An Engineering Tool for Evaluation of Fire Suppression System Performance

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Abstract*– In this paper is presented a description of a new engineering tool for evaluation of water-based fire suppression system (sprinklers), based on a high fidelity description of initial characteristics of the jet (sphere initialization from 4S device). The proposed model has three principal innovative advantages over classical Lagrangian approach: i) Speed: Fast calculation of the spray anywhere; ii) Description of the spray in the phase space, which turns the description of the spray into a time-independent, enabling compact, fast, and useful reconstruction of the spray; iii) Description of the spray as a set of 2D spray dispersion fields allowing considerable simplification of the spray field analysis. As results, a 2D visualization of the spray (volume flux), and an example of volume flux into a surface are reported.

Keywords—Sprinkler, fire-protection, BIM.

I. Introduction

Fire Suppression systems are widely used in order to ensure, protect people and reduced property loss. These systems, generally water based sprays (sprinklers), are installed throughout the world and their performance relies on their capacity to effectively delivery water to the fire source for extinguishment and to nearby surfaces to protection. A comprehensive overview of water based fire suppression is provided in Grant et al. [1].

There are on average over 120 million square feet of new construction each year within the U.S. alone. Nearly every square foot of this space must meet fire protection and life safety standards, which are established by the National Fire Protection Association (NFPA) and adopted in the U.S. by local and state jurisdictions (and by many international jurisdictions as well). The NFPA standards focus on designing for safety, which may often run at odds with aesthetic and functional design imperatives. Currently, the design of fire suppression systems is mostly determined prescriptively with standardized acceptance based on empirical requirements, i.e. there are a limited number of empirically standardized cases.

On the other side, the fire protection requirements can limit the ability of the architect (e.g. large open atriums), the building service engineer (e.g. ducts and pipe routing), or industrial engineer (e.g. storage configurations) to design freely limiting the full potential of the space in form and function. For example, seemingly trivial building design features involving sloped or curved ceilings in storage occupancies (i.e. warehouses) are not permitted by the standards without a performance based analysis which often requires an extensive and expensive fire testing program (in the absence of reliable and accepted analytical engineering design tools) to demonstrate an 'equivalent level of protection' to that offered by a standard rectangular building. The impact of design features such as sloped or curved ceilings, cloud ceilings, obstructions and other rudimentary design features on sprinkler performance is simply not understood, driving this potentially expensive and often empirical design methodology when prescriptive guidance is not available. Only now are measurement and analytical methods available to provide sufficient fidelity to unravel the complex spray patterns and their interactions with the built environment [2].

Recently, high fidelity Computational Fluid Dynamics (CFD) models have been adopted for performance based evaluation of fire protection engineering systems for designs laying outside of the empirically based range of applicability of the codes and standards. This newfound ability to characterize the sprinkler spray with unprecedented fidelity has filled a major gap that previously prevented detailed fire suppression analysis [3]. Even so, CFD methods often requires thousands of CPU hours on computer clusters and need well defined initial conditions. While the CFD based fire suppression analysis approach is useful (especially in its ability to include high fidelity fire interactions) as an R&D tool, it falls short of filling the design tool gap and becoming a viable alternative for fire protection engineers and designers.

Taking into account increasingly innovative building designs such as 'green' buildings, 'tall' buildings, 'mega' warehouses, and 'smart' buildings present design challenges outside the range of applicability of codes and standards, there is a need of a method for quickly, effectively and optimally evaluate water based fire suppression system; a model to be easily used by engineers and architects, and to be include on widely and modern Building Information Modeling (BIM) frameworks with physics based simulation, visualization, and optimization of fire safety system performance. This need has been studied during more than a decade in the *Department of Fire Protection Engineering*, with the support of NSF (U.S National Science Foundation), leading an important advance on the state-of-art of sprinklers systems evaluation methods [4-6], discoveries [7], and recently the creation of a tech Startup (CSS: *Custom Spray Solutions Inc.*). During these years of development and discoveries, an essential answer to the critical fire suppression analysis question "What is the spray?" have been provided throughout the development of a "Spally-resolved Spray Scanning System" or "4S" and the analysis framework.

The 4S synthesizes spray measurement and analysis frameworks as illustrated in Fig. 1, providing high-fidelity spray characteristics enabling evaluation of component or system level performance of fire sprinklers. The 4S consists of 1) flow control and conditioning; 2) mechanical sphere patternation; 3) integral line patternation; and 4) optical sphere

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patternation systems. These systems are comprised of and integrated by automation and synchronization; instrumentation; data acquisition; and analysis processes. The patternation systems (2–4) provide important information about the spray details representing terabytes of data and millions of drop size realizations for a given sprinkler. The details are provided in references [4-6].

While the 4S provides unprecedented fidelity leaving nothing to guess about spray details, another fundamental question has to be answered to achieve a complete evaluation of water based fire suppression system: "Where does the spray go?". In this context, this paper describes a new engineering tool providing a fast and flexible global sprinkler spraying performance (e.g. local water delivery rates and spray characteristics on any number of arbitrary surfaces of interest within the spray), seeking to serve as a part of a quickly, effectively and optimally method to evaluate water based fire suppression system.

II. MODEL DESCRIPTION

Evaluation of sprinkler spraying performance is challenging due to the complex spatio-stochastic behavior of the spray first generated by the sprinkler and then dispersed into its surroundings. Every second, millions of drops varying in size and velocity are delivered to target surfaces, making the complete characterization of the spray at every location a difficult task, taking into account the fact that the spray generating from each sprinkler is unique. While the information of spray (diameter of drops, velocity and angle) at each location and time would require an extremely large amount of data (order of Terabytes), statistical analysis of spatio-stochastic spray behavior is required.

The engineering model provides a useful solution for this problem. It is first based on a compact set of statistical parameters allowing the complete description of the spray in an *initialization sphere*, obtained with the 4S device:

A. Inputs from 4S: Spray Injection Boundary

The engineering model uses the high fidelity initial conditions obtained with the 4S device. This inputs are defined with physical measurements of the water delivered to both the mechanical sphere patternator (2 in fig.1a) and optical sphere patternator (4 in fig.1a). From the mechanical sphere patternator, the volume flux through the surface of the initialization sphere $\dot{V}''(\theta,)$ is measured, where θ is the elevation angle and ϕ is the azimuthal angle, with the origin on the sprinkler. From the optical sphere patternator, high resolution images of the spray are captured using a laser-based shadowgraphy imaging technique. This images are evaluated to generate a representative drop diameter, $d_{v50}(\theta,\phi)$, drop size distribution parameter, $\Gamma(\theta,\phi)$, and reference velocity, $u_0(\theta,\phi)$ at every measurement location, being the input (*initialization sphere*) for the reduced order model possessing the local characteristics of the sprinkler. An example of volume flux parameters over an initialization sphere is presented on fig.2 . The local spray measurements captured with each subsystem and used to develop the complete spray characterization are summarized in Table 1.

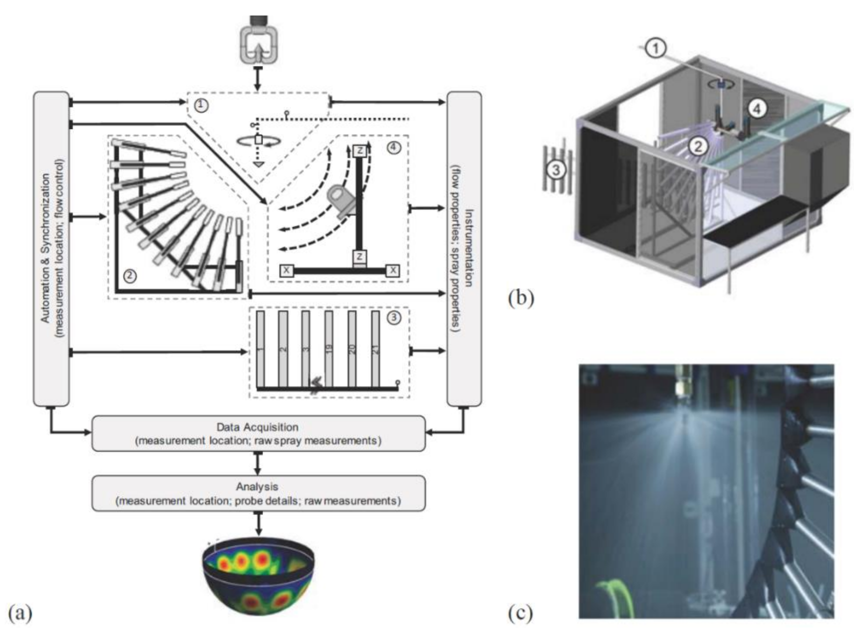

Figure 1. Spatially-resolved Spray Scanning System (4S); (a-b) measurement processes (rectangles) and system elements (dashed regions); 1) flow control and conditioning; 2) mechanical sphere patternation; 3) integral line patternation; 4) optical sphere patternation; (c) photograph of facility in operation. [4]

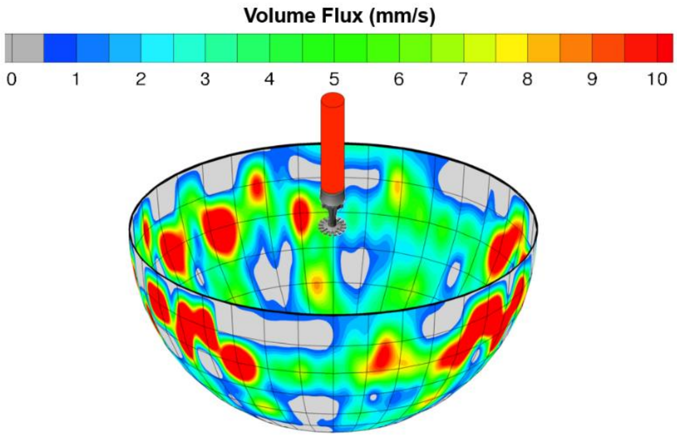

Figure 2. Volume flux parameters over an initialization sphere

TABLE I
INPUT PARAMETERS FROM 4S DEVICE.

Subsystem	Parameter	Description
Mechanical Sphere Patternator (2)	$\dot{V}''(\theta,\phi)$	Volume flux (mm/s)
Optical Sphere Patternator (4)	$dv_{50}(\theta,\phi)$	Volume median diameter (mm)
Optical Sphere Patternator (4)	$\Gamma(\theta,\phi)$	Distribution parameter
Optical Sphere Patternator (4)	$v_0(\theta,\phi)$	Reference velocity (m/s)

For each position (θ,ϕ) in the initialization sphere, the quantity of volume delivered can be calculated from the cumulative drop distribution function $f_v(\theta,\phi,d)$ [5]:

$$F_v(\theta,\phi,d) = F_{v,\Omega}(\theta,\phi)\, F_{v,d}(d \mid \theta,\phi) \tag{1}$$

Where d is the drop diameter, and Ω is the solid angle. In Equation 1, $F_v(\theta,\phi,d)$ is decomposed into two parts: The first, $F_{v,\Omega}(\theta,\phi)$, is the cumulative volume flow, and describes the probability of any drop being at a given initial location. This is described in terms of the local 4S measured volume flux $\dot{V}''(\theta,\phi)$ (from the mechanical sphere patternator).

The second part $F_{v,d}(d \mid \theta,\phi)$ describes the probability of a particular drop being at a given initial location, and can be expressed in terms of similarly measured local drop size distributions $d_{v50}(\theta,\phi)$ and $\Gamma(\theta,\phi)$ (from the optical sphere patternator) using a Rosin-Rammler distribution, so $F_{v,d}(d \mid \theta,\phi) = f(d_{v50},\Gamma|\theta,\phi)$. These compact distributions are used to generate drops, which are subsequently tracked with phase transformed trajectory analysis. The details about how $F_v(\theta,\phi,d)$ and $F_{v,\Omega}(\theta,\phi)$ are calculated can be found in reference [4].

B. *Classic Lagrangian Formulation*

The conventional Lagrangian tracking formulation is described by:

$$\frac{d\vec{v}}{dt} = \vec{g} - \frac{3}{4d}\frac{\rho}{\rho_w} C_d |\vec{v}|\vec{v} \tag{2}$$

Where ρ is the density of the air, ρ_w is the density of the water, C_d the drag coefficient and $\vec{v}$ 3D is the velocity vector. The principal disadvantage of this formulation is that it needs to be resolved in time. This requirement poses a handicap when considering the end goal of accessing trajectory properties at each spatial location (velocity and angle): The time calculation is finally not useful, as the spray performance analysis is evaluated based on steady state operational performance.

C. *2D Phase Space formulation*

Fig.3 shows a scheme of a single trajectory defined on the 2D phase space. The trajectory properties are defined in terms of the local velocity vector $\vec{v}$ and the local angle between the velocity vector and the vertical ψ. This formulation is more consistent with the natural movement of the drops falling down from a specific injection angle θ (at a plane defined by a constant azimuthal angle ϕ).

From this 2D framework, we can now define the follow set of equations deduced from equation (2):

$$v\frac{dv}{dt} = gw - \frac{3}{4d}\frac{\rho}{\rho_w} C_d v^3 \tag{3}$$

$$\frac{dw}{dt} = g - \frac{3}{4d}\frac{\rho}{\rho_w} C_d v w \tag{4}$$

Here, $v = |\vec{v}|$ and w is the downward directed vertical velocity component. On the initiating sphere, $v = v_0$ and $w = v\cos(\theta)$. These initial conditions suggest that a better choice of variables is v and $\mu = \cos(\psi)$. Moreover, as mentioned above, since we are only interested in the steady state operation of the spray, the time variable is irrelevant. Thus, introducing a dimensionless speed $V = v/v_0$, and dividing equation (3) by equation (4), the velocity characteristic is determined from the solution:

$$\frac{1}{V}\frac{dV}{d\mu} = \frac{\mu - \beta V^2}{(1-\mu)(1+\beta V^2)} \tag{5}$$

On the initial sphere, $V = 1$ and the angular variable $\mu = \mu_0$ where $-1 < \mu_0 < 1$ and is defined by $\mu_0 = \cos(\theta)$. The solutions depend only on the initial angle μ_0 (or θ) and a single parameter β defined as:

$$\beta = \frac{3\rho C_d v_0^2}{4d\rho_w g} \tag{6}$$

Equation (5) is the (μ, V) phase plane representation of the spray. It is interesting to note that all solutions proceed from a set of initial points $(\mu_0, 1)$ in the initialization sphere, to a single sink located at $(1, \frac{1}{\sqrt{\beta}})$, when $\mu - \beta V^2 = 0$ and $\psi = 180°$. The sink point represents the asymptotic state where the droplet is falling vertically at its constant terminal speed.

This dimensionless phase transformation reduces the problem to determining a small number of trajectories, which can be pre-solved and tabulated once and for all over a drop size space valid for any sprinkler. Critically informed by the 4S measured sprinkler database, drop distribution functions for a particular sprinkler are used to initiate the solution.

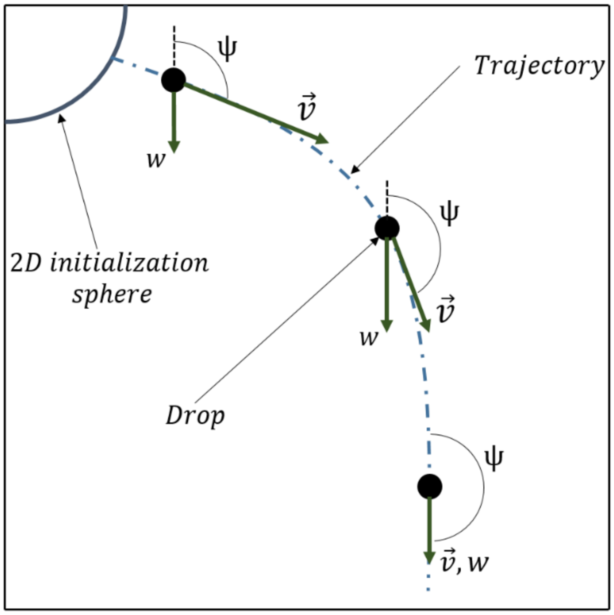

Figure 3. Spatially-resolved 4S measurements of spray characteristics: volume flux.

Determining the wetting performance or flux becomes a simplified 2D course intersection problem in any given azimuthal plane providing remarkable speed improvements over the 3D Lagrangian particle tracking formulation (as much as 500 times).

In contrast with the classic Lagragian formulation, the 2D phase transformed trajectory analysis, the key innovation of the *ROM* are:

1. The spray dispersion can be described in the phase space in terms of three key independent features with a time independent approach, with a compact set of input features. The recognition of this relationship and the formulation of the phenomena, turns the description of the spray into a time-independent, which enables compact, fast, and useful reconstruction of the spray.
2. It has been recognized that dispersion, despite highly 3D spray field features, can be described as a set of 2D spray dispersion fields (governed by Reduced Order Modeling, of one-way drag coupling with the quiescent surroundings) allowing considerable simplification of the spray field analysis.

II. Results

Fig.4 reports a sample azimuthal plane of trajectories informed by 4S measurements (i.e. sprinkler database) initiating from various elevation angles highlighting flux reduction (reduced opacity) and velocity reduction (from red to blue). These planes can also be calculated about the 360 ° sprinkler azimuth to calculate the 3D spray field. We can see that the patterns generated by the trajectories and initialized by the 4S *Spray Injection Boundary* are consistent in, vertical planes.

While the definition of the spray into Cartesian space is important for visualization and design, it is vital to be able to deal with trajectory interception with surface for two fundamental reasons: i) It is essential for water based spray evaluation to calculated the volume flux $\dot{V}$" in desired surfaces, taking into account that the performance of water based sprays depend on their capacity to effectively delivery water to the fire source and nearby surfaces. ii) It is possible that the spray appears into a place with several obstructions or complex architectures, so several trajectories could be interrupted.

For the reasons exposed above, a 3D interpolating function is applied in 3D spray field, generating a *Flux Field Function*. This function allows a detailed knowledge spray properties at any spatial point: The volume flux $\dot{V}$" and the spray properties (drop sizes, trajectory velocity and trajectory angle). Giving that the trajectories are time independent in a steady-state, the *Flux Field Function* are generated from pre-calculated trajectories, tabulated in a lookup table. This table contains all the possible trajectories for a giving set of drop sizes at one injection velocity. The calculation of the *Flux Field Function* is then simplified to a data queries in this lookup table.

Once the *Flux Field Function* is defined, it is possible to easily calculate the volume flux $\dot{V}''$ at all the desired surfaces, as shown in the example of fig.5. To do this, the target surface has to be first identified and then discretized.

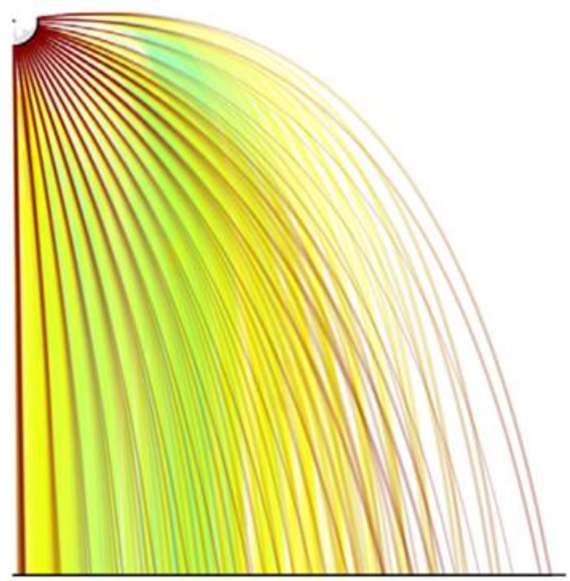

Figure 4. Fast 2D phase transformed dispersion predictions informed by 4S measurements; (a) azimuthal slice showing trajectories and floor intersection 10 m below the sprinkler highlighting flux reductions (reduce opacity) and velocity reduction (from red to blue).

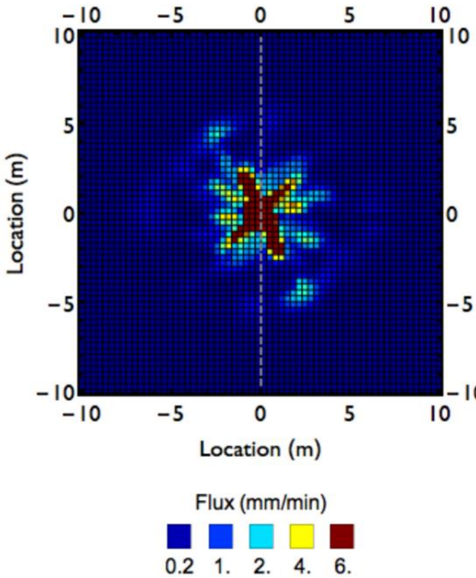

Figure 5. Volume Flux floor coverage distribution 10 m below the sprinkler (same example than fig.4)

The calculation of *Surface Fluxes* is then carry out by intercepting the target surfaces with the *Flux Field Function*, giving the value of volume flux and other spray properties at each point in the surface. It is important to note that, if there are obstructions interrupts the path of a giving group of trajectories, a recalculation of the *Flux Field Function* has to be carry out but without taking into account those trajectories.

III. COMMENTS AND DISCUSSION

Fast access to the *Flux Field Function* with the presented engineering tool provides the opportunity for queries of global spray properties. Alternatively, desired local properties of the sprinkler can be specified, being very useful for sprinklers design and engineering applications. This model has the advantage to be fast, providing fast access of global spray characteristics and its interaction with wetted surfaces anywhere within the throw of the spray (i.e. spray field) to evaluate spraying system design elements (e.g. sprinkler type, number, placement, orientation) and its interaction with its surrounding built (e.g. floor, ceiling obstruction, pillars) or natural (e.g. ground topology) environment;

Currently, the authors are working on the validation and optimization of the model, and it implementation on a BIM environment. This BIM plug-in would have sufficient fidelity for performance-based design of sprinkler, and will serve as tool for improve in fire protection engineering. Further, the this plug-in would extend the use case of BIM to include fire protection system analysis enabling more deeply integrated building performance optimization throughout the entire life cycle of the structure. In the future, the same measurement, analytical, and BIM frameworks could be applied for spray field analysis in other markets that rely on large scale dispersed sprays such as irrigation systems.

IV. CONCLUSIONS

The engineering tool described in this papers, based on a high fidelity description of initial characteristics of the jet (sphere initialization from 4S device), provides a fast global description the spray generated by sprinklers. This model can be used as new engineering tool for evaluation of water-based fire suppression system, allowing a fast access to the spray delivered by the sprinkler at any point, and allowing a description the volume flux in any “wetted” surface. While the proposed tool can be easily incorporated in personal computers, it can be also used to improve and simplify the design of the new generation of sprinklers. Finally, this engineering tool serves as a start model to modernize fire suppression system design while extending the use case of emerging Building Information Modeling (BIM) frameworks to include physics based simulation, visualization, and optimization of fire safety system performance.

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REFERENCES

[1] Grant G, Brenton J, Drysdale D. “Fire suppression by water sprays”. Prog Energy Combust Sci 2000;26:79–130.

[2] Marshall, A. W., "Unraveling Fire Suppression Sprays," Fire Safety Science– Proceedings of the Tenth International Symposium, IAFSS, Maryland, USA, 2011.

[3] Wang, Y., Meredith K., Zhou, X., Chatterjee, P., Xin, Y., Chaos M., Ren, N. and Dorofeev, S., “Numerical Simulation of Sprinkler Suppression of Rack Storage Fires,” Fire Safety Science - Proceedings of the Eleventh International Symposium, IAFSS, Christchurch, New Zealand, 2014.

[4] Jordan, S. J., “Spatially-resolved Spray Measurements and Their Implications,” Fire Safety Science – Proceedings of the Tenth International Symposium, Submitted, IAFSS, Lund, Sweden, 2017.

[5] Myers, T. M, and Marshall, A. W., “A Description of the Initial Fire Sprinkler Spray,” Fire Safety Journal, Vol. 84, p. 1-7, 2016.

[6] S. Jordan, N. Ryder, A. Marshall, Spatially Resolved Spray Scanning System and an Engineering Tool for Evaluating Sprinkler Performance, Proceedings of the 2013 Suppression, Detection and Signaling Research and Applications Symposium, Orlando, FL.

[7] University of Maryland – Ren, N., Baum, H. R., Marshall, A. W., “Method and System for Evaluation of Fire Suppression Systems Performance,” U.S.