Stream as a Model System for Laser Analysis of Mass Transfer in Metered Dose Inhaler Sprays

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KEYWORDS: metered dose inhaler, propellant spray, laser light scattering, experimental model

INTRODUCTION

Important parameters that influence oropharyngeal and lung deposition from metered dose inhalers (MDIs) are the diameter and velocity of the droplets in the propellant spray. Typically, a single actuation from an MDI produces a spray that lasts only for a fraction of a second, making it difficult to study the transient heat and mass transfer processes that control droplet evaporation. Pressurized formulations can be delivered via constant valves to allow longer observation, but in this case, evaporative cooling can lead to a large temperature drop in the MDI, affecting the properties of the spray. In the study presented here, an experimental model is developed that uses a single droplet stream which is unaffected by evaporative cooling and can be studied for extended periods of time by laser light scattering.

HFA 134a and HFA 227 are the most common propellants used in MDIs. Their high vapor pressure provides the driving force for effective droplet generation but it also makes these propellants incompatible with commercially available droplet generators. The droplet generator developed in this work uses the vibrating orifice principle (1) and was fitted with a custom liquid feed system that can withstand the high pressure of the propellants.

OPERATING PRINCIPLE

The droplet generator produces a single jet of propellant via an orifice disk that is held inside an orifice cup. Liquid propellant enters the cup through a feed tube and exits through the orifice. The cylindrical liquid column passing through the orifice is unstable, thus induced to break up into droplets. A periodic disturbance, with proper amplitude and frequency, is applied to control the breakup process to produce uniform droplets. These disturbances are acoustic vibrations induced in the orifice by applying a voltage to a piezoelectric ceramic bonded to the orifice cup. The droplet diameter, D_p, can be selected by controlling the volume flow rate, $\dot{V}$, and frequency, f. It is also related to the orifice diameter, D_O:

$$D_p = \sqrt[3]{\frac{6\,\dot{V}}{\pi f}} \qquad \text{with} \qquad \dot{V} = c\,\frac{\pi D_O^2}{4}\sqrt{\frac{2\Delta p}{\rho}}$$

where Δp and ρ represent the pressure drop across the orifice and the HFA propellant density, respectively. C is a constant describing the impact of the orifice shape.

However, monodisperse droplet production is only possible for droplet diameters that are in a range of approximately $1.7D_O < D_P < 2.5D_O$. The optimum droplet production frequency can be calculated as a function of orifice diameter and material properties using classical jet disintegration theory (2). For HFA 134a, the optimum frequencies for 10, 20, and 35 μm orifices were calculated to be 760 kHz, 380 kHz, and 220 kHz, respectively.

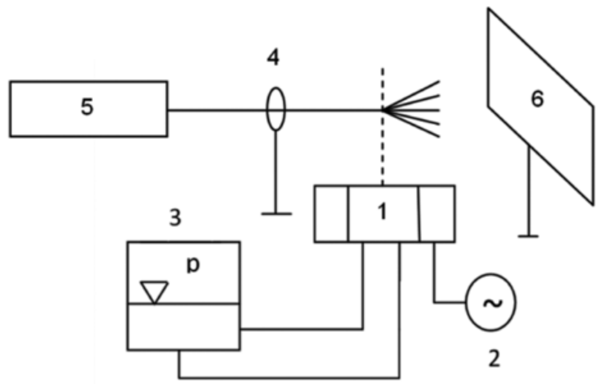

Figure 1. Experimental setup: 1. vibrating orifice droplet generator; 2. pulse generator; 3. pressurized propellant supply system; 4. focusing lens; 5. LASER; and 6. screen.

EXPERIMENTAL SETUP

A schematic of the experimental setup is shown in Figure 1. The propellant feed system can be charged with HFA propellants under pressure and utilizes regulated nitrogen gas supply to control the pressure drop across the orifice. Orifices with diameters of 5μm, 10μm, 20μm, and 35μm were used in the vibrating unit of the droplet generator. The operating pressure for HFA 134a propellant was 800-1000 kPa. A high precision frequency generator (DS340, Stanford Research Systems, Sunnyvale, CA, USA) was used to induce the orifice vibrations. To determine the frequency range in which monodisperse droplets were produced for any given orifice diameter, a deflection test on the emerging droplet stream was performed (3). The deflection test is the application of a laminar cross flow of air to the droplet chain. Monodisperse droplets experience the same drag force in the transverse direction and, hence, will be deflected by a fixed angle whereas polydisperse droplets will be dispersed in different directions.

The propellant droplets were probed using either an argon ion laser (Innova 70, Coherent, Santa Clara, CA, USA) operated at a wavelength of 514.5 nm, or a diode laser (Lasiris, Coherent, Santa Clara, CA, USA) operated at a wavelength of 680 nm. The lasers were used either unfocused or were focused onto the droplet chain at different distances from the orifice using a lens with a focal length of 150 mm. The light scattering from the droplets was imaged with a digital camera from a white screen located 450 mm from the droplet stream.

RESULTS

The droplet generator was successfully operated with isopropanol and with HFA 134a with various orifice disks, feed pressures, and excitation frequencies. Suitable operating conditions were found for all orifice sizes, including 5 μm, leading to the production of monodisperse propellant droplets in a diameter range of 10–50 μm. Stable droplet streams were generated, reaching more than 1 hour of continuous production, limited by the occurrence of partial or complete orifice obstruction with particulate contaminants.

Figure 2 shows typical light scattering patterns observed from the droplet chains. The left pattern was generated from HFA134a while the right pattern was created by isopropanol droplets. The right side also shows a schematic representation highlighting the two components of the pattern, circular fringes and horizontal bars. Fraunhofer diffraction theory was employed to calculate the droplet diameter form the circular fringe pattern (4). The pattern in Figure 2b was generated from droplets at a distance of 5 mm from the orifice and corresponded to a droplet diameter of 36 μm. The horizontal bars are generated when multiple droplets with regular spacing are in the laser beam at the same time, acting like a diffraction grating. From the separation of the horizontal bars the droplet spacing can be calculated (5). This is a very useful measure, because the droplet spacing yields the droplet velocity simply by multiplication with the production frequency. From the pattern in Figure 2b, a droplet velocity of 4.9 m/s was derived.

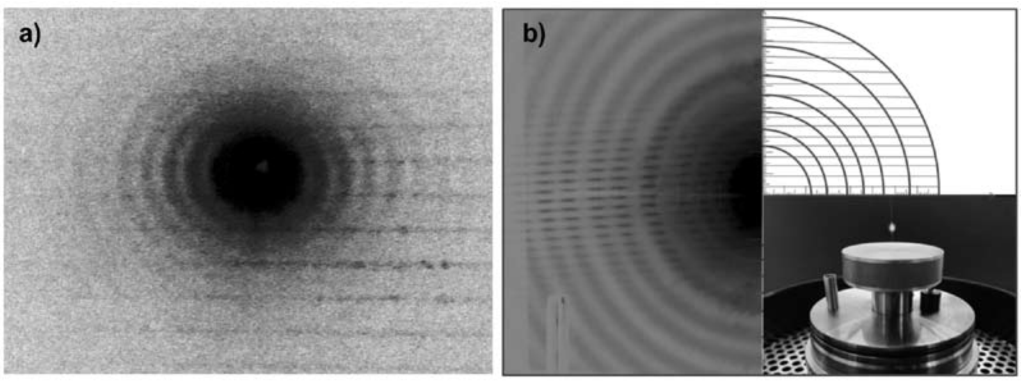

Figure 2. a) Light scattering pattern from HFA 134a droplets (35μm orifice / 200 kHz), b) Pattern from isopropanol droplets (20 μm orifice / 63.4 kHz). The insert shows the droplet stream illuminated by the laser.

CONCLUSION

Monodisperse droplet streams of high pressure propellants can be produced by controlled disintegration of liquid jets with a custom vibrating orifice generator. The generator is capable of producing droplets of sizes and velocities similar to droplets generated in commercial MDIs (6). The propellant droplets can be produced for extended periods of time making it a suitable model system for the study of heat and mass transfer in propellant sprays. Laser light scattering provides droplet diameter and velocity as a function of distance from the generator. This information can be used to calculate droplet diameter as a function of time, i.e., evaporation rates. The new droplet generator is a useful idealized experimental model for the investigation of mass transfer in propellant sprays.

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