Investigating the Effects of Sprinkler Sprays on Fire-Induced Doorway Flows: A Two-Part Study

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Introduction to the Combined Study

Architects are constantly challenging the fire protection field with unique structures and features that cannot be protected utilizing current prescriptive design and installation guidelines. To solve such unique design problems, fire protection engineers increasingly use performance based designs that require a complete understanding of a fire scenario and the ability to predict the fire behavior with practical engineering tools. With the practice of performance based design becoming increasingly common, additional research to improve and expand these methods is needed.

The use of fire sprinklers is a long-standing and well-established technique for providing life safety and property protection. However, very few engineering tools exist for predicting the effects of sprinkler sprays. The lack of tools can be attributed to the complexity involved in predicting the interaction between the sprinkler spray and the fire environment as well as the impact of the sprinkler spray on the fire growth process. In addition, the majority of fire deaths occur due to smoke inhalation and nearly two thirds of these deaths occur outside of the room of origin [1]. The evidence therefore suggests that understanding the spread of combustion gases from the room of origin is important to providing life safety. The ability to predict the impact of a sprinkler on the spread of combustion gases from the compartment of fire origin would be a valuable engineering tool for use with performance based design techniques.

An effective engineering tool would either be very simple to use or easily applied to currently used methodologies for performance based design. In general, performance based design is either done with basic empirical and theoretical equations, using computational methods such as Fire Dynamics Simulator (FDS), or a combination of both hand calculations and computer based models. Currently sprinklers are minimally accounted for in performance based design fire scenarios. This omission is due to the lack of a method to incorporate the interaction of the sprinkler spray with the fire. The ability exists today to input sprinkler sprays into numerical models. However, this method has not been idealized, and historically, the models have not been reliable. A more practical and simplistic approach is to investigate the effect of sprinkler sprays away from the spray pattern and fire interaction. Such an approach may allow for accounting for sprinklers during a performance based calculation in a simple method until more advanced methods become more reliable.

This paper presents work towards the development of a set of simple tools that can be used to account for sprinkler sprays in performance based design fire scenarios. Included is experimental work, originally conducted as a Master of Science thesis at Worcester Polytechnic Institute [2], that investigates the effect of sprinkler sprays on fire-induced doorway flows. Also included is simulation work based upon the experimental data to investigate the ability of FDS to predict the impact of the sprinkler on doorway mass flows. The experimental work demonstrates that a sprinkler-dependent cooling coefficient can be used to alter currently used buoyancy equations to predict the reduction in mass flow out of a doorway when a sprinkler is spraying. The FDS simulation study showed reasonable agreement to the experimental results.

Part 1 - Investigating Sprinkler Sprays on Fire-Induced Doorway Flows: Experimental Tests

Background

Previous work on smoke movement with the influence of sprinkler sprays has been conducted but no study has addressed the topic using a method that can be directly applied by a field engineer. Earlier studies are complicated and rely on knowledge of droplet diameter and sprinkler spray distribution that can only be measured using complicated and expensive techniques [3-11]. These studies have important implications, but the inclusion of droplet size and distribution as variables make the work impractical for use as an engineering tool because of the difficulty in measuring these parameters.

A simplified method, developed by Emmons [12, 13], exists to predict the mass flow through a vent during a fire. The equation for mass flow out of a vent per unit time, \( \dot{m}_{out} \), is given by [13]:

\[
\dot{m}_{out} = \frac{2}{3} C_D W \rho_\infty \sqrt{\frac{T_\infty}{T_G}} \left( \frac{T_\infty - T_G}{T_G} \right) g (H - Z_N)^{3/2} \tag{1}
\]

where \( C_D \) is the discharge coefficient, \( W \) is the vent width, \( \rho_\infty \) is the ambient density, \( T_\infty \) is ambient temperature, \( T_G \) is the upper gas layer temperature, \( g \) is acceleration due to gravity, \( H \) is the vent height, and \( Z_N \) is the neutral plane height.

Equation 1 uses Bernoulli’s principle to allow for a simple velocity expression in terms of a hydrostatic pressure difference and density. The model is based on the static pressure difference between the upper gas layer in the compartment and ambient environments outside of the compartment. The change in pressure forces the upper layer to flow out of the vent. The velocity in the doorway changes with the height above the neutral plane. Integrating a function consisting of velocity multiplied by ambient density and doorway width over the distance from the neutral plane to the top of the doorway produces a generic mass flow out of the vent given by [14]:

\[
\dot{m}_{out} = \int_{Z_N}^{H} v(z) \rho_\infty W dz \tag{2}
\]

For a fire scenario, it is best to report mass flows in terms of temperature. Utilizing the ideal gas law, temperature can be substituted into Equation 2. This final form, after integration, is what is reported as Equation 1.

This model has been verified by several experimental studies [15-17]. Steckler measured the mass flows created at the doorway for 4 different fire sizes (31.6, 62.9, 105.3 and 158 kW), 8 fire locations, and 10 vent sizes to show the validity of Equation 1. His experimental data shows that a discharge coefficient, \( C_D \), of 0.73 is needed to calculate the mass flow out of a compartment [15]. Steckler’s results establish that the fire location, vent size, and fire size do not influence Equation 1. Nakaya [16] investigated the effects of an adjacent room connected to the room of origin and showed that the model is applicable even when a hot upper gas layer is formed outside of the room, although his discharge coefficient \( C_D \), was slightly lower at 0.68. Equation 1 is an effective engineering tool due to its simplicity and reliance upon temperatures that can easily be predicted from a fire scenario.

Limited work had previously been done to investigate the impact of a spraying sprinkler inside the compartment of origin on the classic model (Equation 1). The work in this study analyzes the applicability of the model to predict the change in mass flow created with the inclusion of a TYCO Series LFII Residential Sprinkler (SIN TY2234) in a fire scenario.
The TYCO Series LFII Sprinkler is a pendent sprinkler with a 4.9 K-factor. Experiments were designed to keep all parameters in Equation 1 constant with the exception of $T_G$ and $Z_N$, which are expected to change with fire size. Additionally, $C_D$ may change because it is an experimentally determined value. Based on experimental data collected in this study, it is shown that a correction term can be incorporated in Equation 1 to predict fire-induced doorway mass flows for a residential fire scenario when a sprinkler is spraying, so long as the flow is stratified at the doorway. This study also shows that the spraying sprinkler in a compartment reduces the mass flow out of the doorway (about 20%), owing to the cooling effect of the spray on the upper gas layer. The study thus develops a proof of concept for determining the effects of a spraying sprinkler on fire-induced mass flows out of a vent.

Experimental Design

A total of 24 tests were conducted at Tyco Fire Suppression & Building Products Residential Test Facility located in Cranston, RI. The test compartment was sized 9.75 m long, 4.88 m wide and 2.44 m high as shown in Figure 1. The compartment dimensions were selected to represent the standard UL1626 fire test room, which requires protection from two sprinklers. The room contained a single doorway 1.04 m wide and 2.24 m high. The room was constructed with gypsum board ceilings, plywood walls with a black fire resistant coating, and a concrete floor. All openings besides the doorway, including cracks and seams, were sealed to prevent unwanted mass losses.

![Figure 1](image-url)

Figure 1- Fire compartment layout and instrumentation locations. The corner thermocouple tree was comprised of 13 Type-K thermocouples (bead diameter) located 0.15 m apart beginning 0.15 m below the ceiling. The doorway thermocouple tree consisted of 6 Type-K thermocouples spaced 0.18 m apart. The bidirectional probe tree consisted of 6 probes spaced 0.18 m apart.

A square premixed air-propane burner with sides measuring 0.46 m was used to simulate a steady state fire at the opposite corner of the room from the doorway as shown in Figure 1. A premixed fire was chosen to decrease the impact of the sprinkler spray on the heat release rate of the fire. It is assumed that the spraying sprinkler has a negligible effect on the fire heat release rate. The fuel and air levels were measured with volumetric flow meters, which allowed for adjustment of fire size while maintaining a stoichiometric mixture. Steady state fires were used so that there was little variability between tests.
Data was collected thirty minutes after the ignition of the fire, which allowed the compartment to be heated to a quasi steady state.

Three fire sizes were tested, 45 ±5 kW, 75 ±5 kW, and 100 ±5 kW. The heat release rates were found by converting the selected fuel volumetric flow rate into a mass flow rate. The mass flow rate was then used to calculate the heat release rate of the fire. These fire sizes were selected because they cover a wide range of activation times for a residential sprinkler exposed to a steady state fire. The smallest fire size would not generate temperatures sufficiently high enough to activate the sprinkler. Selecting the small fire was done to provide comparisons to sprinklers that would have a lower activation temperature and also to collect data on neutral plane changes for comparison to larger fires. The largest fire size will activate the sprinkler after a very short period of time. An increase in fire size would not produce a significant advantage because the change in time to activation would be minimal. The fire sizes tested in both Steckler et al. [15] and Nakaya et al.’s [16] research ranged between 30 and 158 kW, which is comparable to the selected fire sizes of the current study.

A TYCO Series LFII Pendent Residential Sprinkler (SIN TY2234) was used for this study. The same sprinkler head was used for all experiments to promote consistency between tests. The sprinkler was located 2.44 m from the walls closest to the fire source as shown in Figure 1. This position was selected because it was the farthest the sprinkler could be located away from the fire according to its designed spacing requirements. Only one sprinkler was used during testing to prevent sprinkler spray from directly impinging the plane of the doorway. A flow rate of 49.2 LPM was used for all testing. The flow rate was selected because it is the minimum flow allowed for the sprinkler spacing selected in the compartment. Additionally the minimum flow was used because it was assumed to be a worst case scenario. An increase in flow rate would introduce more water into the test space and also produce smaller droplet sizes, which theoretically would create a greater reduction of mass flow out of the doorway. The sprinkler was manually controlled, so the automatic activation device was removed from the sprinkler.

The doorway temperatures and flow velocities were measured by an instrument tree containing both bare bead thermocouples and bidirectional velocity probes (both spaced 17.8 cm apart as shown in Figure 2). The tree covered half of the doorway height and was designed to be adjustable across both the height and width of the doorway. The use of a steady state fire produced invariant doorway conditions that allowed for the movement of the doorway instrumentation and a larger number of measurements. Measurements were taken at six different tree locations in the doorway as shown by the dashed lines in Figure 2. A total of 36 temperature and velocity measurements were recorded during each test. All thermocouples used during experimentation were Type-K 24 gauge.

The bidirectional velocity probes were aligned with the flow at the doorway. It was assumed throughout all testing and analysis that the streamlines in the doorway were horizontal, which is also an assumption made when developing Equation 1. The probes measure the stagnation pressure produced by the flowing gas and compare that to the pressure slightly less than static measured by the downstream end of the probe. The differential pressures were measured by Omega PX655 high accuracy, low pressure bidirectional pressure transmitters.

The area of the doorway was held constant throughout all testing. Each of the 36 recorded differential pressures and their associated temperature measurements were used to calculate a local mass flux. Assuming that the mass flux at the edges of the doorway were zero, a linear interpolation method was used to find 100 mass fluxes between each measurement location. Each of the interpolated values had an associated area that was multiplied with the mass flux to produce a local mass flow. The summation of the positive mass flows (exiting the doorway) produced total mass flow out of the compartment.
To arrive at the total mass flow out, a calculation method had to be derived. For a fire scenario it is most appropriate to express density in terms of temperature and assume that the composition of the upper layer is mostly air. Therefore the use of air properties and the ideal gas law create a very simple expression for density based on temperature [18]. The use of this information produced a local mass flux equation to determine experimentally measured flows given by:

$$m'' = \frac{24.71}{T} \sqrt{T\Delta P}$$  \hspace{1cm} (3)

where $T$ is the local temperature and $\Delta P$ is the pressure difference reported by the bidirectional probes. The constant in Equation 3 was developed from several other constants including the bidirectional probe calibration factor [19] and ambient air properties [18]. The total mass flow out was then determined as:

$$\dot{m} = \sum_{k=1}^{n} A \dot{m}_k''$$  \hspace{1cm} (4)

where $A_k$ is the area around each mass interpolation point, $\dot{m}_k''$ is the interpolated mass flux which when positive is outflow and negative is inflow.

Figure 3 shows a surface plot of an experiment without a sprinkler created from the data obtained from the doorway measurements. The test results shown in Figure 3 had a mass flow out of the compartment of 0.72 kg/s and a flow in of 0.70 kg/s. Figure 3 also allowed for the determination of the neutral plane height. The locations in the doorway at which the flow changes from positive to negative were found. This height varies across the width of the door and the average height is reported as the neutral plane height.

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**Figure 2-** Doorway temperature and bidirectional velocity probe measurement locations.

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**Figure 3** shows a surface plot of an experiment without a sprinkler created from the data obtained from the doorway measurements. The test results shown in Figure 3 had a mass flow out of the compartment of 0.72 kg/s and a flow in of 0.70 kg/s. Figure 3 also allowed for the determination of the neutral plane height. The locations in the doorway at which the flow changes from positive to negative were found. This height varies across the width of the door and the average height is reported as the neutral plane height.
The upper gas layer temperature was determined using a thermocouple tree comprised of 13 Type-K 24 gauge thermocouples placed in a corner of the compartment as shown in Figure 1. The thermocouple beads were spaced 0.15 m apart, starting 0.15 m below the ceiling and ending 0.3 m above the floor. The upper gas layer temperature was calculated by examining the compartment temperature profile, determining the location of the smoke layer interface, and averaging the temperatures above the interface.

A maximum standard deviation of 9 K was found for the upper gas layer temperatures reported. The small variation in temperatures indicates that the upper gas layer was effectively at a uniform temperature. The location of the smoke layer interface was found by identifying the two heights over which the greatest reduction in temperature was measured and using the average of the selected heights. Ambient temperature was determined from a third thermocouple tree placed outside of the compartment. The tree consisted of four thermocouples spaced 0.6 m apart, beginning 0.5 m above the floor. The average of these temperatures produced the value used for ambient temperature.

**Experimental Error**

Three sources of error were present in the calculation of the doorway mass flows, the bidirectional probes, the differential pressure transmitters, and the thermocouples. The bidirectional velocity probes were individually calibrated in a plunge tunnel and had a calibration factor of 0.93 to 0.94. This value is equivalent to calibration factors reported in McCaffrey and Heskestad’s original probe study [19]. The reported error
associated with a bidirectional probes with this calibration constant is about 7% [19]. The bidirectional pressure transmitters were accurate within 0.25% of their full scale readings. Temperature measurements made by the Type-K thermocouples had an error of 1%. The bidirectional probe, pressure transmitter, and thermocouple data was used to calculate the experimental mass flow at the doorway. The error associated with each instrument measurement was propagated through the mass flow calculation process using an error analysis technique reported by Taylor [20]. The use of this technique produced a random, normally distributed mass flow error of approximately ±7% [2]. The average error of ±7% is reported throughout the remainder of this report in graphs and figures.

Results and Analysis

Table 1 summarizes the data gathered from the twenty-four tests conducted as part of this study. The table shows data collected for unsprinklered test runs “D” and test runs with the sprinkler spraying “W”. Two tests are always conducted back to back without turning the fire source off. This process eliminates any human error involved with setting the fuel and air flow rates, producing a set of tests most appropriate for comparison. Grouped tests are designated with matching numeric values in the test number column.

<table>
<thead>
<tr>
<th>Test #</th>
<th>$\dot{Q}$ (kW)</th>
<th>$T_G$ (K)</th>
<th>$T_a$ (K)</th>
<th>$Z_N$ (m)</th>
<th>$\dot{m}_{out}$ (kg/s)</th>
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<td>300</td>
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<td>0.42</td>
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<tr>
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<td>299</td>
<td>1.44</td>
<td>0.55</td>
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<tr>
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<td>1.33</td>
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<td>338</td>
<td>297</td>
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<td>0.59</td>
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</table>
Inflow/Outflow Balance
Conservation of mass dictates that mass inflow should be equal to mass outflow at the doorway. Experimental values should be the same assuming that the room is sealed to prevent un-monitored mass flows, and that the fire generates negligible mass. The maximum mass introduced by the fire for this work was 1.7% of the mass leaving the compartment [2]. Table 2 lists the mass flows into and out of the compartment showing that the mass flow in and mass flow out are equal within their error boundaries. The mass introduced by the fire was not included in the results shown in Table 2 because it had an insignificant impact.

Table 2 - Comparison of mass flow into and out of compartment, showing mass balance is achieved within experimental error.

<table>
<thead>
<tr>
<th>Test #</th>
<th>$\dot{Q}$ (kW)</th>
<th>$\dot{m}_{out}$ (kg/s) $\pm 7%$</th>
<th>$\dot{m}_{in}$ (kg/s) $\pm 7%$</th>
<th>$\dot{m}<em>{out} / \dot{m}</em>{in}$</th>
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<tr>
<td>12D</td>
<td>96</td>
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<tr>
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<td>96</td>
<td>0.59</td>
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</table>

Room Stratification
The stratification of the upper and lower gas layers can be found by using the thermocouple tree data at the corner of the compartment as shown in Figure 4. Figure 4 shows the temperature as a function of height within the compartment for tests 10D and 10W. It is clearly visible that at the location of the upper gas layer thermocouple tree, two stratified layers exist for both the sprinklered and unsprinklered cases. This observation proves that given the current experimental design configuration, a two-zone system can be approximated inside the compartment away from the sprinkler spray. Similar observations are true for the temperature distribution at the doorway.

Figure 4 - Temperature measurements inside the compartment away from the spraying sprinkler showing two distinct stratified layers in both the unsprinklered and sprinklered cases.
Neutral Plane
It is interesting to note that the non-dimensional neutral plane height at the doorway does not change with sprinkler activation. Figure 5 shows the non-dimensional neutral plane height, $Z_N/H$, with respect to non-dimensional upper gas layer temperature, $T_G/T_\infty$. Figure 5 shows there is a consistent neutral plane height (1.4 m) for all 24 fire tests. The small range of fire sizes conducted in this study may have attributed to this stationary neutral plane height. Steckler also reported similar results with neutral plane changes of only 0.06 m with tests of constant vent size and fire location but varying fire sizes [15].

![Figure 5](image-url)

Figure 5- Non-dimensional neutral plane location versus non-dimensional upper gas layer temperature. The neutral plane height is constant for every test regardless of heat release rate or a spraying sprinkler.
**Discharge Coefficient**

An idealized mass flow through a vent assumes that the flow is incompressible, isothermal, frictionless, and has no heat losses [18]. Flow is not ideal in practice, so the assumptions previously stated are compensated for with a discharge coefficient, $C_D$. In all previously reported work, $C_D$, lies between 0.68-0.73 [15,16]. The calculation of a discharge coefficient requires the use of experimental data as compared to an idealized mass flow rate calculated with $C_D=1$ in Equation 1. Therefore, an error is associated with the discharge coefficients reported in previous studies. This error was assumed to be the same as the reported experimental mass flow error, which was approximated at 10% [15]. Figure 6 shows that the discharge coefficient for both the unsprinklered and sprinklered experiments. The discharge coefficient was 0.77, a statistical equivalent to the 0.76 coefficient reported for the unsprinklered tests and comparable to the discharge coefficients reported in previous studies.

Given that for this study both the doorway neutral plane height and $C_D$ do not change, it can be said that $m_{out}$ is a function of the upper gas layer temperature alone. This information, along with the knowledge that the value of $C_D$ is appropriate, indicates that Equation 1 can be used to predict mass flows leaving a doorway or vent even after a sprinkler is activated.

![Figure 6](image-url)

*Figure 6-* Determining the discharge coefficient for both un-sprinklered and sprinklered tests is done by calculating the slope of a best fit line. The $C_D$ of 0.77 for both cases is very similar to the $C_D$ of 0.76 for only the un-sprinklered case.
Impact of Sprinkler Spray

The relationship between $m_{out}$ versus heat release rate is shown in Figure 7. The average of both the sprinklered and unsprinklered tests for each heat release rate is shown. It is observed that sprinkler activation causes a reduction in measured mass flows leaving the compartment. The errors associated between each group of tests do not overlap, proving that a significant decrease in mass flow occurs with the operation of a sprinkler. Additionally, the average reduction in mass flow is consistent from test to test with a value of 21%. The consistent reduction suggests that the change in fire size does not impact the cooling effectiveness of the sprinkler spray. Figure 8 shows a side-by-side comparison of tests 8D and 8W. This comparison shows the major reduction in flow leaving the doorway. Figure 8 also shows the equal neutral plane heights for a sprinklered and unsprinklered scenario.

Figure 9 shows the experimentally measured mass flow rate leaving the compartment versus non-dimensional upper gas layer temperatures. The theoretical curve established from Equation 1 is also shown in this plot. This curve utilizes the discharge coefficient, $C_D = 0.77$, and average neutral plane height, $Z_N = 1.4$ m, found in this study. Figure 9 shows that the cooling effect of the sprinkler, influencing a change in $T_G$, is the only variable driving the change in mass flow out of the doorway. Figure 9 illustrates that both experimental values and predicted values, found from Equation 1, show good agreement.

![Figure 7](image-url)  
**Figure 7** - Average experimentally determined mass flow out of compartment versus heat release rate, showing the reduction in mass flow out of the compartment.
Figure 8 - Comparison of doorway flows for tests 8D and 8W showing the reduction in mass flow leaving the doorway and the equivalent neutral plane heights for both tests. Test 8D had an experimentally determined mass outflow of 0.68 kg/s and test 8W had an experimentally determined mass outflow of 0.55 kg/s. The reduction in mass flow between the two tests was 19%.

Sprinkler Cooling Coefficient

Figure 9 shows that applying the classical doorway mass flow equation to a sprinklered compartment is possible. The results are applicable to the specific compartment size, sprinkler type, sprinkler flow and fire sizes studied, where flow remains stratified at the doorway. The results suggest that it is possible to account for changes to flow of gases out of a doorway upon sprinkler activation without having detailed knowledge of the sprinkler spray profile and the interaction of the sprinkler spray with the fire environment within the compartment of fire origin. The results also suggest that a simple tool can be created for use with performance based designs for three reasons. The first is the elimination of the complexity involved in determining post sprinkler activation fire scenario information. The second is that the variable driving the mass flows is upper gas layer temperature, which is easily predicted with current methods. The third is that the reduction in mass flow as a result of sprinkler application is a constant percentage. For these three reasons a constant value, referred to as the sprinkler cooling coefficient, can be applied to the classical doorway flow equation to account for the change in mass flow.
A sprinkler cooling coefficient can be assigned to the TYCO Series LFII Residential Sprinkler (TY2234), which was used in this testing. The experimental results suggest that the cooling coefficient should be approximately 0.84 because the minimum reduction in mass flow rate for all tests conducted as part of this program was 16%. An adjusted vent mass out flow equation is given by

\[
m_{\text{out}} = \frac{2}{3} C_d C_S W \rho_z \sqrt{\frac{2 T_s}{T_G} \left(1 - \frac{T_s}{T_G}\right) g (H - Z_N)^{3/2}}
\]  

(5)

where a new variable \(C_s\), called the sprinkler cooling coefficient, is introduced. Equation 5 could prove to be a reliable method to account for a spraying sprinkler in a compartment fire.

**Conclusions and Future Work**

The current study has shown that fire-induced doorway mass flows can be predicted for a residential fire scenario when a sprinkler is spraying. The TYCO Series LFII Residential Pendent Sprinkler (TY2234) consistently reduced the mass flow exiting the doorway. The neutral plane is not affected by the inclusion of a sprinkler in the fire scenario and a two-zone environment exists at some distance beyond the sprinkler spray pattern. Application of the experimental results to a buoyancy based equation shows that mass flows exiting a doorway can be predicted during a fire with sprinkler activation by using a cooling coefficient (Equation 5) that can be experimentally determined. The ability to calculate the changes to vent flows when a sprinkler activates can lead to improved predictions of fire environments outside of the room of origin in sprinklered occupancies, ultimately leading to an engineering design tool for performance based design.

The work conducted during this project was limited to a single sprinkler type, a single water flow rate and a set of small steady state fires. For greater understanding of how sprinkler sprays effect fire-induced doorway flows future work is required. This work includes testing different types of sprinkler heads, increased number of sprinklers, increased water flow rates, and different sprinkler locations with respect to the doorway and growing fires. An extension of this research has already been completed, which focused on the effect of sprinkler sprays on the transport of toxic products [22].

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Figure 9- Predicted and experimentally measured mass flow rates leaving the compartment for both sprinklered and unsprinklered cases. The mass flow is predicted assuming a constant neutral plane.
Part 2 - Investigating Sprinkler Sprays on Fire-Induced Doorway Flows: Numerical Simulation

The ability to calculate the changes to vent flows when a sprinkler activates can lead to improved predictions of fire environments outside of the room of origin in sprinklered occupancies, ultimately leading to an engineering design tool likely based on numerical simulations. Hence, for the current study, numerical calculations using NIST Fire Dynamics Simulator (FDS) are compared with real scale compartment experimental data for free burn and sprinklered cases.

Mass flow rate and temperature are typical parameters used to quantify the flow induced by a fire in a compartment. Hence, numerical results for doorway mass flow rate and temperature are compared with the experimental data for three fire sizes in order to validate the numerical model. Then, using current experimental data for sprinkler characteristics, numerical calculations for doorway mass flow rate and temperature are compared with the experimental data for the three fire sizes of the sprinklered case.

The FDS calculations have reasonable agreement with current experimental results for doorway flow, except near the interface between the upper and lower layer. This shows promise for the eventual use, with more investigation, of FDS to predict changes to vent flows due to sprinkler activation for more complicated configurations.

Background

For a compartment fire, the mass flow rate, temperature and neutral plane height are typical parameters used to quantify the fluid dynamics in the doorway. These have been intensively measured and studied by various researchers [5, 10, 12-16, 22-27], however, few have studied the effect of sprinkler spray on classic doorway mass flow equations. Crocker [2] analyzed the mass flow rate and temperature in a compartment doorway for a fire scenario with and without sprinkler spray. In his study, a single spraying sprinkler in the compartment is found to reduce the mass flow out of the door by about 20%, which is believed due to the cooling effect of the spray on the upper gas layer.

Compared with experimental measurements and manual calculations, computational fluid dynamics (CFD) can provide more comprehensive analyses. However, in order to develop a CFD design tool for quicker and less expensive investigation of the physical and chemical mechanics in the real compartment fires, it is necessary to validate it by comparing numerical calculations with experimental data for various scenarios. The current study establishes a FDS model and compares results with the experimental data obtained by Crocker [2]. Full scale compartment tests of three different fire sizes for both free burn and with sprinkler spray were conducted. The simulations for mass flow rate, velocity and temperature in the doorway are presented and analyzed.

Model Parameters

The current study models a fire in a three dimensional room with an open doorway according to Crocker’s experiments [2]. The test compartment dimensions are 9.75 m (length) by 4.88 m (width) by 2.44 m (height). The room is constructed with gypsum board ceilings, plywood walls with a black fire resistant coating and a concrete floor. The open doorway is 1.04 m (width) by 2.24 m (height). A 0.46 m² burner with premixed air/propane is used in the physical model according to the experiment setup. The fire compartment layout and instrument locations are shown in Figure 1.
The computational domain enclosing the compartment is chosen because the open doorway is connected with the ambient environment. The whole domain is divided into 120×70×30 computational cells. Each cell has dimensions of 0.1 m × 0.1 m × 0.1 m. The initial time step for calculation is set to 3 s. It is noted that time step is normally set automatically during the FDS calculations by dividing the size of a mesh cell by the characteristic velocity of the flow [28]. The total calculation duration is 15 minutes, when the fire tests are assumed to be steady state.

The boundary conditions for the computational domain are set to “open” to the ambient for the front side. The other sides are set to adiabatic solid surfaces according to the test room setup. Note that because the large scale fire tests were conducted sequentially in experiments, the initial gas temperatures in the enclosure vary along the vertical direction due to the stack effects by the previous test. For example, the initial gas temperature difference between bottom and ceiling is about 17 K in the sprinklered test with a fire size of 45 kW, while the difference in the unsprinklered test with a fire size of 100 kW is more than 32 K. Such variance cannot be neglected and is illustrated in FDS inputs according to the experimental data in each test. The initial temperatures on the surfaces of side walls in each test are set to the averaged gas temperature inside the test room. The following table lists thermal properties of the fuel, walls, and floor used in FDS according to the SFPE handbook [29].

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (kJ/kg/K)</th>
<th>Thermal Conductivity (W/m/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum (Ceiling)</td>
<td>1440</td>
<td>0.48</td>
<td>0.84</td>
</tr>
<tr>
<td>Concrete (Bottom)</td>
<td>2100</td>
<td>0.88</td>
<td>1.37</td>
</tr>
<tr>
<td>Plywood (Side Walls)</td>
<td>545</td>
<td>1.215</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Thermal Properties of Propane are:
Heat of Combustion: 46.3 mJ/kg; Carbon Monoxide Yield: 0.005g/g; Soot Yield: 0.024g/g.
Sprinkler Spray Characteristics

Once a sprinkler is activated in the FDS simulation, the droplet sizes, temperatures, and trajectories of a representative sample of the water droplets will be calculated. Thus the initial conditions of spray characteristics such as water flow rate, initial droplet velocity, averaged droplet diameter, spray angles and offset location are needed. A water flow rate of 49.2 L/min was obtained for the TYCO Series LFII Sprinkler model used in Crocker’s experiment [2]. A pair of spray angles illustrating droplet spread areas was measured to be $\theta_{\text{min}} = 34^\circ$ and $\theta_{\text{max}} = 56^\circ$ respectively. Offset represents the radius of a sphere surrounding the sprinkler where the water droplets are initially placed in the simulation. Figure 2 shows representative sprinkler spray angles and offset. The offset location (i.e., breakup from continuous stream to droplets) was estimated in a strobe booth by visual observation as 0.15 m. The initial droplet velocity and the average droplet diameter are assumed to be 7.2 m/s and 250 µm. Figure 2 also shows the definitions of spray angles and offset from the sprinkler.

FDS Outputs

In present study, the mass flow rate, velocity, and temperature profiles in the doorway are calculated according to the experimental setup in FDS output. The hot gases flowing out of the doorway and the fresh air flowing into the compartment can be obtained in FDS output as integrated quantities. Note that in FDS, a plane is specified rather than a point in calculating the mass flow rates. The temperature and velocity profiles in the doorway are calculated at the locations that were measured experimentally.

Ceiling temperatures in the same locations measured by experiments are also calculated as well as gas concentrations including oxygen, nitrogen, and carbon dioxide for various locations. These results will be presented elsewhere.
Figure 3- FDS calculations for the evolution of (top) temperature and (bottom) velocity at $y=4.707$ and $z=1.78$ in the compartment doorway using a different grid resolution for a fire size of 45 kW and an ambient temperature of 21.8 °C.
**Grid Resolution**

Grid independence is important to verify the numerical simulations because it directly influences the truncation error or even rationality of numerical results. In principle, a very dense grid can ensure the accuracy of the calculation but the calculation time may be wasted unnecessarily. In practice, the grid sizes are usually increased and the time step decreased according to a certain ratio for calculations. If the deviation between the neighboring results is small enough, the grid can be considered as grid independent.

Figure 2 shows the grid independence tests for the FDS simulation on the operation condition of a fire size of 45 kW. Results for velocity and temperature at a certain point were compared against grids doubled and halved in resolution along the three coordinate directions. Calculation performed with fine or coarse grids did not change the results for temperature significantly. As for the velocities, the differences between the three results are apparent (the maximum deviation is up to 50%) especially at the beginning stage when the instable nature of turbulent flow is determined by the eddy sizes that are very small at the beginning and sensitive to the grid sizes. Decreasing the grid spacing may increase the accuracy, and using Direct Numerical Solution (DNS) of the governing equations can improve the calculation accuracy but is not economic because of the greatly increased calculation time.

During the calculation in FDS, the time step is adjusted so that the CFL (Courant, Friedrichs, Lewy) condition is satisfied; hence, a check of the time step independence is not conducted in present study.

![Figure 4](image.png)

**Figure 4** - Doorway fluid flow profiles. (a) Unsprinkled fire test with a fire size of 100 kW; (b) Sprinklered fire test with a fire size of 100 kW
Results
The agreements between numerical outputs with the experimental data are crucial to determine the simulation accuracy. In order to validate FDS application in this study, the numerical calculations are compared with the experimental results measured by Crocker [2] under the same operational condition with/without sprinklers.

Figure 3 illustrates the comparison of doorway fluid dynamics for the sprinklered and unsprinklered fire test with the same fire size of 100 kW. The doorway fluid flows in both tests are unstable at the beginning because of the sharp pressure gradients in the test room. Then the profiles come to steady state after about 3 minutes. The doorway velocities in the unsprinklered test (-0.95 m/s – 1.7 m/s) are higher than those in the sprinklered test (-0.8 m/s – 1.35 m/s) because of the water suppression in the sprinklered test. The negative symbol represents inflow direction and the velocities are all in X direction.

Unsprinklered Test Results
Unsprinklered (i.e., free burn) tests with fire sizes equal to 45 kW, 75 kW, and 100 kW were simulated. The numerical calculations for the doorway velocity, mass flow rate, and temperature are compared with the experimental data in Figures 3 – 5 shown on the following pages. In general, the agreements between numerical calculations and experimental data for velocities and mass flow rate are reasonable along the vertical line in different horizontal locations of the doorway. Specifically, the numerical calculations have excellent agreement with experimental data away from the door edges (when y=0.52 m and y=0.87 m) but near the door edge (y=0.17) calculations show stronger zigzag characteristics than experimental measurements.

The agreements between numerical calculations and experimental data for temperature are generally reasonable except for a significant discrepancy near the interface between the lower and upper layer.

Sprinklered Test Results
Sprinklered tests with fire sizes equal to 45 kW, 75 kW, and 100 kW were simulated. The numerical calculations for the doorway velocity, mass flow rate and temperature are compared with the experimental data in Figures 6 – 8. A TYCO Series LFII Residential Pendent Sprinkler was used.

Similar to the unsprinklered case, the agreements between numerical calculations and experimental data for velocities and mass flow rate are reasonable along the vertical line in different horizontal locations of the doorway. The agreements between numerical calculations and experimental data for temperature are also reasonable, except near the interface height.

Discussion
Notice that the doorway fluid dynamics, especially the neutral plane height, change only slightly with different fire sizes and with/without sprinkler spray. This phenomenon is most likely due to the sprinkler narrow spray coverage (34 and 56 spray angles) and the far distance between the doorway and the burner locations (up to almost 10 m distance between the burner and the doorway). The small fire sizes (45-100 kW) in the tests may also contribute to such stationary fluid dynamics in the doorway.

Conclusions
Numerical calculations by FDS are compared with the experimental data of Crocker [2] for compartment doorway velocity, mass flow rate, and temperature for three different fire sizes of both free burn tests and sprinklered tests. These comparisons show that FDS calculations have reasonable agreements with the experimental results except near the interface between the upper and lower layer. This result shows promise for the eventual use, with more investigation, of FDS to predict changes to vent flows due to sprinkler activation for more complicated configurations.
Investigating the Effects of Sprinkler Sprays on Fire-Induced Doorway Flows: A Two-Part Study

Figure 5 - Comparison of the experimental and numerical results for ➊ local velocities, ➋ temperatures, and ➋ mass flow rates at the open door in a compartment fire under the operation condition of a fire size of 45 kW without a sprinkler.
Figure 6- Comparison of the experimental and numerical results for
1 local velocities, 2 temperatures, and 3 mass flow rates at the open door in a compartment fire under the operation condition of a fire size of 75 kW without a sprinkler.
Investigating the Effects of Sprinkler Sprays on Fire-Induced Doorway Flows: A Two-Part Study

Figure 7 - Comparison of the experimental and numerical results for local velocities, temperatures, and mass flow rates at the open door in a compartment fire under the operation condition of a fire size of 100 kW without a sprinkler...
Investigating the Effects of Sprinkler Sprays on Fire-Induced Doorway Flows: A Two-Part Study

Figure 8- Comparison of the experimental and numerical results for local velocities, temperatures, and mass flow rates at the open door in a compartment fire under the operation condition of a fire size of 45 kW with a TYCO Series LFII Sprinkler

- Local Velocities
- Temperatures
- Mass Flow Rates
Figure 9- Comparison of the experimental and numerical results for local velocities, temperatures, and mass flow rates at the open door in a compartment fire under the operation condition of a fire size of 75 kW with a TYCO Series LFII Sprinkler.
Investigating the Effects of Sprinkler Sprays on Fire-Induced Doorway Flows: A Two-Part Study

Figure 10- Comparison of the experimental and numerical results for (1) local velocities, (2) temperatures, and (3) mass flow rates at the open door in a compartment fire under the operation condition of a fire size of 100 kW with a TYCO Series LFII Sprinkler.
Conclusion to the Combined Study

The two-part study of the effect of sprinkler sprays on fire-induced doorway flows has shown that the prediction of fire-induced vent flows is possible even when a sprinkler spray is cooling the environment. The experimental part of this study determined that a sprinkler spray reduced the mass flow out of the doorway by a consistent percentage of the unsprinklered fire scenario. The doorway neutral plane was not affected by the sprinkler spray, which left the reduction in upper gas layer temperature to be the driving parameter of change in mass flow. Due to the consistent nature of the mass flow reduction, it was concluded that a sprinkler cooling coefficient, $C_S$, could be applied to the general vent mass flow equation to account for a spraying sprinkler. The cooling coefficient is a sprinkler dependent value and can be determined experimentally. The use of the cooling coefficient only requires the knowledge of unsprinklered fire conditions, which eliminates the need to perform complicated calculations. Due to the limited nature of this experimental study, further investigation is required but the initial findings suggest that the sprinkler cooling coefficient can be a simple engineering tool used to account for a sprinkler in fire scenario calculations.

The second part of the study utilized the collected experimental data to validate a FDS simulation of the tested scenario. The simulation results had reasonable agreements with the experimental data. These results suggest that upon further research, a validated FDS simulation can be used as an engineering tool to determine the mass flow out of a vent for a sprinklered fire. In conclusion to this combined study, it was determined that the development of simple engineering methods to account for a sprinkler in fire scenario calculations is possible. While further research is required before these tools can be applied, the initial findings are promising.
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Jeremiah Crocker is a Project Engineer with the New Technology Team of Tyco Fire Suppression & Building Products located at the Cranston Technology Center in Cranston, Rhode Island. As a graduate of Worcester Polytechnic Institute’s Mechanical and Fire Protection Engineering programs, Jeremiah obtained his M.S. studying the effect of sprinkler sprays on fire-induced mass flow rates. Jeremiah has published peer-reviewed papers and presented at industry conferences on this subject. Employed by Tyco since October 2007, Jeremiah has been involved in a wide range of applied research and product development projects focused on enhancing the performance of fire suppression systems.

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References


Investigating the Effects of Sprinkler Sprays on Fire-Induced Doorway Flows: A Two-Part Study
Nomenclature

\( \dot{m}_{\text{vent}} \) Mass flow rate leaving vent [kg/s]

\( C_D \) Vent discharge coefficient

\( W \) Width of doorway [m]

\( \rho_\infty \) Ambient density [kg/m\(^3\)]

\( T_\infty \) Ambient temperature [K]

\( T_G \) Upper gas layer temperature [K]

\( T_s \) Average experimental ceiling jet temperature [K]

\( g \) Gravity [m/s\(^2\)]

\( H \) Doorway height [m]

\( Z_N \) Neutral plane height [m]

\( C_s \) Sprinkler compensation coefficient

\( \dot{Q} \) Heat release rate of fire [kW]

\( \dot{m} \) Local mass flow rate determined from bidirectional probes [kg/s]

\( T \) Local temperature related to bidirectional probes [K]

\( A \) Local area related to bidirectional probes [m\(^2\)]

\( \Delta P \) Differential pressure measured by bidirectional probes [Pa]

\( r_{\text{offset}} \) Offset location [m]

\( \theta_{\text{min}} \) Sprinkler minimum spray angle [ ]

\( \theta_{\text{max}} \) Sprinkler maximum spray angle [ ]