Validation Study for Smoke Detector Response in FDS

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Abstract

A study was conducted to assess the smoke detector activation predictive capability of the Fire Dynamics Simulator (FDS) model using a threshold smoke concentration method for photoelectric detectors and flaming fires. A series of experiments measuring smoke detector response was conducted in a 11.0 m by 7.3 m by 3.7 m high room generating data to assess the accuracy of computer fire model predictions of detector activation time. The room included a single opening 2.44 m high and 1.83 m wide centered in one of the short walls. Experiments were conducted for two ceiling configurations, one that was smooth and one with two 0.3 m wide, 0.3 m deep solid beams.

The fire source was a gaseous fuel burner fed with different mixtures of propane and propene that produced soot yields ranging from 0.010 g_{soot}/g_{fuel} to 0.072 g_{soot}/g_{fuel} and a ramping fuel flow that ranged from 30 s to 1800 s to nominal heat release rate of 30 kW. The activations of two different models of photoelectric smoke detectors, each with a range of alarm set points and installed at various locations on the ceiling and beams, were recorded. A comparison between experimental measurements and predictions of detector activation using FDS version 6.7.4 were made. Across the detector sensitivity range and fire scenarios studied, the predictions compared favorably to the experimental results.

Keywords: Fire detection, smoke detectors, compartment fires, Fire Dynamics Simulator

Introduction

When it comes to predicting smoke detector activation there is a choice to be made from solving simplified algebraic equations, running zone fire models, or running CFD fire models which is driven by the user needs and computational resources. Recently, the predictive capability of the zone fire model CFAST's fixed smoke concentration detector activation sub-model was compared to the experimental results for the flaming gaseous fires describe below [1]. Overall the CFAST results compared favorably, with the prediction of smooth ceiling experiments generally better than the beamed ceiling experiments. The CFAST predictions with the smoke detection sub-model were much better than the fixed temperature rise model (for any temperature rise chosen) over the range of conditions examined. A comparison is being undertaken here to assess the smoke detector activation predictive capability of the fire model FDS using the same smoke concentration threshold method employed with the CFAST study.

Fire model validation is typically performed by comparing model simulations with experimental measurements to identify a given level of accuracy for a given range of parameters and type of fire scenarios. FDS software [2] is subjected to ongoing validation testing of the model [3]. Smoke detector activation is both a categorical event and a continuous time-to-alarm value, thus model accuracy assessment should consider both event classifications and deviations from predicted to measured alarm times.

Modeling Scenarios in FDS

In CFAST, the detector activation occurs when the upper layer smoke concentration reaches a fixed value. In FDS, the smoke obscuration threshold model compares the local grid cell smoke concentration to a fixed obscuration level where a detector is located for detector activation. The room was modeled with 10 cm cubic grid cells. The computational domain extended for 4 m outside the room opening to allow for modeling of the flow leaving the room. The drywall on the walls was modeled with 12.7 cm thick gypsum, with ambient temperature of 25 °C prescribed on the outside. The smoke coagulation and deposition routines were not considered.

Two photoelectric-type smoke alarms were considered, one with an infrared light emitting diode emitter (herein referred to as photoelectric detector) and one with an infrared laser diode emitter (herein referred to as laser detector), and each detecting forward scattered light. Both are treated identically with their nominal sensitivity adjusted to the corresponding flaming fire soot obscuration at alarm. The nominal sensitivity is related to the ANSI/UL 268 smoke box smoldering cotton wick obscuration at alarm [4]. A correction factor of 3.5 was applied to the smoke concentration at alarm to adjust the smoke obscuration for flaming soot which scatters less light than an equivalent amount of the smolder smoke. The value of 3.5 was empirically determined and is the same value used in the CFAST modeling study [1].

Table 1 shows the nominal pre-alarm and alarm sensitivities (denoted as SP for set point) and the adjusted sensitivities for photoelectric and laser detectors responding to flaming fire smokes. The threshold method assumes smoke aging does not affect detector response.

As soot agglomerates grow, they form larger agglomerates which absorb and scatter about the same amount of light as the original un-aged agglomerates, thus for flaming fires, smoke aging may not have a significant effect on light scattering detector response. No smoke entry delay was accounted for in the threshold method which would be a reasonable assumption for modern smoke detectors if the local velocity was relatively high (> 0.2 m/s) [5].

Table 1. Nominal detector sensitivities and corrected sensitivities for flaming soot.

Detector	Sensitivity Setting	ANSI/UL 268 Sensitivity %/m (%/ft)	Flaming Sensitivity %/m Obscuration
Photo 1	SP1, Pre-alarm	3.21 (0.99)	10.9
Photo 1	SP2, Alarm	5.34 (1.66)	17.8
Photo 2	SP3, Pre-alarm	4.84 (1.50)	16.2
Photo 2	SP4, Alarm	7.51 (2.35)	24.6
Laser 1	SP1, Pre-alarm	1.63 (0.50)	5.59
Laser 1	SP2, Alarm	3.24 (1.00)	10.9
Laser 2	SP3, Pre-Alarm	3.24 (1.00)	10.9
Laser 2	SP4, Alarm	6.41 (2.00)	20.7

Experimental

A series of experiments measuring smoke detector response was conducted in a 11.0 m by 7.3 m by 3.7 m high room generating data to assess the accuracy of computer fire model predictions of detector activation time. The room included a single opening 2.44 m high and 1.83 m wide, centered in one of the short walls. Experiments were conducted for two ceiling configurations, one that was smooth and one with two 0.3 m wide, 0.3 m deep solid beams. The beams spanned the shorter ceiling dimension, partitioning the ceiling into three equal areas. Figure 1 shows a schematic of the detector/alarm locations and other measurement locations for the smooth ceiling configuration, and Fig. 2 is a schematic of the beamed ceiling configuration.

Each fire scenario was repeated three times for both the smooth and beamed ceiling configurations with the six fire scenarios. A detector maintenance report was run on the fire alarm control panel each day before experiments were begun to confirm that all detectors were operational and drift compensation levels were within acceptable limits. No detectors indicated a maintenance alert during the experimental campaign.

See [1] for results from other measurements gathered for two scenarios of representative middle of the room ceiling temperature, flow velocity and smoke obscuration values obtained and their repeatability.

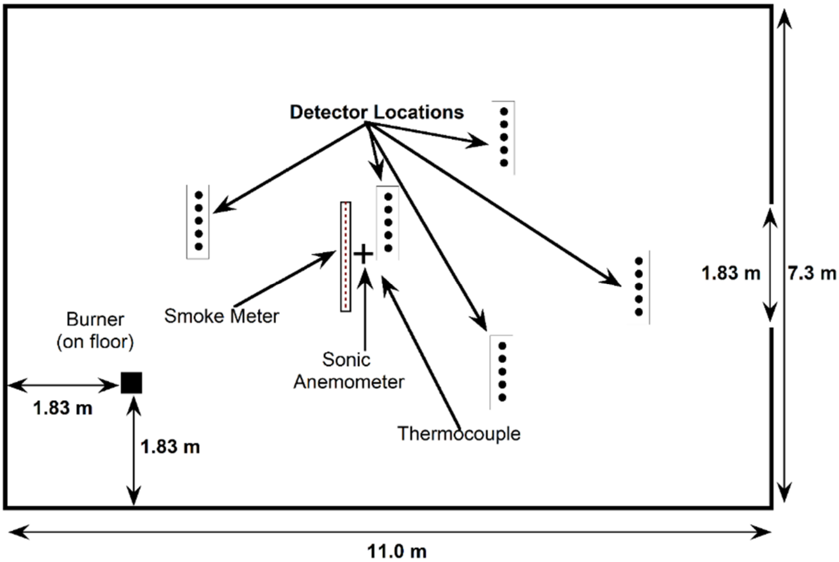

Fig. 1. Schematic diagram showing the placement of ceiling-mounted detectors (small circles), a ceiling smoke meter and the burner fire source (floor location) for the smooth ceiling configuration.

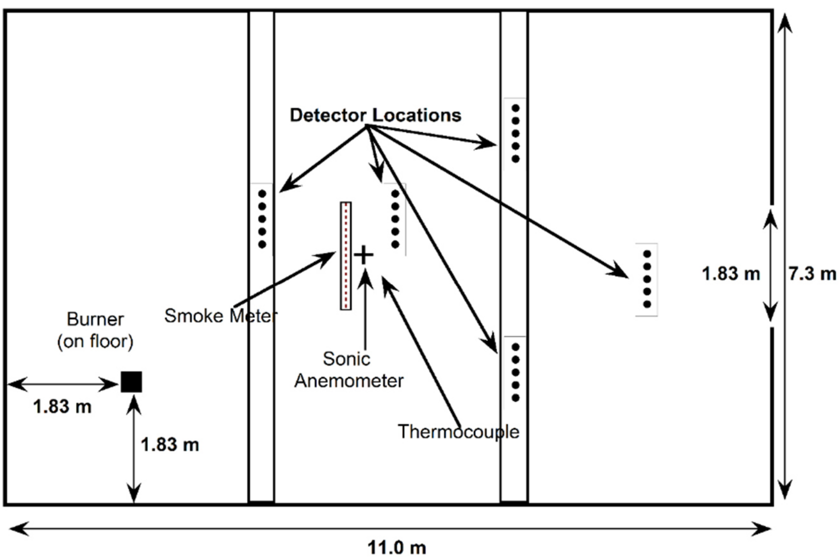

Fig. 2. Schematic diagram showing the placement of ceiling-mounted detectors (small circles), a ceiling smoke meter and the burner fire source (floor location) for the beamed ceiling configuration.

Table 2 details the various scenarios examined for the flaming sooty fires. The experimental design was formulated to capture a wide range of detector exposure conditions by manipulating the fire growth rate and the soot yield of a flaming gaseous fuel burner. The heat release rates (HRR) are nominal values from the fuel flow rates and the net heat of combustion of the fuel mixtures. The HRR at ignition (Ign.) was held at a steady value until the ramp value exceeded it.

Smoke from the various fuel mixtures was characterized with experiments using the NIST furniture calorimeter. The average specific extinction coefficient for all fuel mixtures was 7.9 m^2/g (± 0.4 m^2/g), and the measured soot yields at 30 kW fire size were (± 10 %): Propane – 0.010 g_{soot}/g_{fuel}, 25/75 mix – 0.022 g_{soot}/g_{fuel}, 50/50 mix – 0.033 g_{soot}/g_{fuel}, Propene – 0.072 g_{soot}/g_{fuel}.

Table 2. Fire Scenarios.

Scenario	Propane mole fraction	Propene mole fraction	HRR at Ign. (kW)	Ramp time to 30 kW (s)	30 kW hold time (s)
1	0	1.00	3.0	30	150
2	0.50	0.50	3.0	300	60
3	0.50	0.50	3.0	900	60
4	0.75	0.25	6.0	900	60
5	0.75	0.25	6.0	1800	60
6	1.00	0	3.0	30	210

Comparison of Experimental Results to Model Predictions

The ability of the model predictions to classify the experimental results by predicting detector activations and non-activations correctly is an important comparison. Where all measured activations were modeled as activations and all non-activations were modeled as non-activations, classification is perfect. The deviation from perfect classification is characterized by the sensitivity and selectivity. The sensitivity, the proportion of detector activations that were predicted to be activations, is defined as the ratio of the true positives (TP) to the sum of the true positives and false negatives (FN), TP/(TP+FN).

Likewise, specificity, the proportion of detector non-activations that were predicted to be non-activations, is defined as the ratio of the true negatives (TN) to the sum of the true negatives and false positives (FP), TN/(TN+FP) where N is the number of detectors and TN = (N-FP-FN-TP). Table 3 shows the sensitivity and selectivity for the FDS and CFAST (from ref. [1]) simulations. Overall, the results for FDS and CFAST predictions are comparable. A decrease in detector set points would increase sensitivity but likely decrease selectivity.

Table 3. Sensitivity and Selectivity for modeled detector activations

Detector, Ceiling Configuration	FDS		CFAST	
	Sensitivity (%)	Selectivity (%)	Sensitivity (%)	Selectivity (%)
Photo, smooth	80	100	98	100
Photo, beamed	89	100	67	100
Laser, smooth	89	90	99	90
Laser, beamed	96	96	85	100

In general, for an unbiased assessment of model uncertainty through regression analysis, only cases with both high sensitivity and specificity should be considered. The FDS results show high sensitivity and selectivity; therefore, linear regression through the origin of experimental versus modeled detector activation time for all of the separate cases was performed. Figs. 1 and 2 show the comparisons for the different detector set points and room configurations.

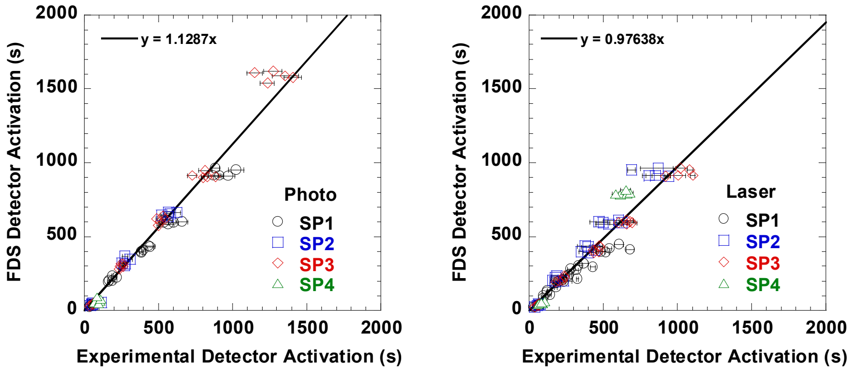

Fig. 1. Smooth ceiling configuration predicted versus experimental detector activations for the photoelectric detector (left) and laser detector (right). The symbols represent the four different set points specified. The line and equation are for a linear best fit line passing through the origin. Error bars represent ± one standard deviation of the repeated experimental values.

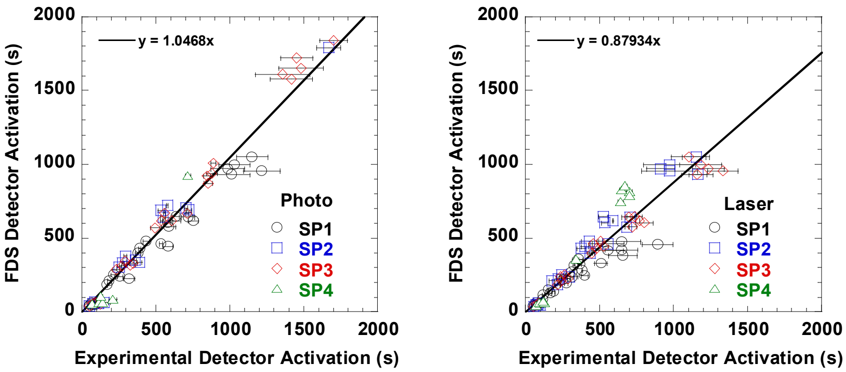

Fig. 2. Beamed ceiling configuration predicted versus experimental detector activations for the photoelectric detector (left) and laser detector (right). The symbols represent the four different set points specified. The line and equation are for a linear best fit line passing through the origin. Error bars represent ± one standard deviation of the repeated experimental values.

The slopes range from 0.88 to 1.13 with the data points clustered around the fit lines indicating good linearity. An apparent trend is larger slope for the photoelectric detector compared to the laser detector, and larger slope for the smooth ceiling than the beamed ceiling. It is not clear if these apparent trends are related to biasing from the modeling assumptions or the detector sensitivity assumptions.

Conclusions

A threshold smoke concentration method for photoelectric detector activation in flaming fires was used in FDS simulations of room fire experiments. The threshold value for detector activation was specified as 3.5 times the extinction coefficient of the detector reference set point to primarily account for the scattering signal difference from smoldering wick smoke and flaming soot. For the scenarios considered, predictive results for the two detectors modeled showed good sensitivity and selectivity. Linear regression of the predicted versus experimental detection times showed slopes ranging from 0.88 to 1.13 for the four sets of configuration and detector data.

References

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