1. J. P. Crocker, A. S. Rangwala, N. A, Dembsey, and D. J. Le Blanc, **"The Effect of Sprinkler Spray on Fire Induced Doorway Flows: New Tools for Performance Based Design,"** *Fire Tech.*, Vol. 46 (2), 347-362, 2010.

Investigation of Sprinkler Sprays on Fire Induced Doorway Flows

Crocker J. P., Rangwala A. S. and Dembsey N. A., Department of Fire Protection Engineering, Worcester Polytechnic Institute, Worcester MA*

LeBlanc D. J., Tyco Fire Suppression & Building Products, Cranston, RI.

Abstract. Performance based methodologies are becoming increasingly common in fire safety due to the inability of prescriptive codes to account for every architectural feature. Fire Sprinkler suppression systems have long been used to provide property protection and enhance life safety. However, very few methodologies exist to account for the impact of sprinkler sprays on fire scenarios. Current methods are extremely complicated and difficult to use as an engineering tool for performance based design. Twenty four full scale fire tests were conducted at Tyco Fire Suppression & Building Products Global Technology Center to determine a simple method for accounting for the impact of a single residential sprinkler on fire induced doorway flows. It was found that a spraying sprinkler reduced the mass flows at the doorway while maintaining two stratified layers away from the sprinkler spray. The mass flow reduction was consistent and could be predicted through the use of a simple buoyancy based equation. The current study suggests that the buoyancy equation can be altered through the use of a constant cooling coefficient (equal to 0.84 for a Tyco LFII (TY2234) sprinkler) based on the test results reported in this paper. This study is a proof of concept and the results suggest the methodology can be applicable to similar situations.

Key Words: Performance Based Design, Sprinkler Spray, Vent Flow

Introduction

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 which 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 are 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. This 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.

Previous work on smoke movement with the influence of sprinkler sprays has been conduced but no one 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 which can only be measured using complicated and expensive techniques [2-10]. 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 [11, 12], exists to predict the mass flow through a vent during a fire. The mass flow out of a vent per unit time, $\dot{m}_{out}$, is given by [13]:

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

where C_D is the discharge coefficient, W is the vent width (m), ρ_∞ is the ambient density in (kg/m^3), T_∞ is ambient temperature (K), T_G is the upper gas layer temperature (K), g is acceleration due to gravity (m/s^2), H is the vent height (m), and Z_N is the neutral pane height (m).

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 static air 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 mass flow out of the vent given by [13]:

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

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 the equation 2. This final form is what is reported as Equation 1.

This model has been verified by several experimental studies [14-16]. 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 showed that a discharge coefficient, C_D of 0.73 is needed to calculate the mass flow out of a compartment [14]. Steckler's results established that the fire location, vent size and fire size do not influence Equation 1. Nakaya [15] investigated the effects of an adjacent room connected to the room of origin, as well as the effect of larger fires (maximum of 593 kW). Nakaya showed that the model is applicable even when a hot upper gas layer is formed outside of the room and higher temperatures were present, 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 which can easily be predicted from a fire scenario.

No work has been done to investigate the impact of a spraying sprinkler inside the compartment of origin on the classic model (Equation 1). This work analyzes the applicability of the model to predict the change in mass flow created with the inclusion of a Tyco LFII residential sprinkler (SIN TY2234) in a fire scenario. The Tyco LFII is a pendent sprinkler with a 4.9 K-factor. This work keeps 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. It is also shown in this study 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 meters wide and 2.24 meters 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.

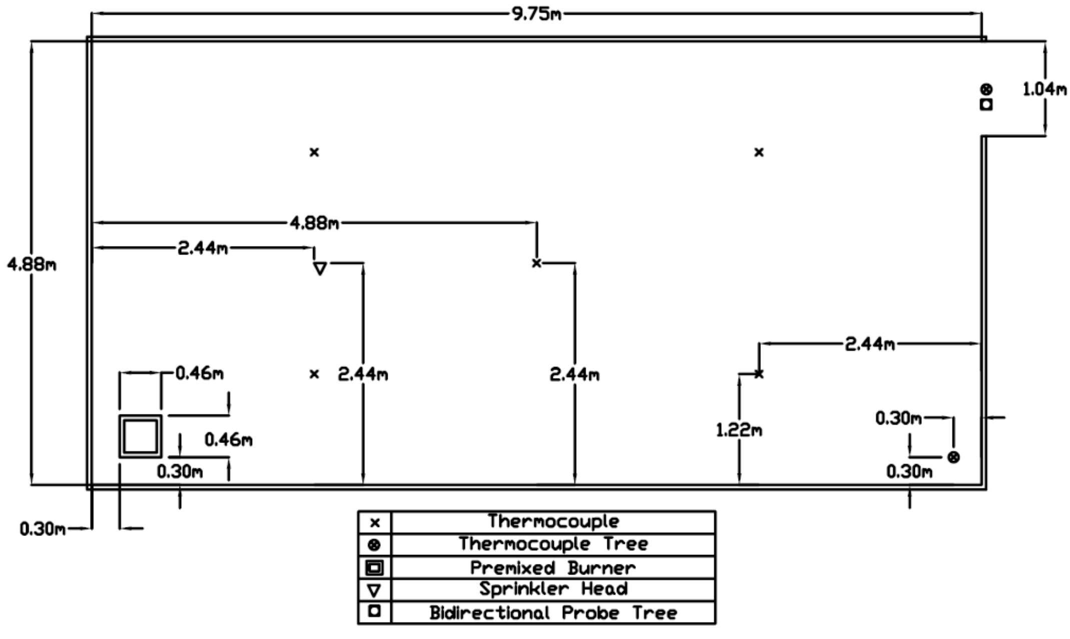

Figure 1: Fire compartment layout and instrumentation locations. The corner thermocouple tree was comprised of 13 Type-K thermocouples (bead diameter) located 0.15 m apart beginning 0.15 m below the ceiling. The doorway thermocouple tree consisted of 6 Type-K thermocouple spaced 0.18 m apart. The bidirectional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

A square premixed air-propane burner with sides measuring 0.46 meters 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, 42 ±5 kW, 75 ±5 kW and 96 ±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. This was done to provide comparisons to sprinklers that would have a lower activation temperature and also to collect data on neutral plane changes of very small fires as compared to larger fires. The largest fire size can 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 Steckler et al. [14] ranged between 30 and 158 kW, which is comparable to the selected fire sizes of the current study.

A Tyco 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 liters per minute (13 gallons per minute) was used for all testing. This was selected because it is the minimum flow allowed for the sprinkler spacing selected in the compartment. The minimum flow was used for testing 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 which 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.

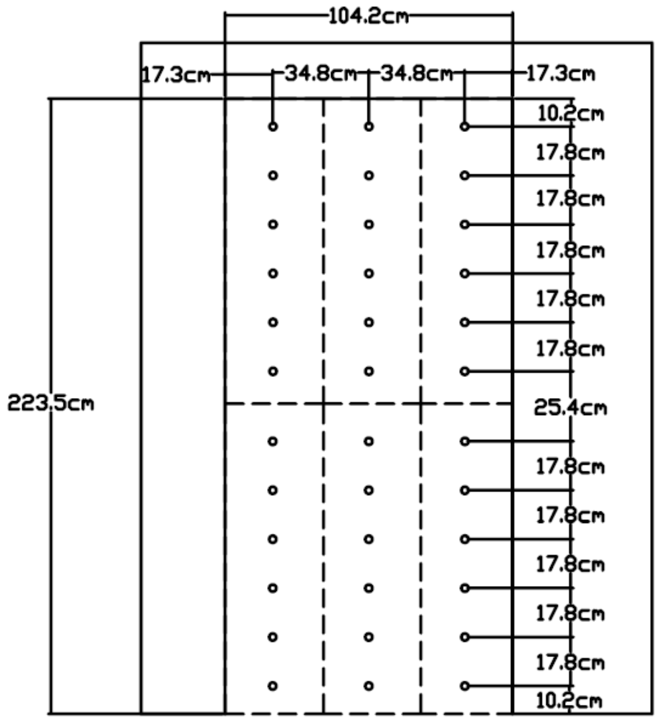

Figure 2: Doorway temperature and bidirectional velocity probe measurement locations.

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 pressure was 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 different 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 which was multiplied with the mass flux to produce a local mass flow. The summation of these flows that were positive (leaving the doorway) produced a mass flow out of the compartment.

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 [17]. The use of this information produced a local mass flux equation to determine experimentally measured flows given by:

$$\dot{m}'' = \frac{24.71}{T}\sqrt{T \Delta P}\,, \tag{3}$$

where, T is the local temperature (K) and ΔP is the pressure difference reported by the bidirectional probes (Pa). The constant in Equation 3 was developed from several other constants including the bidirectional probe calibration factor and ambient air properties [17]. The total mass flow out was then determined as:

$$\dot{m} = \sum_{k=1}^{n} A_i \dot{m}''_k\,, \tag{4}$$

Where, A_i is the area around each mass interpolation point (m^2), $\dot{m}''_k$ is the interpolated mass flux (kg/m^2s) 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 was reported as the neutral plane height.

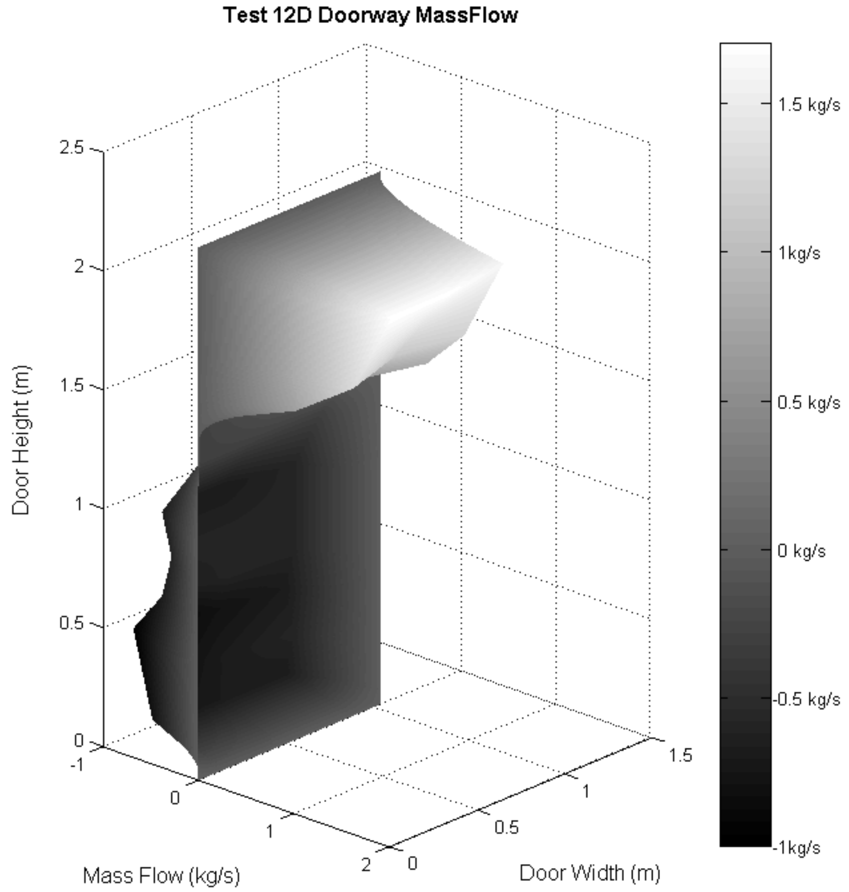

Figure 3: Surface plot of doorway mass flow. Negative mass flows represent flow into the compartment and positive mass flows represent flow out of the compartment.

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 [14], as shown in Figure 1. The thermocouple beads were spaced 0.15 meters apart starting 0.15 meters below the ceiling and ending 0.3 meters 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 8.35 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 these. Ambient temperature was determined from a third thermocouple tree placed outside of the compartment. The tree consisted of four thermocouples spaced 0.6 meters apart beginning 0.5 meters 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 0.93-0.94. This value is equivalent to calibration factors reported in McCaffrey and Heskestad's [18] original probe study. The reported error associated with a bidirectional probes with this calibration constant is about 7% [18]. The bidirectional pressure transmitters were accurate within 0.25% of its 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 [19]. The use of this technique produced a random normally distributed mass flow error of approximately ±10% [20]. The average error of ±10% is reported throughout the remainder of this report in graphs and figures.

Results & Analysis

The data gathered from the twenty-four tests is summarized in Table 1. 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 eliminates any sources of human error involved with setting the fuel and air flow rates and produces a set of tests most appropriate for comparison. The grouped tests are shown by matching test numbers followed by either a "D" or "W".

Table 1: Summary of experimental results. "D" denotes unsprinklered test results (dry tests), and "W" denotes a sprinklered test (wet test). Matching numbers in a test name signify that the tests were run back to back.

Test #	$\dot{Q}$ (kW)	T_G (K)	T_∞ (K)	Z_N (m)	$\dot{m}_{out}$ (kg/s)
1D	42	326	301	1.43	0.52
1W	42	309	300	1.34	0.42
2D	42	327	299	1.44	0.55
2W	42	309	300	1.33	0.41
3D	42	323	299	1.37	0.51
3W	42	308	299	1.31	0.42
4D	42	335	295	1.45	0.58
4W	42	312	294	1.43	0.42
5D	75	352	299	1.36	0.72
5W	75	331	301	1.41	0.58
6D	75	355	300	1.38	0.71
6W	75	333	301	1.37	0.60
7D	75	355	301	1.42	0.69
7W	75	325	302	1.34	0.54
8D	75	364	301	1.45	0.68
8W	75	332	297	1.46	0.55
9D	96	408	305	1.40	0.88
9W	96	354	308	1.43	0.61
10D	96	389	306	1.43	0.80
10W	96	357	307	1.46	0.62
11D	96	385	305	1.39	0.79
11W	96	348	306	1.36	0.64
12D	96	376	301	1.45	0.72
12W	96	338	297	1.46	0.59

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 unmonitored 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 [21]. Table 2 lists the mass flows into and out of the compartment showing that the mass flow in and mass flow out were 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.

Test #	$\dot{Q}$ (kW)	$\dot{m}_{out}$ (kg/s)	$\dot{m}_{in}$ (kg/s)	$\dot{m}_{out} / \dot{m}_{in}$
4D	42	0.58	0.56	1.05
4W	42	0.42	0.45	0.92
8W	75	0.55	0.54	1.02
12D	96	0.72	0.70	1.02
12W	96	0.59	0.65	0.90

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 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. The smoke layer interface was found to be below the neutral plane height for each of the three fire sizes when sprinklered and unsprinklered. This ensures that zone interface height is not required when evaluating the mass flow out of the doorway [22].

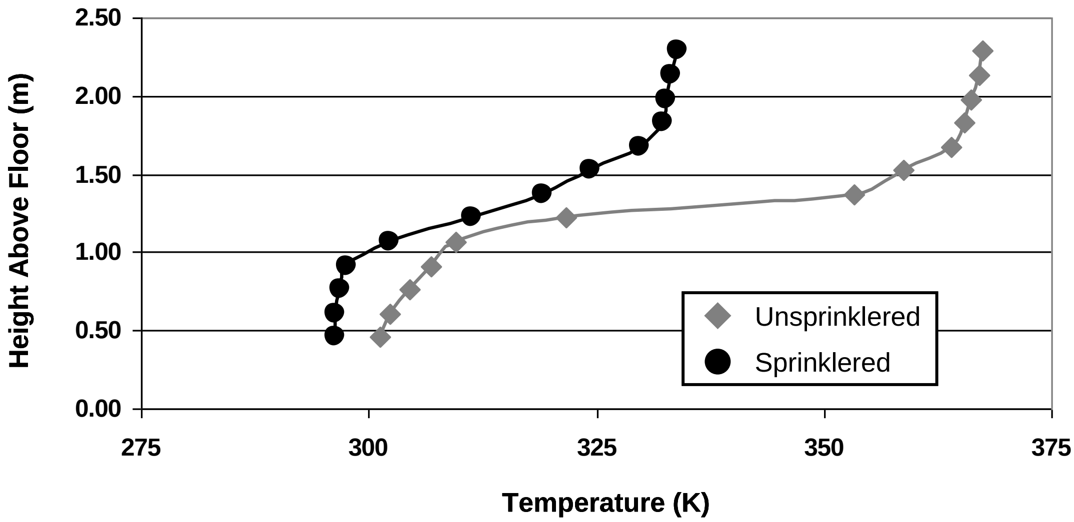

Figure 4: Temperature measurements inside the compartment away from the spraying sprinkler showing two distinct stratified layers in both the unsprinklered and sprinklered cases.

Neutral Plane

It is interesting to note that the neutral plane height at the doorway does not change with sprinkler activation. Figure 5 shows the non-dimensional neutral plane height (Zn/H) with respect to non-dimensional upper gas layer temperature (T_G/T_∞). Figure 5 shows there is a consistent neutral plane height (1.4m) 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 [14] 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.

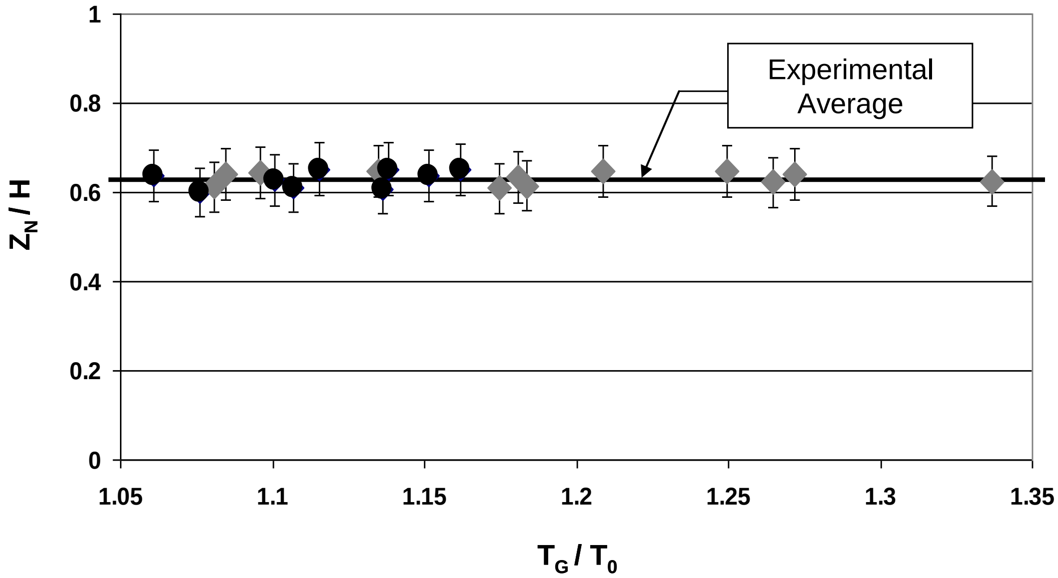

Figure 5: Non-dimensional neutral plane location versus non-dimensional upper gas layer temperature. The neutral plane height is constant for every test regardless of heat release rate or a sprinkler spraying.

Discharge Coefficient

In all previous work reported in the literature the discharge coefficient, (C_D), lies between 0.68-0.73 [14,15]. An idealized mass flow through a vent assumes that the flow is incompressible, isothermal, frictionless and has no heat losses [17]. Since the flow is not ideal in practice, and the assumptions are compensated for with a discharge coefficient, C_D. 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, there is error 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 generally around 10% [14]. Figure 6 shows that the discharge coefficient for both the unsprinklered and sprinklered experiments. The discharge coefficient was 0.77 which is statistically equivalent to the 0.76 coefficient reported for the unsprinklered tests and comparable to the discharge coefficients reported in previous studies [20].

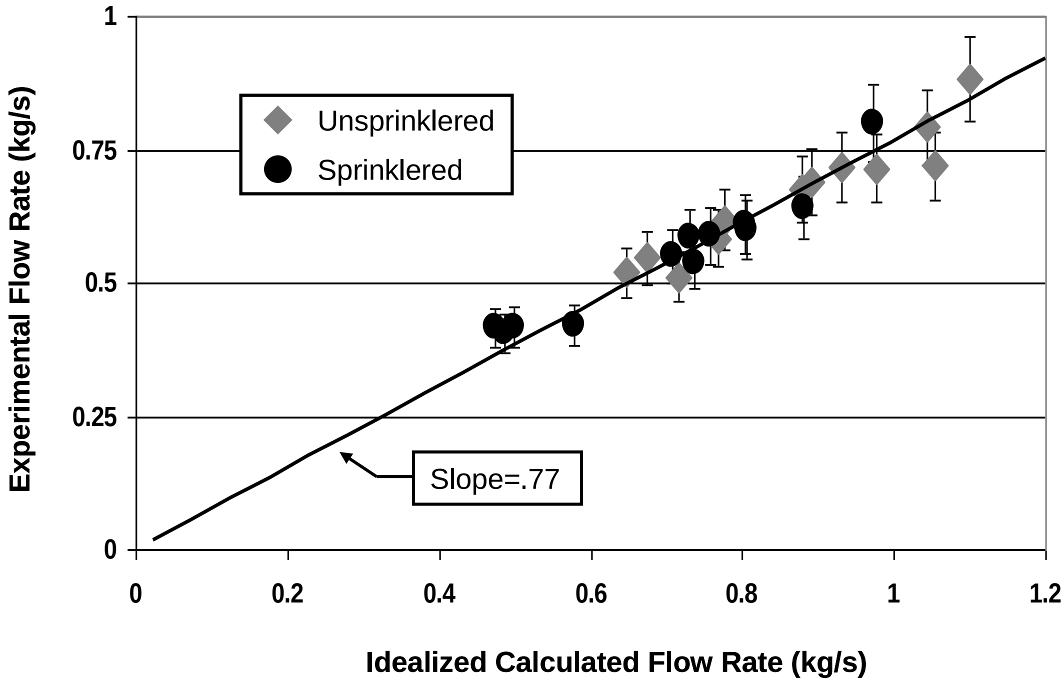

Figure 6: Determination of discharge coefficient with both unsprinklered and sprinklered tests. The C_D of 0.77 for both cases is very similar to the C_D of 0.76 for only the unsprinklered case.

Given that for this study both the doorway neutral plane height and C_D do not change it can be said that $\dot{m}_{out}$ 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.

Impact of Sprinkler Spray

The relationship between $\dot{m}_{out}$ versus fire 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. The average reduction in mass flow for all experiments is 21%. Figure 8 shows a side by side comparison of tests 8D and 8W. This comparison shows the major reduction in flow leaving the doorway. This figure also shows the equal neutral plane heights for a sprinklered and unsprinklered scenario.

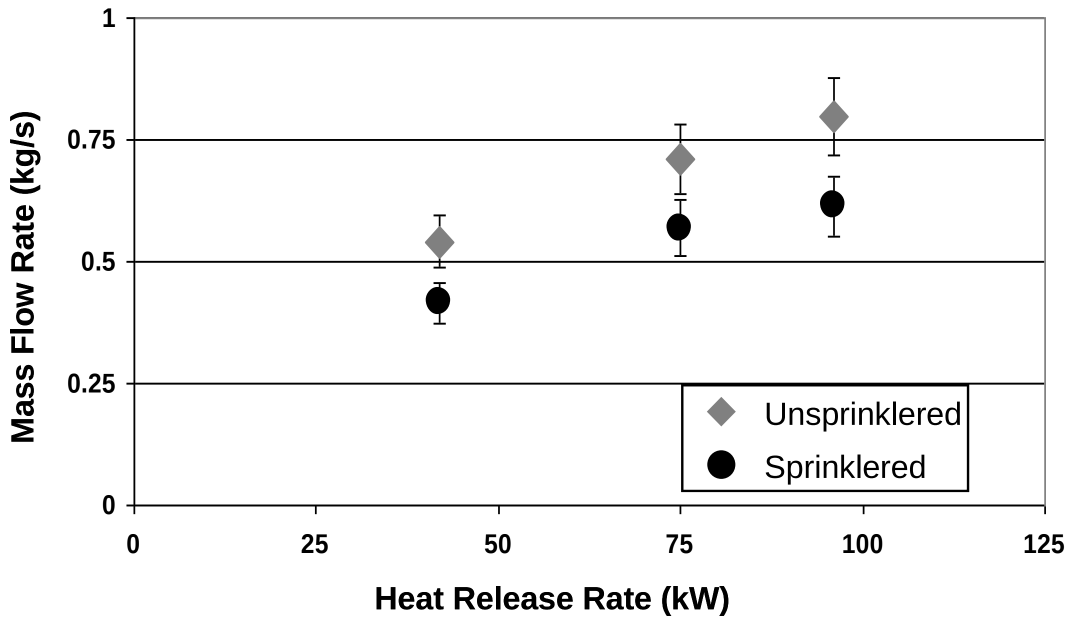

Figure 7: Average experimentally determined mass flow out of compartment versus fire heat release rate, showing the reduction in mass flow out of the compartment.

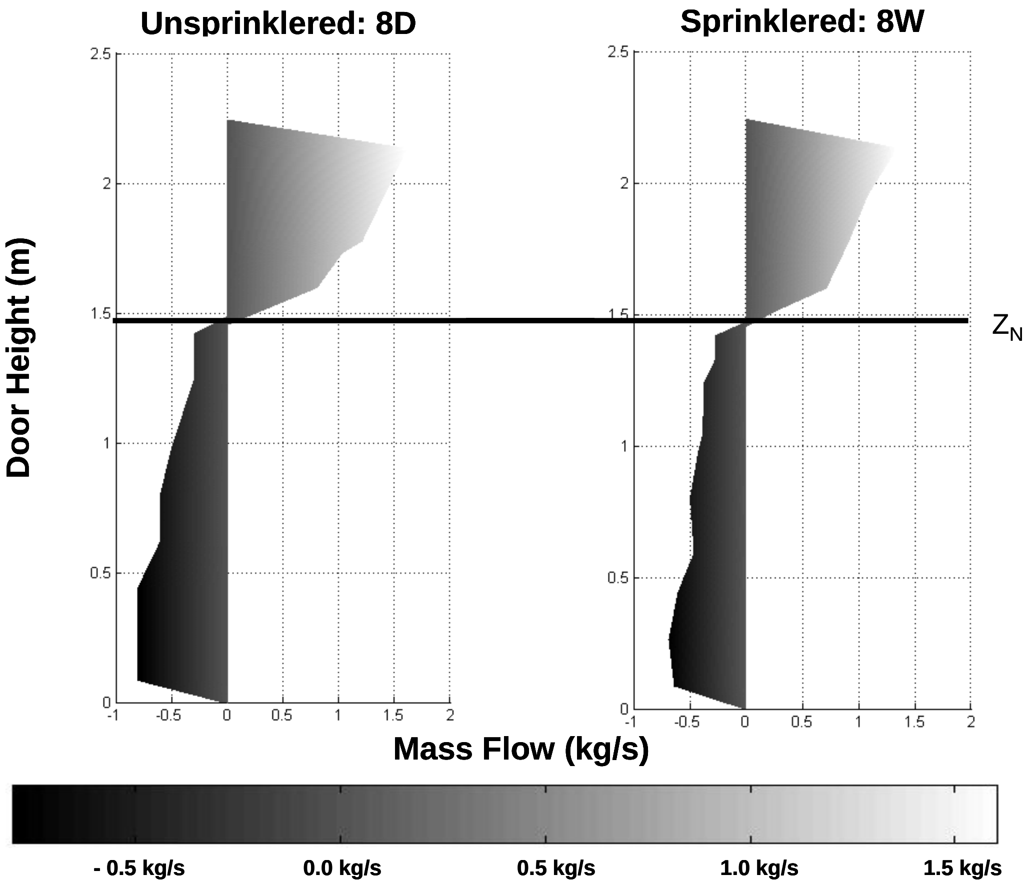

Figure 8: Comparison of doorway flows for tests 8D and 8W showing the reduction in mass flow leaving the doorway and the equivalent neutral plane heights for both tests. Test 8D had an experimentally determined mass outflow of 0.68 kg/s and test 8W had an experimentally determined mass outflow of 0.55 kg/s. The reduction in mass flow between the two tests was 19%.

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 (Cd = 0.77) and average neutral plane height (Zn = 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 and predicted values (Equation 1) show good agreement.

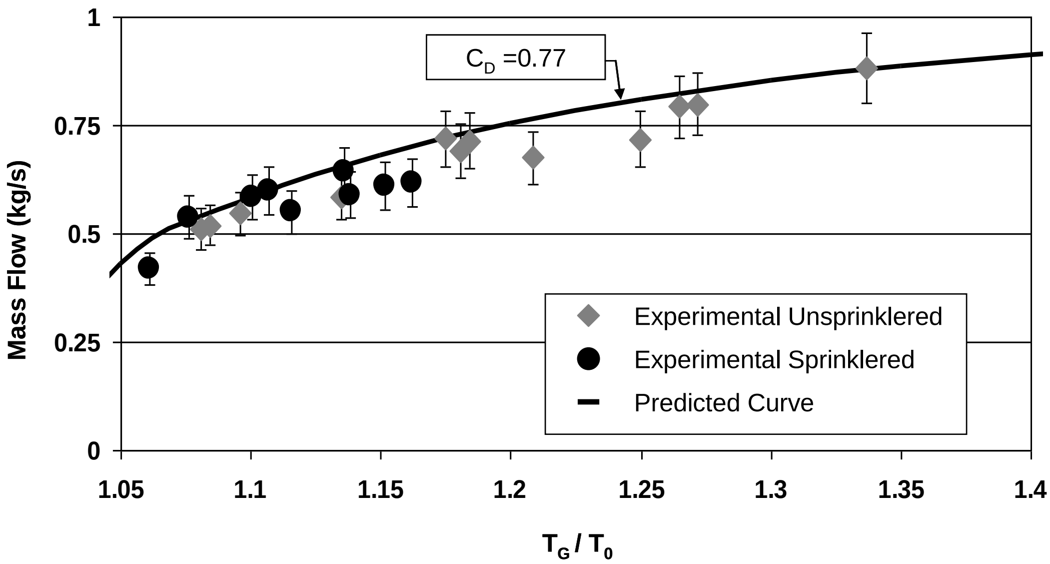

Figure 9: Predicted and experimentally measured mass flow rates leaving the compartment for both sprinklered and unsprinklered cases. The mass flow is predicted assuming a constant neutral plane.

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 this specific compartment size, sprinkler type, sprinkler flow and fire sizes, where flow remains stratified at the doorway. The results suggest that this type of analysis can be extended to additional situations. These results also 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 origin. This can lend itself to performance based design techniques because the reduction in mass flow is consistent throughout testing. The results imply that knowledge of the temperature reduction resulting from a sprinkler spray does not need to be known to predict the impact of the sprinkler spray on doorway mass flow rate.

A sprinkler cooling coefficient can be assigned to the Tyco LFII sprinkler (TY2234) which can account for the reduced mass flow. This testing suggests 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 updated vent mass out flow is given by:

$$\dot{m}_{out} = \frac{2}{3} C_D C_S W \rho_\infty \sqrt{2 \frac{T_\infty}{T_G}(1 - \frac{T_\infty}{T_G}) g} \left(H - Z_N\right)^{3/2}, \tag{5}$$

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 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 a complete 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.

Nomenclature

$\dot{m}_{out}$ Mass flow rate leaving vent [kg/s]

C_D Vent discharge coefficient

W Width of doorway [m]

ρ_∞ Ambient density [kg/m^3]

T_∞ Ambient temperature [K]

T_G Upper gas layer temperature [K]

T_{CJ} 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]

ΔP Differential pressure measured by bidirectional probes [Pa]

Acknowledgements

Special thanks to Tyco Fire Suppression & Building Products Global Technologies Center for generously devoting facilities and resources. The authors would like to thank Dr. John Woycheese for helping to initiate this project.

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