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Developing Detector Siting Rules from Computational Experiments in Spaces with Complex Geometries

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ABSTRACT

The National Institute of Standards and Technology (NIST) is conducting a 4-year research project wherein a computational fluid dynamics (CFD) computer code is utilized to map temperature, flow velocities, and particle densities in spaces with complex ceiling geometries. Through parametric variation of independent variables for the fire and the space, the number and location of smoke or thermal sensors required to assure response prior to a critical fire size is determined. The first year addressed horizontal ceilings with open beams or joists, and the second year adds sloped ceilings.

In addition to the geometric studies, several special studies have been conducted. These include detection of low energy fires (as low as 100 W), stratification of fire gases in spaces with a vertical thermocline which exceeds the plume temperature, and obstructions which do not come completely to the ceiling. A unique method of relating the response of detectors to the predicted conditions has been developed which can be utilized with any CFD model or with experimental data. The data analysis is being used to produce siting rules for inclusion directly into existing codes. The paper will review the results of the first 2 years of the project and present some thoughts on the potential for these techniques to greatly improve the technical basis for the utilization of fire sensors in complex installations. Published by Elsevier Science Ltd.

1 INTRODUCTION

The rapid activation of fire detection and suppression systems in response to a growing fire is one of the important factors required to provide for life safety and property protection. Rapid activation requires that sensors be located at optimal distances both beneath the ceiling and radially from the fire. Ceiling obstructions, such as beams and joists, and ceiling slope can significantly modify the smoke flow and must be taken into consideration when a particular detection system is designed. At present, the standards used to guide the design of these systems contain very little quantitative information concerning the impact of beamed ceilings on sensor placement.

A multi-year, International Fire Detection Research Project sponsored by the National Fire Protection Research Foundation (NFPRF) was initiated to provide quantitative information on the impact of beams, ceiling slope, and forced ventilation on the movement of smoke. During the first year of the project, numerical modeling was validated and additional simulations of level, beamed ceilings were completed.[1] During the second year, numerical simulations of smoke movement in response to sloped, beamed ceilings were conducted. Based on the projected smoke movement, activation times of smoke and heat sensors were calculated. Recommendations on sensor selection and placement were made based on the activation studies.

During years 3 and 4 of this project the effects of HVAC systems on smoke flow and detector response will be studied.

2 MODELING ASSUMPTIONS

CFDS-FLOW3D[2] was used to perform the numerical simulations. The region of interest was divided into a collection of small rectangular boxes or control volumes. The flow or exchange of mass, momentum and energy between control volumes is determined so that these three quantities are conserved.

The original empirical turbulence parameters proposed by Launder & Spalding[3] (the default in the field model) were used during the first year of this project. A recent analysis given in Notarianni & Davis[4] suggests that the parameter set of Nam & Bill[5] may be superior to the default parameters, and were used in year 2.

Because of the short times for contact between the gas and ceiling surfaces, solid boundaries were generally assumed to be adiabatic. To test whether the adiabatic assumption was reasonable, both conducting and non-conducting ceiling cases were modeled for sloped ceiling cases where beams were perpendicular to the slope, using the thermal properties for wall board. For both smoke and thermal devices, predicted gas temperatures and sensor activation times were found to be not significantly affected by the adiabatic assumption.

Radiation effects were not included explicitly in the calculation except that only a fraction of the heat release rate was assumed to contribute to convective heating of the smoke and air. The rest of the heat was considered to be radiated away. The radiative fraction was taken to be 35% for all simulations.

The total number of grid cells used to represent the various geometries varied from 13 000 to 25 000. The fire was centered on two symmetry planes (for flat ceilings) or one symmetry plane (for sloped ceilings) for all cases. For sloped ceiling, the side opposite the symmetry plane was also chosen to be a wall and was located at a distance of 7.3 m (24 ft) from the symmetry plane. The high side of the slope was a combination of wall and open boundary conditions. Ceiling beams were represented by thin surfaces which are mechanisms within the field model for preventing fluid from moving directly from one grid cell to another. The region below the high end of the sloped ceiling and far from the fire did not significantly affect flow either below the ceiling or near the fire. Therefore this region was not included in the calculations in order to save computer time.

The fires used in the simulations were fast, medium and slow growth "t^2" fires designed to reach 1.055 MW (1000 Btu/s) in 150, 275, 600 s, respectively.[6] In year 2, only the medium growth curve was used since it represents the broadest range of actual fires which might be encountered in practice, and the previous study[1] showed that the results were not sensitive to the fire growth rate.

The fire was modeled by releasing energy over several grid cells. The number of grid cells occupied by the fire was varied during the simulation such that the maximum energy release per volume would be about 2.6 MW/m^3 which approximates the heat release rate of a 0.46 m (1.5 ft) high stack of wood pallets.[7]

Comparisons between full-scale experiments performed by Heskestad & Delichatsios[8,9] and numerical experiments[1,10] using the field model[2] show that CFD techniques can be used to predict smoke flow under beamed ceilings.

3 CASE STUDY

3.1 Scope

This study was designed to demonstrate how beam depth, beam spacing, and ceiling height impacted heat and smoke movement. For flat ceilings, beam depths of 0, 0.1, 0.2, 0.3 and 0.61 m (0–24 in.) were studied at spacings of 1.2, 1.5, 1.8, 2.0 and 2.4 m (4–8 ft) with ceiling heights varying from 3.3 to 8.5 m (11–28 ft). Ceiling slopes of 10, 25 and 50° were studied for beams running parallel to the slopes at depths of 0.10, 0.20, 0.30 and 0.61 m (4.0, 8.0, 12 and 24 in.), beam spacings of 1.2 m and 2.4 m (4 ft and 8 ft), and ceiling heights of 3.4 m and 4.6 m (11 ft and 15 ft). Beams running perpendicular to a 25° slope were studied for beam depths of 0.15, 0.30 and 0.46 m (6.0, 12 and 18 in).

Special cases with gaps between the beam and the ceiling were studied for a ceiling slope of 50° and a beam spacing of 1.22 m (4 ft), for beams parallel to the ceiling, and a ceiling slope of 25° and a beam spacing of 2.4 m (8 ft) and for beams perpendicular to the ceiling.

Ceiling slopes of 10, 25 and 50° with no beams, i.e. smooth ceiling cases, were included and several of the beamed ceiling cases were done with two different venting configurations.

3.2 Analysis

Smoke detector activation was calculated by assuming that particle density would correlate with temperature and that smoke detectors would activate when the temperature reached a value of 13°C above ambient.[9] For heat sensors, the activation temperature was chosen to be 57°C (135°F) and the thermal inertia of the sensing element to be represented using the differential equations developed in Heskestad & Smith.[11]

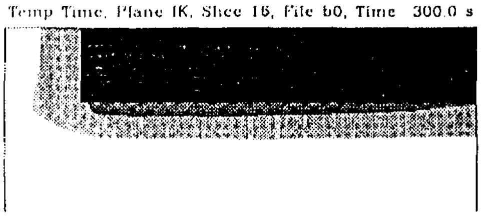
$$\frac{dT_L}{dt} = \frac{\sqrt{U(t)}}{RTI}(T_g(t) - T_L(t))$$

$$T_L(0) = T_g(0)$$

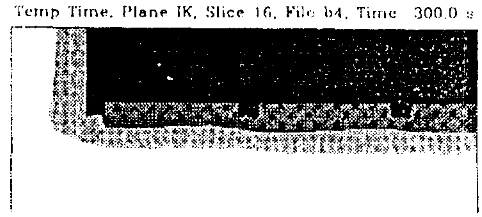
where T_L is the link temperature, RTI is a measure of the sensor's sensitivity to temperature change (thermal inertia), and T_g and U are the gas temperature and flow velocity calculated by the field model. RTI values used in these studies included 50, 100 and 300 $(m\,s)^{0.5}$. This model assumes that forced convection is the dominant mode of heat transfer and ignores heat loss due to radiation and conduction.

4 OBSERVATIONS

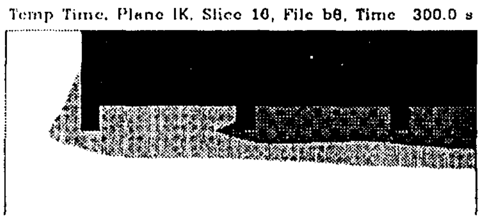
Representative observations are given here for the effect of beam depths, spacing, ceiling height, and slope on smoke flow and detector response. A more thorough documentation of these observations may be found in Forney *et al.*[1] and Davis *et al.*[12]



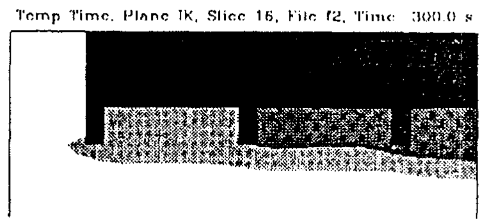
(a) smooth ceiling



(b) 0.1 m (4 in) beam depth



(c) 0.2 m (8 in) beam depth



(d) 0.3 m (12 in) beam depth

Fig. 1. Shaded contour plot of smoke detector response volumes for 1.22 m (4 ft) beam spacings, 3.35 m (11 ft) ceiling height at several beam depths. Dark (light) grey represents 100 kW (1 MW) activation region.

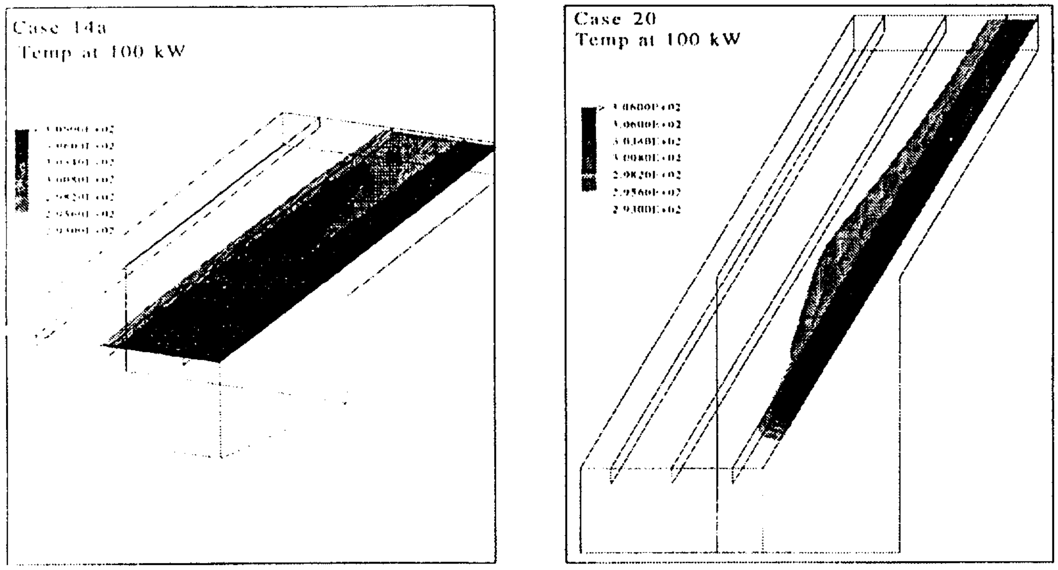
4.1 Level ceilings

When beams are sufficiently deep no flow gets into adjacent channels. This can result in earlier sensor activation times under beamed ceilings than under smooth ceilings, provided that a sensor is located in every channel. A related observation is that beams cause flow near the ceiling to slow down and as a result, temperatures are higher near the ceiling for beam cases than for non-beam cases. Due to the dependence on $\sqrt{\textit{flow velocity}}$, heat detectors can be adversely affected by the reduced ceiling jet velocity. The activation time (time normalized to when a fire reaches 1 MW) of sensitive sensors (smoke detectors or RTI = 50 heat detectors) is independent of fire growth rate. Figure 1 shows the effect of beam depth on sensor activation.

Conditions in beam channels may be equivalent (in the sense that a sensor will activate in the same time) to conditions under beams.

4.2 Beams parallel to the ceiling slope

Many of the observations stemming from calculations involving sloped ceilings occur due to the component of the buoyancy force parallel to the sloped ceiling. This force component produces an asymmetrical flow



(a) 10 degree slope (b) 50 degree slope

Fig. 2. Contour plots of smoke detector response for two slopes with 0.30 m (12 in.) deep beams and a t^2 fire that reaches 100 kW in 87 s.

situation where flow down the sloped ceiling is slowed while flow up the sloped ceiling continues to be accelerated.

Beams trap flow more effectively as the ceiling slope is increased. Beams which may not be deep enough to trap flow on ceilings with only small slopes may be extremely effective in trapping flow as the ceiling slope is increased. Figure 2 illustrates this by comparing the trapping capability for 0.30 m (12 in.) beams for 10 and 50° sloped ceilings with beams 2.4 m (8 ft) on center at a fire size of 100 kW. For the 25 and 50° ceiling slope, the smoke detectors will activate in only the first channel, while for the 10° ceiling slope, smoke detectors will activate in the first and second channels since at this slope, the beams are not as effective at constraining the hot gas flow.

Similarly, the greater the ceiling slope, the less the flow penetrates down the slope from the fire center. Figure 2 compares the penetration distance from plume center for a 10° slope ceiling and a 50° slope ceiling for a ceiling height of 3.4 m (11 ft), beam depth of 0.30 m (12.0 in.), beam separation of 2.4 m (8.0 ft), and fire size of 100 kW. For the 10° slope, smoke detectors would activate nearly to the back wall. Very little down-slope penetration is observed for the 50° slope case. For all cases analyzed, only smoke detectors will activate at the 100 kW fire size. Thermal sensor activation has not occurred at either 3.4 m (11.0 ft) or 4.57 m (15.0 ft) ceiling heights at this fire size.

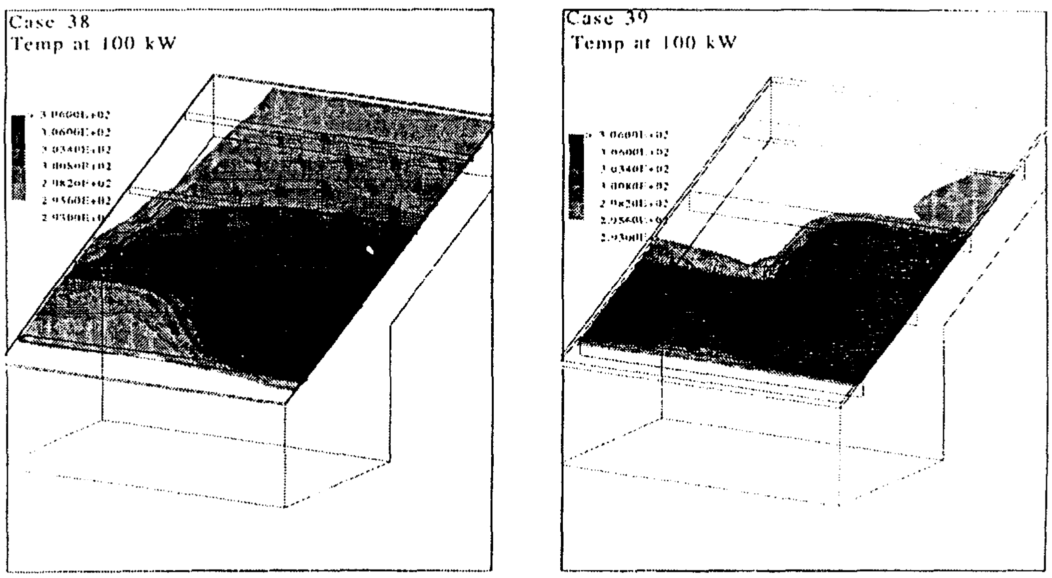
Activation conditions under beams may be equivalent to activation conditions in adjacent beam channels. The speed of the gas decreases as the plume nears the ceiling but then accelerates along the ceiling slope.

4.3 Beams perpendicular to the ceiling slope

Perpendicular beams cause the gas flow to be, in part, re-directed along the beams. The component of the buoyant force parallel to the ceiling will still be a factor in accelerating the gas along the ceiling slope. Since there is significant flow directed along the beam, the presence of a wall will stop the gas flow along the beam and make it move up over the beam at the wall location.

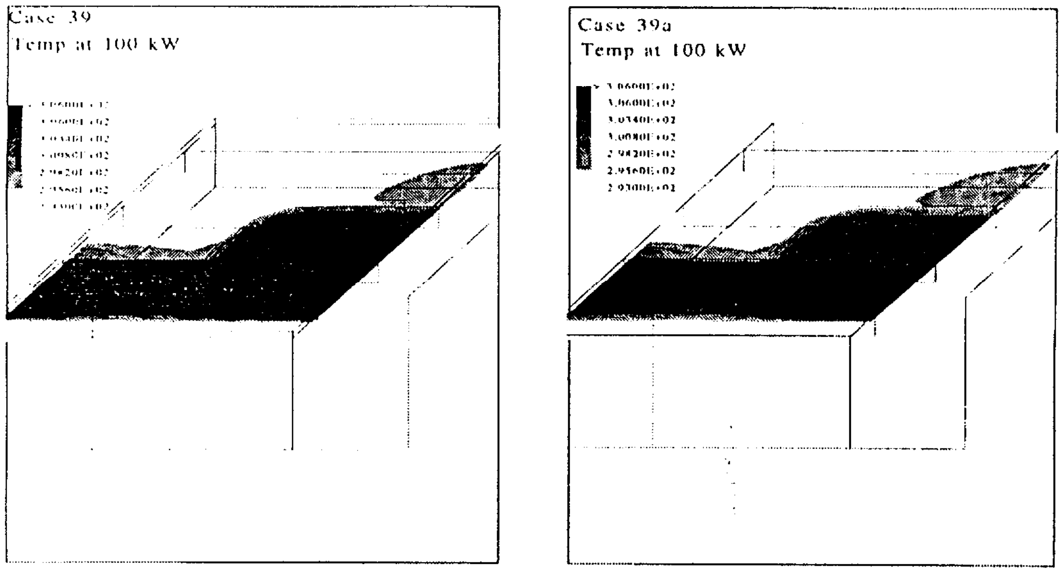
Perpendicular beams impede the flow up the ceiling. The 0.15 m (6 in.) beams permit more flow than the 0.45 m (18 in.) beams which tend to channel more flow along the beams, as shown in Fig. 3.

When the upslope flow starts to fill a higher beam channel, conditions for detection 0.076 m (3.0 in.) beneath the beam are equivalent to the conditions in the higher channel. Comparison of conducting and non-conducting ceilings (see Fig. 4) demonstrated that the adiabatic assumption was reasonable. Increasing the ceiling slope decreases the effectiveness of the perpendicular beams in impeding the flow of smoke up the ceiling.



(a) 0.15 m (6 in) beam depth (b) 0.46 m (18 in) beam depth

Fig. 3. Contour plots of smoke detector response for two beam depths for a 25° sloped beamed ceiling and a t^2 fire that reaches 100 kW in 87 s.



(a) 100 kW, non-adiabatic (b) 100 kW, adiabatic

Fig. 4. Effect of the non-adiabatic assumption on smoke detector response for a 25° sloped beamed ceiling with 0.46 m (18 in.) deep beams.

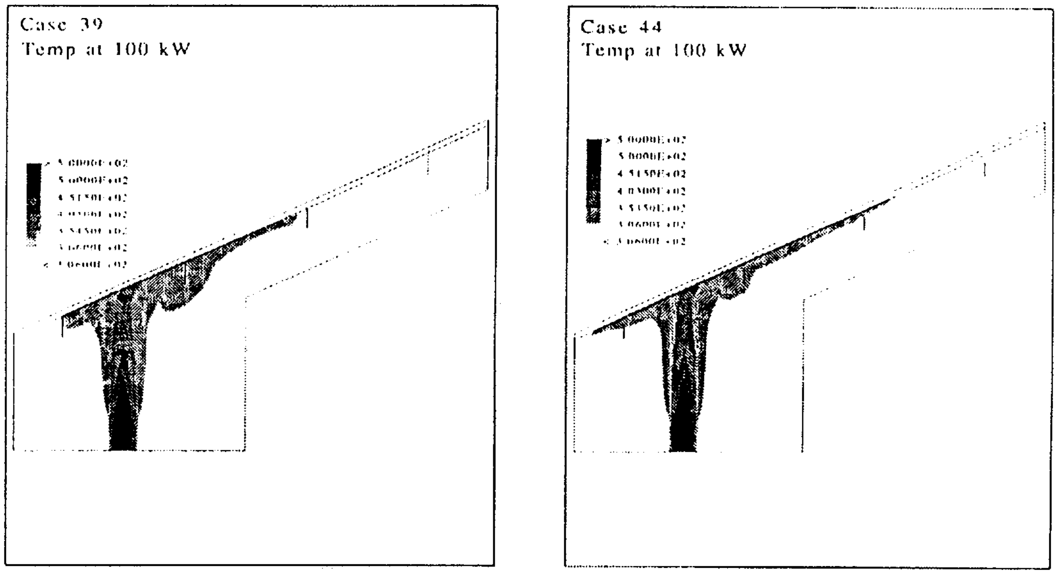
4.4 Parallel beams with gaps

The presence of a gap between the top of the beam and the ceiling should provide some access for gas flow into adjacent beam channels. The simulation used for this study was a 50° sloped ceiling with 0.30 m (12 in.) beams 1.22 m (4.0 ft) on center with the beams running parallel to the slope. The gap was located next to the ceiling and was 0.076 m (3.0 in.) deep. The gap allows the gas flow to reach additional adjacent channels. For each fire size, the presence of the gap allows smoke detectors to activate in an additional adjacent channel. The upslope activation of smoke detectors and heat sensors is decreased when a gap is present. The presence of a gap does not permit activation of heat sensors in additional beam channels for the 1 MW fire size.

4.5 Perpendicular beams with gaps

The presence of a gap between the top of a beam and the ceiling should permit hot gas flow to move more freely in the upslope direction. The simulation used to study this case was a 25° sloped ceiling with a 0.13 m (5 in.) gap in a 0.46 m (18 in.) beam.

The gap permitted more rapid flow up the ceiling slope. Comparing



(a) 100 kW, no gap (b) 100 kW, 0.13 m (5.0 in) gap

Fig. 5. Contour plots illustrating the effect of gaps at the top of a beam on smoke detector response. Each case has a 25° sloped beamed ceiling with 0.46 m (18 in.) deep beams.

contour plots in Fig. 5 show activation at larger distances from the plume center for smoke detectors.

The gap permitted downslope flow with activation of smoke detectors and heat sensors in beam channels below the plume center as shown in Fig. 5(b). The presence of the gap reduces the thickness of the activation region underneath the beams, as shown in Fig. 5(b).

5 CONCLUSIONS

For level ceilings, siting rules were developed which allow flexibility in locating sensors on either the ceiling or the bottom of beams where the depth of the ceiling layer is sufficient to assure equivalent activation. The effect of deep beams in trapping flow and the existence of "dead air" spaces was shown. For sloped ceilings, it was generally observed that increasing the ceiling slope caused the flow velocity up the slope to increase. When the beams run parallel to (up) the slope, they channel the flow, causing it to accelerate more. The effect is similar to that observed in the first year with horizontal, beamed ceilings for the flow in the direction parallel to the beams, but more pronounced due to the acceleration of the flow up the slope. This increased flow channeling is insensitive to the depth of the beams over the range of beam depths studied. Increasing the slope also decreases the downslope penetration of the flow, so that for slopes greater than 10° the row of sensors at the low end of the sloped ceiling (located half the spacing from the wall) is unlikely to activate unless the fire is very near the lower wall, and then the accelerated flow would cause the next row up the slope to activate quickly. Thus, in these cases it is felt that this lowest row of sensors may be omitted.

When the beams run perpendicular to (across) the slope they impede the flow and cause it to slow in the up-slope direction and spread further across the ceiling within the channel. Again, the effect is similar to the horizontal, beamed ceiling with the flow component perpendicular to the beam direction. Here, the beam depth influences the effect since deeper beams produce more channeling, but the effect of the ceiling slope is reduced as the flow has less chance to accelerate before being turned by the beam.

This work clearly demonstrates the potential of CFD codes as a means of conducting computational experiments to study complex flow phenomena. The detailed results provided by the code exceed the level of detail possible to measure in physical experiments. The techniques for determining sensor response volumes can be used in both physical and computational experiments as a means to study detector placement. Thus, the techniques demonstrated in this study represent a powerful new tool for providing a better technical basis for detector siting rules in international codes and standards.

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