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Numerical Simulation of Sprinkler Performance

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Summary

Rapidly changing building designs, uses, materials, contents, fire protection and the general intermix of industrial/commercial and residential occupancies has created a need to understand the potential hazards and losses from fires and performance of fire protection systems under conditions that may not be specifically addressed by historic fire testing and codes. In the absence of an accurate understanding of potential fire events, excessively conservative decisions are made, usually increasing costs and creating barriers to innovation. It is impractical and in many cases too hazardous to physically test fire scenarios of interest. The only practical means to provide the insight and performance assurance historically provided by physical testing for the performance of fire protection systems is to develop computational simulations capable of creating virtual large scale fire experiments.

In cooperation with individual sprinkler manufacturers, the National Fire Sprinkler Association, Factory Mutual Research Corporation, and Underwriters Laboratories, an industrial fire simulation (IFS) system is being developed at NIST to generate predictions of fires in industrial facilities protected entirely or in part by automatic fire sprinklers. The IFS system consists of a large eddy simulation (LES) based fire model, with specified means to measure input data and deliver results. This technology will allow industry to gain valuable insight into the interaction of fire sprinklers with industrial storage fuel fires and other fire protection systems, such as roof vents and draft curtains. It will provide a new means to evaluate the facilities designs for cases that are not practical to test because of size, safety, or expense. This system will enable a movement from demonstrated performance by physical testing to reliable performance evaluation by engineering calculation.

Numerical Model

The numerical model at the heart of the industrial fire simulation system is based on techniques commonly used in computational fluid dynamics (CFD). Often these types of models are referred to as "field models" by the fire research community, to distinguish them from "zone models". The basic idea behind most CFD models is to divide the space of interest into small control volumes or computational cells, and in each cell compute the density, velocity, temperature, pressure and species concentration based on conservation laws of mass, momentum and energy. The accuracy of the results often depends on the number of cells used to discretize the volume of interest. The technique being applied in the IFS system is referred to as large eddy simulation (LES). The idea behind this approach is to divide the test space into as many cells as possible (in this case, hundreds of thousands to over a million) to resolve as much of the convective motion of the gases (air, smoke) as possible. In this way, much of the mixing of the hot gases from the fire with the cool surrounding air can be captured directly, reducing the dependence on empirical entrainment or turbulence parameters that are often subject to much debate and uncertainty.

The IFS system was used in the recent NFPA Research Foundation Sprinkler, Vent and Draft Curtain study [1]. For the modeling effort, the FMRC Standard Plastic Commodity, or Group A Plastic, was studied to determine its thermal properties and burning characteristics. The work started out in the cone calorimeter and LIFT (Lateral Ignition and Flame spread Test) apparatus, and eventually moved to slightly larger scale. The study continues, especially in regard to the burning behavior of the commodity in the presence of a sprinkler spray. Efforts are also underway to expand the list of materials from Group A Plastic to cover Commodity Classes I-IV and various other commodities.

Sprinkler Characterization

Accurate prediction of the activation and spray characteristics of automatic sprinklers is crucial in predicting the growth or suppression of fires. There are presently standard tests to determine some of the necessary parameters needed by the numerical model to predict sprinkler activation, but as yet no standard test methods for obtaining a given sprinkler's droplet size distribution and initial spray characteristics.

The temperature of the sensing element of an automatic sprinkler is estimated from the differential equation presented by Heskestad and Bill [2]

$$\frac{dT_l}{dt} = \frac{\sqrt{u}}{\mathrm{RTI}}(T_g - T_l) - \frac{C}{\mathrm{RTI}}(T_l - T_m) \qquad (1)$$

where T_l is the link temperature, T_g is the gas temperature in the neighborhood of the link, T_m is the temperature of the sprinkler mount, and u is the gas velocity. The thermal sensitivity of the sprinkler is indicated by the value of RTI. The heat lost to the mount due to conduction is characterized by the "C-factor", C. A heated wind tunnel (plunge test) is used to determine both of these parameters by creating an environment in which the air velocity and temperature, plus the mount temperature, are held at constant values. Work is presently underway at the University of Maryland by Prof. Marino Di Marzo to add a third term to Eq. (1) that will account for cooling of the sprinkler element by small water droplets carried aloft by the buoyant fire plume after the activation of the first sprinkler. It is believed that the phenomenon known as "sprinkler skipping" is caused by the wetting of unactivated sprinklers by previously activated sprinklers. To quantify this effect, a vertical wind tunnel has been constructed at Maryland, through which hot gases from a burner pass over an array of small atomizing water nozzles. The small droplets are deposited on various heat sensitive instruments and ultimately actual sprinklers. Early results indicate that the cooling effect of small amounts of water on devices with comparable RTI values to standard response sprinklers is substantial, leading to delays or preventing the activation of the devices.

Because second and third ring sprinklers are very sensitive to small droplets of water that may be carried aloft by the fire plume, it is vital for accurate prediction of this phenomenon that the droplet size distribution from a given sprinkler be characterized. The droplet size distribution of the sprinkler spray is expressed in terms of its Cumulative Volume Fraction (CVF), a function that relates the fraction of the water volume (mass) transported by droplets less than a given diameter. Typically, this function is represented very well by a combination of log-normal and Rosin-Rammler distributions [3]

$$F(d) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^d \frac{1}{\sigma\, d'} \, e^{-\frac{[\ln(d'/d_m)]^2}{2\sigma^2}} \, dd' & (d \leq d_m) \\ 1 - e^{-0.693\left(\frac{d}{d_m}\right)^\gamma} & (d_m < d) \end{cases} \tag{2}$$

where d_m is the median droplet diameter (*i.e.* half the mass is carried by droplets d_m or smaller in diameter), and γ and σ are empirical constants equal to about 2.4 and 0.58, respectively. The median drop diameter is a function of the sprinkler orifice diameter, operating pressure, and geometry. Research at Factory Mutual has yielded a correlation for the median droplet diameter [4]

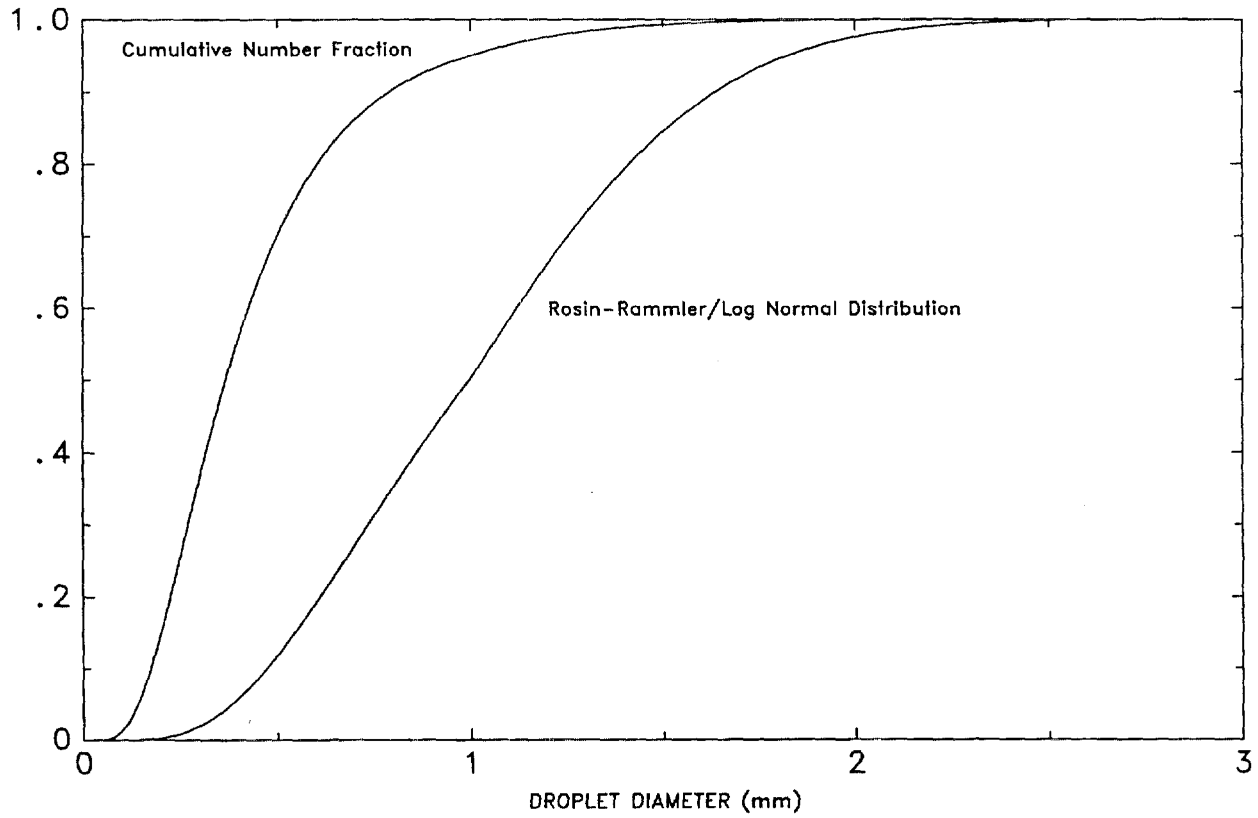

FIGURE 1: Cumulative Volume Fraction and Cumulative Number Fraction functions of the droplet size distribution from a typical industrial scale sprinkler. The median diameter d_m is 1 mm, $\sigma = 0.58$ and $\gamma = 2.43$.

$$\frac{d_m}{D} = c\,\mathrm{We}^{-\frac{1}{3}} \tag{3}$$

where D is the orifice diameter of the sprinkler and c is a sprinkler dependent constant. The

Weber number, the ratio of inertial forces to surface tension forces, is given by

$$\mathrm{We} = \frac{\rho_w U^2 D}{\sigma_w} \tag{4}$$

where ρ_w is the density of water, U is the water discharge velocity, and σ_w is the water surface tension (72.8×10^{-3} N/m at 20°C). The discharge velocity can be computed from the water flow rate, which in turn is computed from the sprinkler's operating pressure Δp and K-factor:

$$\pi \left(\frac{D}{2}\right)^2 \rho_w U = \dot{m}_w = K\sqrt{\Delta p} \tag{5}$$

Combining these formulae yields a correlation for the median drop diameter

$$d_m = c \left(\frac{\rho_w \sigma_w \pi^2}{16}\right)^{\frac{1}{3}} \frac{D^2}{(K^2 \Delta p)^{\frac{1}{3}}} \tag{6}$$

where all of the parameters except c are reported by the sprinkler manufacturer. FM reports that c appears to be independent of flow rate and operating pressure. Three different sprinklers were tested in the study with orifice diameters of 16.3 mm, 13.5 mm, 12.7 mm and c values of approximately 4.3, 2.9, 2.3, respectively. The strike plates of the two smaller sprinklers were notched, while that of the largest sprinkler was not.

There are several techniques used to measure water droplets from sprinklers. The device used by Factory Mutual in the above cited research was an Optical Array Probe (OAP). The instrument consists of an elliptical ribbon of helium-neon laser light that illuminates a photodiode detector array. Droplets pass between the laser and detectors, and a maximum horizontal drop width (diameter) is determined for each droplet from its shadowing pattern on the photodiodes. The shadows are formed by droplet diffraction, refraction, and absorption. The droplet diameter determined by the OAP is equal to the sum of the widths of the blocked diodes; a diode is considered blocked if its incident laser light intensity is reduced by a given fraction. Presently, Underwriters Laboratories is bringing on-line a Phase Doppler Particle Analyzer (PDPA). This method is based upon the principles of light scattering interferometry. Measurements are made at a small, non-intrusive optical probe defined by the intersection of two laser beams. As a droplet passes through the probe volume, it scatters light from the beams and creates an interference fringe pattern. A receiving lens located at an off-axis collection angle projects a portion of this fringe pattern onto several detectors. Each detector produces a Doppler burst signal with a frequency proportional to the droplet velocity. The phase shift between the Doppler burst signals from the different detectors is proportional to the size of the spherical droplets.

Sprinkler Skipping

Even though much of the research described above is still ongoing, it is instructive to perform some preliminary calculations that will hopefully guide the research. Consider an 18 m (60 ft) high enclosure with a large floor area and standard response 17/32 in sprinklers (RTI 110 $(\mathrm{m\,s})^{\frac{1}{2}}$, 200 $(\mathrm{ft\,s})^{\frac{1}{2}}$) spaced 3 m (10 ft) apart near the ceiling. A rapidly growing fire

(32 MW in 75 s) is positioned at the floor directly beneath one sprinkler. A numerical grid of dimension 96 by 96 by 54 is used to model a volume of dimension 30.5 m by 30.5 m by 18.3 m. The first sprinkler activates at 63 s. The sprinkler flows at 30 gpm, and the median volumetric diameter based on Eq. (6) is 1.3 mm. The second ring of sprinklers is skipped, and sprinklers in the third ring begin activating at 100 s (see Fig. 2). The reason for the skipping can be found by examining the water droplet concentration and temperature near a second and third ring sprinkler. At the second ring sprinkler, 10 ft away from the first activated sprinkler, the amount of water present is enough to cool the sprinkler element sufficiently to prevent its activation. At the third ring, much of the water carried aloft by the plume and ceiling jet has evaporated. Since the gas temperature at the third ring is still high enough to activate the sprinkler, it does.

This calculation is based on some preliminary measurements. As the research unfolds, better estimates of sprinkler skipping and other phenomena will be made with the numerical model.

References

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