

A PRACTICAL METHOD FOR DESIGNING A VIRTUAL SPRINKLER SPRAY

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ABSTRACT

A common problem faced by the fire protection engineering community is how to analyze the effectiveness of fire suppression technology, such as sprinkler sprays, in performance based designs. With recent improvements in both computer technology and numerical techniques, new algorithms have been incorporated in Computational Fluid Dynamics (CFD) modeling programs which allow spray technology to be integrated into simulations. However, due to the complex nature of real world sprinkler sprays, the process of defining a virtual sprinkler spray involves specifying a large number of specific parameters that describe the droplet size, droplet velocity and spatial flux distribution of water at various locations within the spray. Direct experimental measurement of these parameters is often difficult, expensive and time consuming due to the large quantity of data which must be collected and processed to fully characterize the spray. In addition, the characterization process typically involves the use of complicated techniques which are still the subject of significant research and development.

The proposed method is a practical alternative to using direct measurements of the individual characteristics of the spray to develop a virtual spray in a numerical simulation. Rather, the process consists of utilizing measurements of the environmental conditions generated by a sprinkler spray within a typical test compartment, along with basic statistical optimization techniques, to generate the specific simulation input conditions which accurately describe the spray pattern. To illustrate the utility of the proposed approach, a specific example of the process is presented in which a virtual simulation of a residential sprinkler spray is designed and validated within the Fire Dynamics Simulator (FDS) version 5.2 software, with reasonable results.

INTRODUCTION

Automatic sprinklers have become a critical component of fire safe building design. As building architecture and engineering evolve, there is increased demand for new and improved performance based design tools that can facilitate the application of fire suppression technology within new and unique building designs. To address the demand, improvements in both computer technology and numerical techniques have made the development of new algorithms for incorporating spray technology in Computational Fluid Dynamics (CFD) modeling programs such as Fire Dynamics Simulator (FDS) possible. Unfortunately, in order to appropriately utilize these new tools, a comprehensive understanding of the individual characteristics of the sprinkler spray and how it interacts with the fire environment is required.

The fundamental mechanisms which govern the performance of water based fire suppression technology have been studied by a wide range of researchers over the last several decades. In particular, Grant et. al. (2000) provide a comprehensive overview of the many different aspects of the subject. In addition, the general makeup and characterization of spray technology has been studied by such researchers as Heskestad (1972), Dundas (1974), Yu (1986), Sheppard (2002) and several others. Ren (2010) has recently produced a comprehensive overview of new methods for characterizing sprays, and Marshall (2011) has been using these new state-of-the-art techniques to develop a more robust understanding of the fundamental physics behind spray formation and overall structure. While much of the fundamental research has been utilized in the development and improvement of CFD-based spray algorithms, it has also highlighted the wide variation in spray characteristics – even within the same sprinkler or nozzle family. These findings have contributed to the difficulty in validating these algorithms for a wide range of spray

types and developing a generalized approach to specifying the related input conditions.

The performance of a specific fire sprinkler is governed by a set of key characteristics. These include geometric attributes that describe where and how the water discharged from the sprinkler is distributed within space as well as properties governing the heat transfer of the droplets. The geometric attributes of the spray are important because the heat generated by a fire within a compartment is not typically distributed evenly throughout its volume and therefore care must be taken to ensure that the spray interacts appropriately with the various buoyancy driven flows. The primary heat transfer characteristics (including droplet size, droplet velocity and droplet temperature) are important because they govern the rate and magnitude of the heat exchange between the water droplets and the surrounding air.

In the ideal case, a truly valid simulation of a sprinkler spray would require a complete understanding and reproduction of the following characteristics:

- The spatial distribution of water flux within the spray pattern.
- The spatial distribution of droplet velocity within the spray pattern.
- The spatial distribution of individual droplet sizes within the spray pattern.
- Individual droplet temperature.

However, certain characteristics are far easier to measure than others. The spatial distribution of water within a spray can be reasonably approximated using simple straight-forward methods. For instance, the distribution can be measured by collecting the spray in buckets of a specific size spread over a finite floor area or by measuring the wetted area on a vertical obstruction (wall) a fixed distance away. The distribution can be combined with flux measurements taken near the sprinkler deflector to approximate the overall flux distribution within the spray. In addition, water temperature is relatively simple to obtain through direct measurement but it is essentially impossible to directly measure the size and velocity of every single droplet in the spray. Each of these attributes exists as a statistical distribution and they are reasonably interdependent on one another. Complex methods have been developed such as Particle Image Velocimetry (PIV), Shadowgraphy and Phase Doppler Particle Analysis (PDPA) which can allow for reasonable estimates of these quantities – albeit at the significant expense of time, money and resources. These directly measured values can then

be used to specify the input conditions within a given CFD spray algorithm. Direct measurement is arguably the most robust approach as it can be specifically tied to the physical mechanisms which govern the performance of the spray.

A practical alternative is to take an indirect approach in which measurements of the sprinkler spray during a simple fire test are analyzed to estimate the critical spray characteristics required by the CFD algorithm. Using the indirect approach, the spray can be simultaneously designed and calibrated within the specific CFD algorithm for a given scenario. The proposed process is similar to using genetic algorithms to estimate the kinetic parameters for pyrolysis models based on bench scale test data, which has been used by others (Lautenberger et. al., 2006).

The focus of the current study is the use of a specific method by which the indirect approach can be utilized for designing and validating a virtual sprinkler spray within a given CFD algorithm (FDS5). It essentially consists of taking simple measurements of water flux distribution, wall wetting height and spray induced air temperature and velocity measurements within a compartment doorway. The measurements are then combined with a common statistical optimization technique and a carefully designed set of experiments (numerical simulations) to generate the specific input conditions which define the virtual spray.

METHODOLOGY

Statistical optimization techniques are commonly utilized in product development. According to Derringer and Such (1980), the methodology of the technique is to select a set of conditions, commonly referred to as the x 's, which will produce a desirable combination of properties, or y 's, in the final product. Statistical optimization techniques are particularly useful when the specific physical relationship between the response and independent variables is either unknown or exceedingly complex. The basic method consists of first developing an empirical approximation for the true functional relationship between the x 's and y 's using data collected from a carefully designed set of experiments and then optimizing the system using various simultaneous optimization techniques (Montgomery, 2009). The general process can be broken down into the following steps:

- (1) Define the specific problem, objective and goals of the optimization process.

- (2) Select the specific response variables which will be used in the optimization process (critical outputs) and the desired target values.
- (3) Select the specific independent input variables and value ranges that will serve as inputs in the optimization model.
- (4) Screen out the least significant inputs for the purposes of improving the overall economy of the related experimental program (usually accomplished through economical, lower-fidelity, fractional factorial experimental designs).
- (5) Select the specific experimental design and related optimization approach which will be utilized to meet the desired goals.
- (6) Execute the experimental program.
- (7) Use regression techniques to analyze the data and develop a suitable approximation for the true functional relationship between the inputs and selected response variables. The process typically consists of developing either a first or second order fit of the data using the method of least-squares for each of the response variables as a function of the inputs.
- (8) Use a simultaneous optimization technique to select the specific input value settings which will produce the desired combination of outputs.
- (9) Validate the optimized design.

Each of these steps is important to ensuring that the technique leads the user to the optimum design.

DISCUSSION:

Problem Definition

Since the coupling between water based suppression and pyrolysis modeling in CFD is still an area of emerging research, the focus of the current investigation was to tackle a slightly more simple problem. The goal was to reproduce the sprays induced cooling and related flow effects of a commonly utilized residential sprinkler in FDS. Residential sprinklers are designed to provide life safety by both limiting fire size and cooling the hot upper layer produced by a fire. The production and transport of heat and toxic combustion products is then diminished, extending the available time to escape from a burning structure (Madrzykowski & Fleming, 2008).

In FDS5, sprinkler sprays are represented as a subset of Lagrangian particles which are injected and numerically tracked at each time step during a simulation calculation (McGrattan, 2008). As previously discussed, due to the complexity of real-world spray patterns, there are a number of critical parameters that must be carefully selected by the user to define how these particles function within the

simulation. The critical parameters include physical characteristics such as water flow rate, offset (breakup) distance, orifice diameter, volumetric median droplet diameter, droplet velocity, spray angles and more. Also included are temporal parameters which control the balance between fidelity and computational economy of the simulation.

FDS5 contains two different methods of specifying a sprinkler spray pattern. The first, or “simple” method, is to specify the mean droplet diameter, initial droplet velocity and a pair of latitudinal angles (θ_1 and θ_2 in *Figure 1* below). The angles specify a region of a spherical surface defined at a given radius, r , from the sprinkler deflector in which droplets are evenly injected.

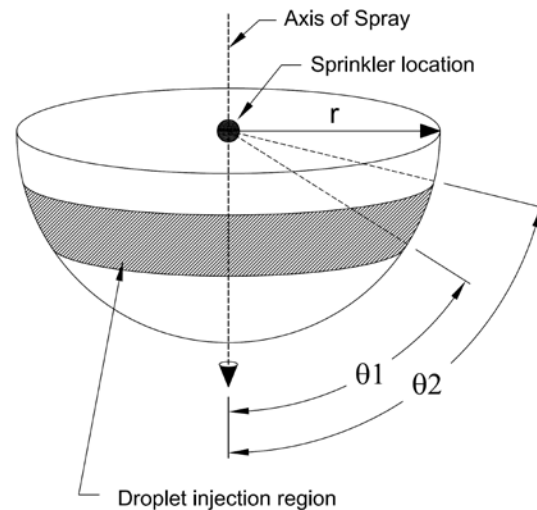


Figure 1: Illustration of droplet injection surface utilized by FDS5.

FDS also contains a second, more “complex” method, in which the spherical injection surface can be broken up into latitudinal and longitudinal regions in which the user can specify where a given percentage of the total spray volume is introduced. Specifying a sprinkler more precisely allows the user to develop a specialized spray as opposed to a spray where the droplets are more evenly distributed between bounding spray angles (McGrattan, 2008).

Due to the fairly idealistic nature of the specific residential spray in question and the ease of its application to the statistical optimization techniques, the simple method was used for the current investigation.

Response Variable Selection

In order to adequately model the sprinkler performance, it is necessary to carefully select the

response variables (outputs) which are utilized in the analysis. The selection of outputs is one of the most critical steps since it directly relates to the balance between complexity and robustness of the model itself. In the case of the residential sprinkler example, the strategy was to utilize variables that were easily measured to a reasonable degree of precision, and would accurately account for the key physical phenomenon associated with spray suppression performance. In relation to fire sprinkler sprays, the critical response variables were broken into two distinct categories: (1) outputs which describe the spray geometry – or spatial distribution of water droplets within the sprinkler spray pattern – and (2) outputs which described in reasonable totality the energy transfer properties of the spray (e.g. evaporative cooling, induced air currents). The primary criteria governing response variable selection was that the quantities had to be continuously variable, easily measured to an adequate level of precision in both a real-world and numerical setting and logically broken down to a singular value output for each response variable selected. For each response variable, a target value was selected from existing test data.

Spray Geometry

In terms of quantities that describe the spray geometry, two basic variables were selected: (1) the average distribution of volumetric water flux at the floor level beneath the sprinkler and (2) the average height of wall wetting a fixed distance away from the nozzle. The average water flux at floor level was a convenient parameter to use since it is a typical quantity measured in the development and listing process of sprinklers. Averaging the measured spatial flux distribution was a reasonable simplification as most sprinklers are designed to provide a fairly uniform density of water at floor level. The average height at which the spray wetted adjacent walls a fixed distance away was also a convenient parameter to use as it is another typical measurement taken during the sprinkler listing process. The combination of average floor density and wall wetting height are assumed to describe in reasonable totality the geometric distribution of water droplets in the spray.

In the case of the specific residential sprinkler utilized, the average flux density at floor level was calculated from data collected in 0.093 m² (1 ft²) square buckets over the entire 4.88 m x 4.88 m (16 ft x 16 ft) coverage area of the sprinkler operating at 0.5 bar (7 psi). The average wall wetting height was taken from the Tyco sprinkler spray pattern data sheet TFP710 (Tyco, 2005).

The simulated spray in FDS tended to produce a semi-parabolic wetting profile on the adjacent compartment walls. As a result, the arithmetic mean wetting height was calculated from the parabolic wetting profile across the length of the coverage area of the sprinkler using equation 1 below. See **Figure 2** for an illustration of the parameters in the equation.

$$\text{Eq. 1: } h_{avg} = h_b + \frac{2}{3}(h_t - h_b)$$

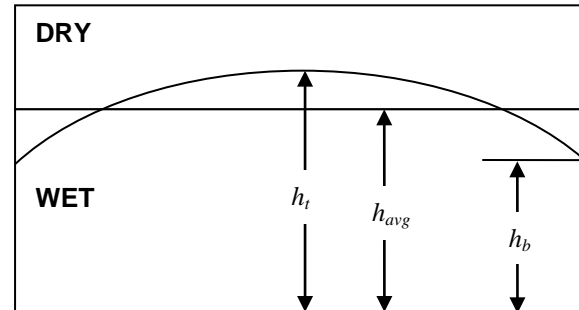


Figure 2: Illustration of the parabolic wall wetting profile generated by FDS. h_t corresponds to the distance between the floor and apex of the wetted surface, h_b is the wetting height at the edge of the sprinkler coverage area, and h_{avg} is the average calculated using Equation 1.

The equation provides a single average value which can be directly compared to the average wall wetting height calculated from the available test data.

Energy Transfer

In addition to the outputs which describe spray geometry, a number of response variables related to the energy transfer characteristics of the spray needed to be identified. The goal was to select spray performance data which could be easily recreated in a computational setting.

For identification of the response variables, data from a comprehensive experimental program conducted at the Tyco Fire Protection Products Research Facility in Cranston, RI was utilized. The experimental program was designed to investigate the impact of sprinkler sprays on fire-induced doorway flows (Adams, 2010). As part of the study, the specific sprinkler in question was sprayed inside a compartment constructed as shown in **Figure 3** below. The compartment had a single 1.04 m (3.4 ft) wide by 2.24 m (7.4 ft) high open doorway. The compartment walls were of wood frame construction covered in a 13.9 mm (0.55 in) thick layer of gypsum board with an exposed (non-insulated) back face. The ceiling was skinned in three layers: first with 1.2 mm thick (18 ga.) corrugated steel, then 18.4 mm (0.72 in) thick plywood and finally with 13.9 mm (0.55 in)

thick gypsum board. Measurements of the spray-induced steady state temperature and velocity values were collected at a large number of separate points using bare bead thermocouples and bi-directional probes across the plane of the door. For the purposes of the analysis, data collected *without a fire* was utilized to isolate the sprinkler spray effects from any interaction between the droplets and the fire itself. From the sprinkler only data, the average values of temperature and velocity were calculated in the central portion of the established flow fields above and below the neutral plane as shown in *Figure 3[LEFT]*. The averaging was done to minimize the influence of uncertainty around the neutral plane region and the fluid boundaries.

It should be noted that for the sprinkler only scenario the inflow and outflow regions are reversed in relation to the two-way, buoyancy driven doorway flows observed in typical fire scenarios. The reversal is caused, in part, by the sprinkler spray being cooler than the ambient environment, resulting in a net cooling effect within the compartment.

Target Values

Utilizing the various techniques described previously, the target values for each of the response variables were selected. These can be found in *Table I*. The average compartment inflow temperature was assumed to be ambient and was therefore neglected in the analysis.

Table 1: Target values selected for the residential sprinkler used in the analysis based on the previous discussion.

Response Variable	Target Value
Avg. floor density [mm/min]	1.23
Avg. wall wetting height [m]	1.83
Avg. outflow velocity [m/s]	0.309
Avg. outflow temp [°C]	28.20
Avg. inflow velocity [m/s]	0.290

Input Variables, Levels, and Ranges

The next critical item which must be considered when utilizing statistical optimization methods is the selection of the appropriate list of input factors, or parameters that will be varied during the analysis. Metaphorically speaking, these factors represent the knobs which can be turned to specific settings to produce the desired values of the response variables. For each factor, low and high values which bound the unknown desired value should be carefully selected based on existing literature, known physical principles and sound engineering judgment. These values define the full spectrum of possible settings that can be used to generate the target responses, typically referred to as the “inference space”. Care should be taken to ensure that the inference space is not set too large, since the subsequently generated polynomial model will typically only be a reasonable approximation of the true functional relationship over a very limited range (Montgomery, 2009).

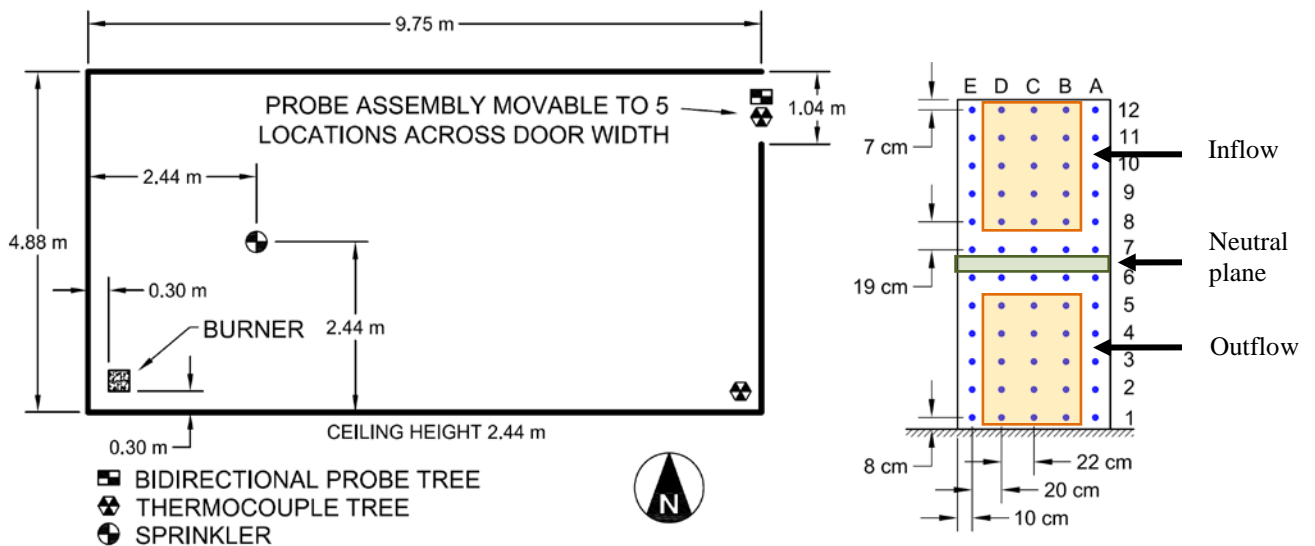


Figure 3: [LEFT] Schematic representation of test compartment utilized in the Tyco doorway flow analysis. NOTE: The general compartment geometry here was used as the basis for the FDS simulations used in the analysis. [RIGHT] Vertical layout of the compartment door depicting temperature and velocity measurement locations (dots). The highlighted regions indicate the areas where the data was averaged to provide the related temperature and velocity response variables.

For the particular given example, the inputs selected were directly related to the critical parameters that control the simple spray algorithm in FDS5 described previously. An initial screening step was completed to identify which independent variables had the most significant impact on each of the response variables. From the sensitivity analysis, the four critical inputs identified were the volumetric median droplet diameter, minimum and maximum spray angles and initial spray velocity. The rest of the inputs including offset distance, droplets per second and others were held constant at their default values in FDS.

Volumetric Median Droplet Diameter

In FDS5, sprays are represented as a combination of a log-normal and Rosin-Rammler distribution of droplet sizes, in which the primary controlling variable is the volumetric median droplet diameter – commonly denoted d_{v50} . In order to select a value for d_{v50} , the FDS5 technical reference guide refers to the basic correlation proposed by Heskestad (1972):

$$\text{Eq. 2: } \frac{d_{v50}}{D} = CWe^{-\frac{1}{3}}$$

In Equation 2, D is the sprinkler orifice diameter, We is the Weber number and C is the related proportionality constant. The specific form of the Weber number utilized in Equation 2 is:

$$\text{Eq. 3: } We = \frac{\rho u^2 D}{\sigma}$$

where ρ is the density of the liquid, u is the orifice discharge velocity and σ is the liquid surface tension (McGrattan, et al., 2009). Using the average value of $C = 2.48$ determined by Dundas (1974), the specific residential sprinkler used in the given example yields a d_{v50} value of approximately 500 μm . Sheppard (2002) observed an average median droplet diameter for a sprinkler of similar design with a slightly larger orifice, operating under similar conditions, to be about 1100 μm . Due to the variation, engineering judgment was used to select the target range of d_{v50} values.

Initial droplet velocity

The initial range of droplet injection velocities was calculated using a slightly more straightforward approach. Typically, the initial droplet velocity V_{sp} can be approximated as the sprinkler orifice jet velocity V_{jet} :

$$\text{Eq. 4: } V_{sp} \approx V_{jet} = \frac{Q_{sp}}{A_{orif}}$$

where Q_{sp} is the volumetric flow rate of the sprinkler and A_{orif} is the cross sectional area of the orifice. For the subject sprinkler, the expression yielded an orifice velocity of approximately 10 m/s at the minimum operating pressure of 0.5 bar (7 psi). However, Sheppard (2002) observed that both the maximum and average spray velocities measured just beyond the breakup region of the spray are typically a bit lower than the orifice velocity, due in part to drag and changes in momentum from the jet interaction with the sprinkler deflector. As a result, a number of FDS simulations were run to determine a reasonable lower limit for the spray velocity. For the analysis, the d_{v50} and maximum spray angle were held constant at 750 μm and 95°, respectively. The spray velocity was varied, starting at the orifice velocity and then slowly reducing until the average wall wetting height was observed to be noticeably lower than the target value. The selection of these limits ensured that the range of input velocities selected would adequately bracket the desired target value for wall wetting height, without the inference space being set too large.

Spray Angles

The range of values for each of the bounding angles defining the spray region was selected using a slightly less rigorous analysis than was used for droplet size and velocity. Visual observations of the sprinkler spray geometry were used to estimate starting values for the bounding angles. Next, a small number of simple FDS simulations were analyzed to ensure that the selected bounding angles adequately bracketed the desired outputs for average floor distribution and wall wetting height. During the simulations, the spray velocity and median droplet diameter were held constant at 10 m/s and 750 μm , respectively.

Water Temperature

Water temperature was not directly measured during the experimental test series. Instead, the initial temperature of the spray was estimated from data collected by a wetted thermocouple near the discharging sprinkler. The overall variation in the measurement was about 3°C. Since the difference between the ambient air and average water temperature observed during the testing was only about 10°C, the experimental uncertainty was approximately 30%. Rather than accept the high level of uncertainty, it was convenient to include the water temperature as a noise variable.

Selected Input Ranges

The selected ranges for the input variables used in the statistical optimization process can be found in *Table 2* below.

Table 2: Selected range of values for the input variables used in the optimization process.

Input variable	Minimum	Maximum
d_{v50} [μm]	500	1000
V_{sp} [m/s]	7.5	10.0
$\theta 1$ (inside angle)	50°	70°
$\theta 2$ (outside angle)	85°	105°
Water Temp [$^{\circ}\text{C}$]	22.0	25.0

Experimental Design

From previous research and experience, it was assumed that a second order polynomial fit of the output data would be required to adequately represent the functional relationship between the various input and response variables. Thus, a five-factor, rotatable, half-fractional central composite experimental design with six center points was utilized to create the matrix of required simulation runs. Based on the design, 32 individual simulations of the sprinklered compartment doorway flow scenario were required to generate data for the statistical analysis. For further detail, a comprehensive overview of Central Composite Design is given by Montgomery (2009).

Experimental Execution (Simulation Details)

Each experimental run consisted of executing a single FDS simulation for a specific combination of the input variables. The geometry was set up and instrumented as depicted in *Figure 3*, within a slightly larger computational domain consisting of 6.25 cm grid cells. Based on the available data, the ambient temperature was specified as 34 $^{\circ}\text{C}$. Each simulation was run until steady state conditions were achieved in the compartment and doorway. The data were processed and values for each of the response variables were recorded.

Statistical Analysis of the Data

Once all of the data had been collected, it was analyzed to develop the statistical model. The analysis involved creating a second order polynomial fit, as shown in Equation 5, for each response variable, y , as a function of the independent (input) variables, x , using the method of least squares.

$$\text{Eq 5: } y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \sum \beta_{ij} x_i x_j + \epsilon$$

Here β represents the various regression coefficients and ϵ is the error term (Montgomery, 2009). In the case being studied, $k = 5$ since there were five input variables. Next, each of the regression equations were simplified by removing terms which did not have a significant effect on the fitted model in order to develop the simplest equation that provides an adequate fit to the data. Fitness was assessed by using a basic analysis of the residuals (difference between the fitted function and the actual data) and the R^2 statistic – see *Table 3*. The described process was completed using the Minitab™ statistical analysis computer software.

Table 3: Fitness of the predictive functions identified using the regression analysis described above based on the simulation results.

Response variable	# terms in reg. eqn.	R^2
Avg. floor flux density	7	99.1%
Avg. wall wetting height	6	94.6%
Avg. outflow velocity	9	90.2%
Avg. outflow temp	6	87.1%
Avg. inflow velocity	9	86.8%

The predictive functions for the response variables were then analyzed using the simultaneous optimization method popularized by Derringer and Suich (1980) to identify the input variable settings that would produce the desired target responses. It is not practical to go into rigorous detail on the specific aspects of the simultaneous optimization approach given the current scope, however an extensive explanation of it is provided in the referenced paper. The process consists of converting each response variable, y_i , to a desirability value, δ_i . The value of δ_i is in the range $0 \leq \delta_i \leq 1$, where 0 is not desirable at all and 1 is the most desirable value. The individual δ_i 's can then be combined using the geometric mean to generate an overall desirability, Δ , for the system, as shown in Equation 6.

$$\text{Eq. 6: } \Delta = (\delta_1 \times \delta_2 \dots \times \delta_k)^{\frac{1}{k}}$$

In order to utilize the process, it is necessary to select a range of acceptable responses in which the target response is the most desirable. In addition, the desirability functions can be modified such that their sensitivity over the range of possible responses is weighted based on their relative importance. The process essentially condenses the problem down to a function of a single variable, which can then be solved via simple computer based search techniques for the combination of inputs which maximize Δ .

Table 4: Summarized results from the statistical optimization process. The values in the validation column were generated by running a final FDS simulation using the optimized settings for the spray inputs.

Input	Optimum Setting	Output	Target	Prediction	Validation
d_{v50} [μm]	870	Avg. floor density [mm/min]	1.23	1.23	1.25
V_{sp} [m/s]	8.50	Avg. wall wetting height [m]	1.83	1.82	1.86
θ_1	70	Avg. outflow velocity [m/s]	0.290	0.266	0.270
θ_2	95	Avg. outflow temp [$^{\circ}\text{C}$]	28.20	28.17	28.26
T_w [$^{\circ}\text{C}$]	25	Avg. inflow velocity [m/s]	0.309	0.318	0.328

To determine the optimum virtual sprinkler design, the described optimization process was completed using the Minitab™ software. The results of the analysis can be found in Table 4.

Model Validation

In order to validate the model, a final FDS simulation was run using the optimized input variable settings identified by the statistical model. From the data in Table 4, it is clear that the predictive model generated by the optimization process provides an extremely accurate representation of the optimized spray design. From Figure 4 below, it is clear that the optimized virtual sprinkler design accurately reproduces the experimentally observed vertical temperature and velocity profiles, including the neutral plane height.

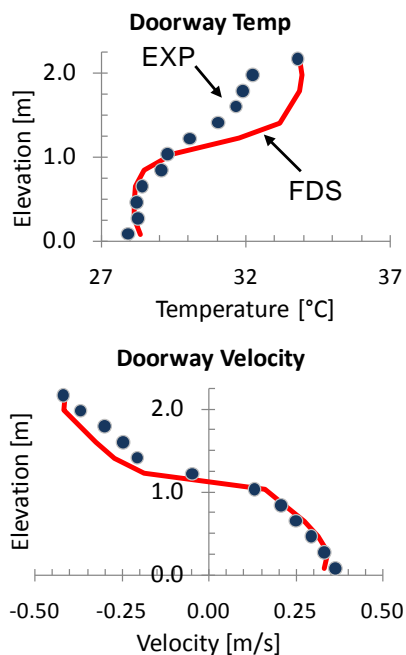


Figure 4: Graphical representation of agreement between the experimental results and the optimized FDS simulation. NOTE: The induced flow effects plots correspond to the data collected at the door centerline.

CONCLUSIONS AND RECOMMENDATIONS

Sprinkler sprays are complex in nature and thus substantial information on their characteristics are necessary for defining a virtual spray in a given CFD algorithm. The numerous different types of sprinklers and variations among sprinkler manufacturers add complexity to defining a virtual sprinkler that can be utilized across a wide range of applications. The method proposed herein provides a practical approach for defining a virtual sprinkler spray for a given situation based on a set of experimentally measured performance characteristics. It consists of using robust, and well validated statistical optimization techniques in conjunction with a carefully designed set of virtual experiments to select an optimum set of inputs for a given CFD algorithm. For a simple example, the method was able to specify a set of inputs for a simulated spray in FDS which reproduced real-world cooling, flow and water distribution observations – with far less effort than trial and error techniques.

It should be noted that the statistical methods described in the example analysis are ideally suited for fairly simple cases where the scenario can be boiled down to a reasonably small set of inputs and outputs. However, the general approach can, in theory, be applied using more sophisticated methods such as Monte Carlo simulations or genetic algorithms to provide solutions for more complex sprays. In addition, a given design for a virtual spray may not be applicable to all possible suppression scenarios. As a result, considerable effort should be made to validate the virtual spray over the range of applications it may be used for, and to quantify the related uncertainty.

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