THEORETICAL CONSIDERATIONS REGARDING FIRE SAFETY USING SPRINKLERS INSTALATIONS

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Abstract: A fire sprinkler is the part of a sprinkler fire system that discharges water when the effects of a fire have been detected, such as when a predetermined temperature has been reached. The paper contains theoretical aspects of modern fire security systems (sprinkler systems), aspects which can be used in order to improve sprinklers quality, reduce production costs and also, to explain the operation processes that are evolving from the moment that the temperature activates the sprinkler, in chronological order.

Keywords: sprinkler, water drops, activation, distribution, transfer, energy.

Fire sprinklers can be automatic or open orifice. Automatic fire sprinklers operate at a predetermined temperature, utilizing a fusible bulb, a portion of which melts, or a frangible glass bulb containing liquid which breaks, allowing the plug in the orifice to be pushed out of the orifice by the water pressure in the fire sprinkler piping, resulting in water flow from the orifice.

The water stream impacts a deflector, which produces a specific spray pattern designed in support of the goals of the sprinkler type (i.e., control or suppression). Modern sprinkler heads are designed to direct a spray downward. Each individual automatic fire sprinkler operates individually in a fire. Contrary to as often shown to the people, the entire sprinkler system does not activate, unless the system is a special deluge type.

Open orifice sprinklers are only used in water spray systems or deluge sprinklers systems. They are identical to the automatic sprinkler on which they are based, with the heat sensitive operating element removed.

The effects of a sprinkler unlocking simulation involve several steps: anticipation of the activation moment, calculation of drops trajectory and water falling as drops on the burning material.

1. SPRINKLERS ACTIVATION

The unloching temperature for a sprinkler can be expresed using the Heskestad and Bill, [1], which uses terms that depends on the heat and radiation process and also on the cooling with the water drops that are drawn into the gas curent, influenced by the already activated sprinklers.

$$\frac{dT_l}{dt} = \frac{\sqrt{|\mathbf{u}|}}{\mathrm{RTI}}\left(T_g - T_l\right) - \frac{C}{\mathrm{RTI}}\left(T_l - T_m\right) - \frac{C_2}{\mathrm{RTI}}\beta|\mathbf{u}| \tag{1}$$

in which T_l represents the unlocking temperature, T_g is the gas temperature near the bulb, T_m is the sprinklers body temperature (the room temperature), β is the water volumic concentration into the gas curent. The detector (bulb) sensitivity is given by the number RTI, **u** is the water relese velocity.

The heat transfer from the sprinkler body to the bulb is given by the "*C* factor". C_2 was determined by DiMarzoand it is a constant for all types of sprinklers [2].

2. SPRINKLER DROPS DISTRIBUTION

Once that the sprinkler was activated, a number of water drops that are falling on the ground or on the hotbed, is analysed. To calculate the drops trajectory, it must be established the original size and velocity of each drop by using stochasting distributions (CVF-Cumulative Volume Function). The Mutual Factory researchers sugested that CVF for an industrial sprinkler can be represented by a normal logarithmical distribution,[3],

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

in which d_m is the medium drop diameter and d is the drop diameter, γ and σ are about 2,4 and 0,6. The medium drop diameter can be determined using the sprinkler diameter, working preasure, and the sprinkler geometry.

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

in which D is the sprinkler diameter, α is a geometry constant. The Weber number, the inertness forces divided by the forces of the superficial tensions, is given by

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

in which ρ_w is the water density, U is water falling velocity, σ_w is the water superficial tension ($72{,}8 \cdot 10^{-3}$ N/m at 20^0C). Water velocity can be calculated from the capacity formula which depends on the working preasure and on the K sprinkler factor. In the numerical algorithm, the size of the sprinkler drop was chosen so that the distribution (2) is respected. Density of probability function is defined for the drop diameter,[4],

$$f(d) = \frac{F'(d)}{d^3} \Bigg/ \int_0^\infty \frac{F'(d')}{d'^3} dd' \tag{5}$$

The drops diameters are selected aleatory, υ is a aleatory variable

$$\nu(d) = \int_0^d f(d')dd' \tag{6}$$

Because not every drop can be fallowed, there are fallowed about 1000 drops per sprinkler per second. The selection procedure is the fallowing: we presume that the water has $\dot{m}$ capacity and that the time between the drop entrance and the numerical simulation is *δt,* for a number of N drops, then we calculate the weight constant C from the mass balance.

$$\dot{m}\,\delta t = C \sum_{i=1}^{N} \frac{4}{3} \pi \rho_w \left(\frac{d_i}{2} \right)^3 \tag{7}$$

The transfered mass and heat for each drop will be multiplied by the weight factor *C*.

3. DISPLACEMENT OF THE WATER DROPS IN THE AIR

For a sprinkler spray of drops, **f** represents the moment transfer from the water drops to the burning gases,[5],

$$\mathbf{f} = \frac{1}{2} \frac{\sum \rho C_D \pi\, r_d^2 \left(\mathbf{u}_d - \mathbf{u} \right) \left| \mathbf{u}_d - \mathbf{u} \right|}{\delta x\, \delta y\, \delta z} \tag{8}$$

in which C_D is the braking coefficient, r_d is the drop ray, $\mathbf{u}_d$ is the drop velocity, $\mathbf{u}$ is the gas velocity, ρ is the gas density, $\delta x \delta y \delta z$ is the network capacity. The drop trajectory is given by:

$$\frac{d}{dt} \left(m_d \mathbf{u}_d \right) = m_d \mathbf{g} - \frac{1}{2} \rho C_D \pi\, r_d^2 \left(\mathbf{u}_d - \mathbf{u} \right) \left| \mathbf{u}_d - \mathbf{u} \right| \tag{9}$$

in which m_d is the weight of the drop. The braking coefficient depends on the local Reynolds number:

$$C_D = \begin{cases} 24/\mathrm{Re} & \mathrm{Re} < 1 \\ 24\left(1 + 0.15\,\mathrm{Re}^{0.687}\right)/\mathrm{Re} & 1 < \mathrm{Re} < 1000 \\ 0.44 & 1000 < \mathrm{Re} \end{cases} \tag{10}$$

$$\mathrm{Re} = \frac{\rho \left| \mathbf{u}_d - \mathbf{u} \right| 2 r_d}{\mu} \tag{11}$$

in which μ is the air dynamic viscosity.

4. THE MASS AND ENERGY TRANSFERED FROM THE DROPS

In the fallowing equation is given the relation for the velocity of the drop lost mass

$$\frac{dm_d}{dt} = -2\pi\, r_d \mathrm{Sh} \rho D \left(Y_d - Y_g \right) \tag{12}$$

in which d and g are refering to the drop and the gas; m_d is the drop weight; D is the vapors difusion coefficient in the air, Y is the mass of the water vapor, Sh is the Sherwood number of the drop, given by an equation that includes Reynolds and Schmidt numbers:

$$\mathrm{Sh} = 2 + 0.6\mathrm{Re}^{\frac{1}{2}}\mathrm{Se}^{\frac{1}{3}} \tag{13}$$

Y_g results from Clausius – Clapeyron equation. To calculate the capacity of the water vapors we will use the the mass of the water vapor expresion, [5],

$$\begin{aligned} Y_d &= \frac{X_d}{X_d\left(1 - M_a/M_w\right) + M_a/M_w} \\ X_d &= \exp\left[\frac{h_v M_w}{\mathcal{R}}\left(\frac{1}{T_b} - \frac{1}{T_d}\right)\right] \end{aligned} \tag{14}$$

in which X_d is the capacity of the water vapors, h_v is the vaporating heat, M_w is the molecular mass of the drop, M_a is the molecular mass of the air, $\mathcal{R}$ is the universal gas constant, T_b is the boiling temperature of the water and T_d is the drop temperature. The drop is heating because of the heat convection transfer through the drop surface from which we substract necessary energy for water vaporisation:

$$m_d c_{p,w}\frac{dT_d}{dt} = A_d h_d\left(T_g - T_d\right) - \frac{dm_d}{dt}h_v \tag{15}$$

in which $c_{p,w}$ is the specific heat of the water, $A_d = 4\pi r_d^2$ is the drop surface, h_d is the heat transfer coefficient given by:

$$h_d = \frac{\mathrm{Nu}k}{2r_d}; \qquad \mathrm{Nu} = 2 + 0.6\mathrm{Re}^{\frac{1}{2}} + \mathrm{Pr}^{\frac{1}{3}} \tag{16}$$

in which Nu is the Nusselt number, k is the air thermal conductivity, Pr is the Prandtl number and is about 0,7 for air. Sh is almost the same as Nusselt number, 0,6, comparing to 0,7 for Prandtl number.

Ultimately, the exchange of mass and energy between the drop and the gas leads to

$$\nabla \cdot \mathbf{u} = \ldots + \frac{\mathcal{R}}{\gamma p_0}\left(\rho \sum Y_i \big/ M_i\right)\frac{\partial T}{\partial t} + \frac{T}{M_w}\dot{m}_w^m \tag{17}$$

in which $\dot{m}_w^m$ represents the water vaporisation velocity. We asume that the liquid water drops are not in a volume, which simplfy the analysis.

5. INTERACTION BETWEEN THE DROPS AND THE THERMAL RADIATION

If the absortion and emisions in the gas phase are temporary negligible in order to simplify the equation, the transport equation by radiation becomes:

$$s \cdot \nabla I_\lambda(\mathbf{x},s) = -[\kappa_d(\mathbf{x},\lambda)+\sigma_d(\mathbf{x},\lambda)]I(\mathbf{x},s)+\kappa_d(\mathbf{x},\lambda)I_{b,d}(\mathbf{x}\lambda)+$$
$$+\frac{\sigma_d(\mathrm{x},\lambda)}{4\pi}\int_{4\pi}\Phi(s,s')I_\lambda(\mathrm{x},s')d\Omega' \tag{18}$$

in which κ_d is the drop absorption coefficient, σ_d is the drop coefficient, $I_{b,d}$ is the emision of the drops. **Φ** *(s, s')* is the leakage function, **x** is a position vector and $N(\mathbf{x})$ is the number of drops.
The local absobtion coefficient are calculated from the local density expresion of the number $N(\mathbf{x})$ and the medium diameter $d_m(\mathbf{x})$

$$\begin{aligned}\kappa_d(\mathbf{x},\lambda) &= N(\mathbf{x})\int_0^\infty f(r,d_m(\mathbf{x}))C_a(r,\lambda)dr\\ \sigma_d(\mathbf{x},\lambda) &= N(\mathbf{x})\int_0^\infty f(r,d_m(\mathbf{x}))C_s(r,\lambda)dr\end{aligned} \tag{19}$$

in which r is the ray of the drop, are the sections of absorption and leakage given by the Mie theory, [6].
The integral is proximated by deviding the total solid angle 4π by an "advanced angle" $\delta\Omega^l$ and an "ambiental angle" $\delta\Omega^* = 4\pi - \delta\Omega^l$. Inside of δΩ, the intensity I_λ (x,s) is approximated as

$$U^*(\mathbf{x},\lambda) = \frac{U(\mathbf{x},\lambda) - \delta\Omega^l I_\lambda(\mathbf{x},s)}{\delta\Omega^*} \tag{20}$$

in which U (x) is the integrated total intensity. The leakage integral is:

$$\frac{\sigma_d(\mathbf{x},\lambda)}{4\pi}\int_{4\pi}\mathbf{\Phi}(s,s')I_\lambda(\mathbf{x},s')d\Omega' = \sigma_d(\mathbf{x},\lambda)\left[\chi_f I_\lambda(\mathbf{x},s)+(1-\chi_f)U^*(\mathbf{x})\right] \tag{21}$$

in which $\chi_f = \chi_f(r,\lambda)$ is a part of the initial intensity inside the solid angle $\delta\Omega^l$. It is defined a section of effective leakage coefficient:

$$\overline{\sigma}_d(\mathbf{x},\lambda) = \frac{4\pi N(\mathbf{x})}{4\pi - \delta\Omega^l}\int_0^\infty (1-\chi_f)C_s(r,\lambda)dr \tag{22}$$

RTE spraying becomes:

$$s \cdot \nabla I_\lambda(\mathrm{x},s) = -\left[\kappa_d(\mathrm{x},\lambda)+\overline{\sigma}_d(\mathrm{x},\lambda)\right]I(\mathrm{x},s)+\kappa_d(\mathrm{x},\lambda)I_{b,d}(\mathrm{x},\lambda)+\frac{\overline{\sigma}_d(\mathrm{x},\lambda)}{4\pi}U(\mathrm{x},\lambda) \tag{23}$$

This equation can be integrated in order to obtain the specificall RTE band. After the bands integration, RTE spraying for *n* band becomes:

$$s \cdot \nabla I_n(\mathrm{x},s) = -\left[\kappa_{d,n}(\mathrm{x})+\overline{\sigma}_{d,n}(\mathrm{x})\right]I_n(\mathrm{x},s)+\kappa_{d,n}(\mathrm{x})I_{b,d,n}(\mathrm{x})+\frac{\overline{\sigma}_d(\mathrm{x},\lambda)}{4\pi}U_n(\mathrm{x}) \tag{24}$$

It is very important for the producers of fire safety equipment to use virtual models in designing modern sprinkler systems, a work that is posssible only by studying the theoretical considerations of sprinklers instalations.

6. CONCLUSIONS

The paper refers to the most important features regarding fire security systems which can be used in order to improve sprinklers quality, reduce production costs and also, to explain the operation processes that are evolving from the moment that the temperature activates the sprinkler, in chronological order.

Automatic fire sprinklers utilizing frangible bulbs follow a standardized color coding convention indicating their operating temperature. Activation temperatures correspond to the type of hazard against which the sprinkler system protects. Residential occupancies are provided with a special type of fast response sprinkler with the unique goal of life safety.

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