Fog Dynamics

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1 Introduction

The lethal power of CBRN agents and their power to cause massive fatalities rely on their ability to disperse and propagate. In this sense, the most dangerous agents are those which are dispersed in the air and penetrate the lungs. For example, casualties caused by inhaling anthrax spores dispersed in the air are two orders of magnitude greater than those caused by a cutaneous infection of the same spores. This is also true for chemical and radiological agents [1].

The activity of a dispersed agent is many times greater than that of the same agent in a bulk or aggregate state. This is a general law and is due to the exponential increase of the surface-to-volume ratio for decreasing sizes of particles, spores, or drops. This principle is also well-known in medicine, i.e., a patient inhales sprayed medicaments to affect the respiratory system quickly [2]. It is also well-known in other fields: for example, coal powder suspended in the air makes an explosion in the atmosphere much worse than any other explosion in mines; even flour suspended in the air makes an explosive mixture that can often cause serious accidents in factories. On the other hand, fog and mist devices have been developed to fight fire with minimum water use. These systems are now becoming very common—for instance, to protect escalators from fire. They have the great advantages of using the optimal amount of water compatible with electric hardware and of being harmless to humans.

Taking this into account, a priority for any rapid response against a CBRN attack should be to collapse any kind of dispersion, fog or smoke, into a physically bulk state. This would avoid further propagation and drastically diminish the lethality and therefore the impact of the attack.

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The main objective of COUNTERFOG project is to design, build, and test a rapid response system for collapsing all kinds of dispersed agents (smoke, fog, etc.) by using a fog made of a solution that could eventually also contain any kind of neutralizing component. It is intended for use in large atriums and buildings as well as in outdoor conditions. It is intended to provide a very fast and early response.

2 Fog Dynamics

Although most solid particles will be far from being spherical, liquid droplets are supposed to be approximately spheres, provided the air velocity around it is not large enough to modify its shape. Therefore, a dynamics model for spheres floating in the air will be a first approach to deal with. The dynamics of the fog may include mechanical and thermal phenomena including mass and heat transport and changes of phase. In this last case, evaporation will shift the size distribution toward smaller diameters, while condensation will do the opposite.

Mechanics of a sphere in a viscous flow is determined by Stokes law [3]. The force exerted by a fluid onto a sphere can be written as in Eq. (1):

$$\vec{F} = 6\,\pi R \mu\,\vec{V} \tag{1}$$

where R is the radius, μ the viscosity of the fluid (air in our case), and V the fluid velocity.

As a well-known consequence of this, the fall of final speed of a particle of density ρ_{p} and radius R can be written as in Eq. (2):

$$\vec{V}_p = \frac{2}{9}\frac{R^2 g\left(\rho_{\mathrm{p}} - \rho_{\mathrm{a}}\right)}{\mu} \tag{2}$$

where g is the gravity and ρ_{a} is the density of air—of the order of one thousandth of that of water.

It means that for a water droplet with a diameter of 2 μm falling in the air at room temperature, the final speed is about 1.2×10^{-4} m/s = 0.72 cm/min, while for a diameter of 10 μm, it will be around 3×10^{-3} m/s = 18 cm/min which is 25 times faster. This means that for a 3-m-high room, it will take around 15 min for all the 10 μm droplets to fall down to the floor.

3 Fog Dynamics Laboratory

As a part of the COUNTERFOG project [4], a laboratory for the study of fog dynamics has been designed and built. This laboratory is provided with a double test room, a control room, and a technical room. Insulated from the environment, temperature is controlled throughout thermally controlled walls, ceiling, and floor providing a very good thermal stability. Temperature can be statically controlled through its walls, ceiling, and floor in a range from 0 °C up to 45 °C with a precision ± 0.1 °C. Water and airflow as well as humidity in room and actual pressure in pipes are registered.

Provided with IP-65 lighting, thermal insulation, compressed air and pressurized liquid pipelines, air filtering, and collecting pool drainage, it can withstand still humid air even in condensing state. It is as well provided with sensors for air and water pressure and flow, temperature, humidity, droplet/particle size, and opacity as well as CO_2, CO, SO_2, CHx, and O_2 concentrations. Dynamics of fog, suspensions in the air and smoke, as well as their interaction can be experimentally measured.

An airborne particle counter Fluke model 985 based on optical counting complying ISO21501–4, JIS B9921, IEC/EN 60825–1:2007, and 21CFR1040.10 is used to measure the concentration of particles floating in air. Counting efficiency is 50% for 0.3 μm and 100% for particles greater than 0.45 μm per JIS. Other instruments measure number of particles floating in the air, living microorganisms, or chemical concentration.

4 Experimental Tests

The COUNTERFOG system for decontamination is based on the generation of a water-based fog. As a part of the mentioned project, the dynamics of water fogs has been experimentally studied for different temperature conditions for air and water.

After 30 s of actuation of a B½ nozzle under working parameters (water and air pressure under 12 bar), a fog is generated with diameter distribution centered in 5 μm as it can be seen in Fig. 1.

Values greater than 10^9 droplets/m^3 (with only 5 ml of liquid water per m^3) are typically obtained. Note that for 10-μm-sized droplets, only 8×10^8 droplets/m^3 store

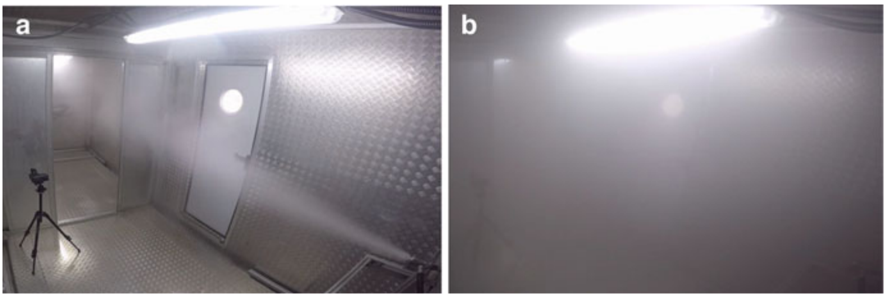

Fig. 1 Test room of the fog dynamics laboratory. (**a**) Test room before the fog was released. (**b**) Test room after 30 s of actuator

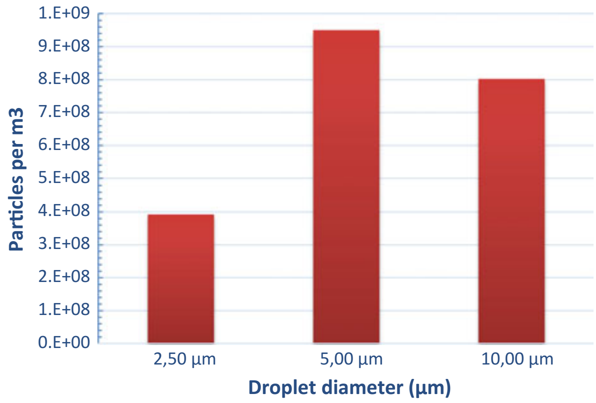

Fig. 2 Evolution of a 5- and 10-µm-sized droplets for several temperature conditions both of the environment and the water of which the fog is made

3.4 ml of liquid water per m^3. This means that a relatively large amount of water is collected on walls, ceiling, and floor during activation of the nozzle.

Typical fog dynamics include falling down, evaporation, and the subsequent reduction of droplet size [5]. Figure 2 shows the evolution of 5- and 10-µm-sized droplets for several temperature conditions both of the environment and the water of which the fog is made. A two-fold behavior is clearly observed. In the first part, the particle counter is saturated showing almost a horizontal straight line. Only when levels are lower than 10^8 particles/m^3 data are more accurate. An extrapolation of the evolution can be done to estimate that the original concentration of droplets is over $10^9 - 10^{10}$ particles/m^3.

According to the expression for the terminal speed, the time it takes for all the droplets from the ceiling to fall down the particle counter should be inversely proportional to the density of water and directly proportional to the viscosity of air. Paradoxically, the hotter the water is, the longer the droplets remain. The higher the temperature of water, the lower the density (decreasing about 0.7% from 10 to 40 °C) that makes 40 °C water fog to remain longer time than 10 °C water fog in the same environment. In the same way, the higher the temperature of air, the lower its viscosity is, and therefore the faster the droplets fall down.

5 Conclusion

As a conclusion it is demonstrated that a fog generated by COUNTERFOG is relatively stable with a droplet size distribution centered 5 µm in diameter. As it was theoretically expected, they slowly fall down while washing out the air. The system and dynamics have demonstrated to be stable from 10 to 40 °C for both water temperature and environment temperature as it can be seen in Fig. 3a–d.

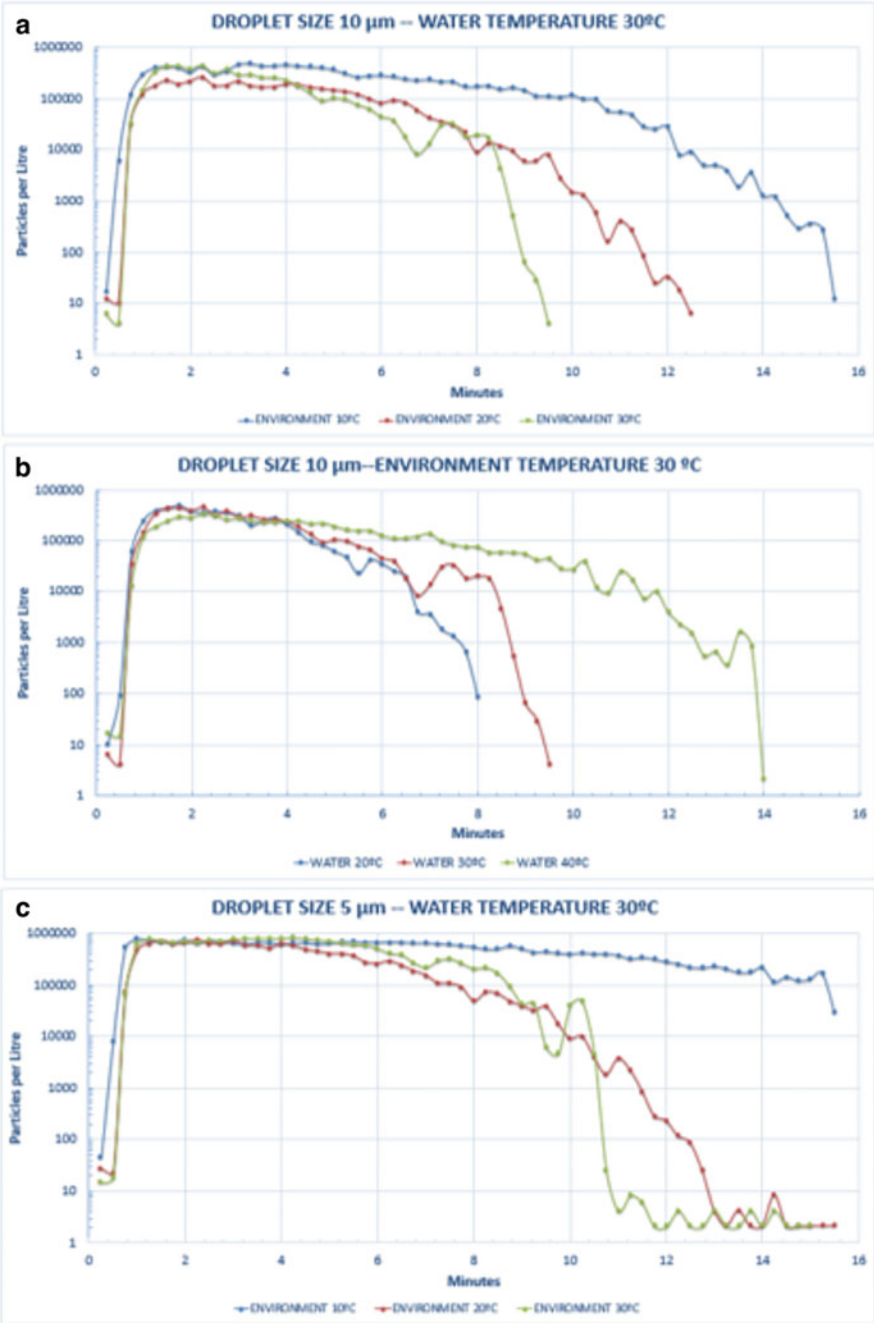

Fig. 3 (**a**) Measurement of the colliding time of droplets of 10 µm at different temperatures without COUNTERFOG application. (**b**) Measurement of the colliding time of droplets of 10 µm at different temperatures with COUNTERFOG application. (**c**) Measurement of the colliding time of droplets of 5 µm at different temperatures without COUNTERFOG application. (**d**) Measurement of the colliding time of droplets of 10 µm at different temperatures with COUNTERFOG application

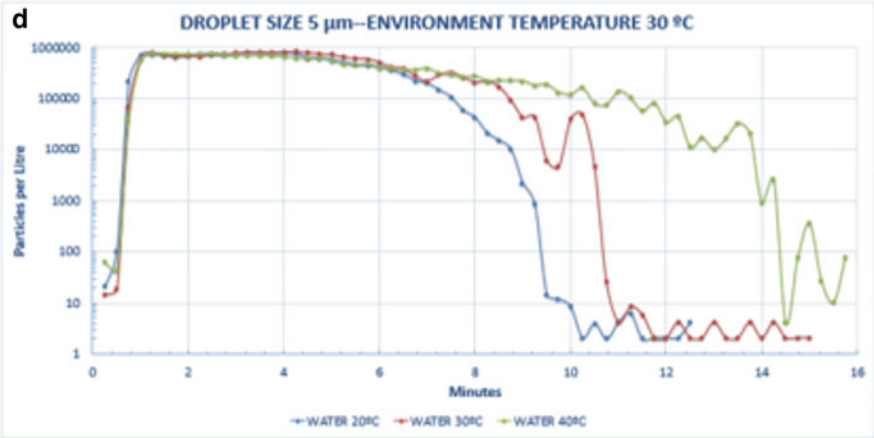

Fig. 3 (continued)

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