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ON SMOKE DETECTOR SITING ON A BEAMED CEILING

Summary

The siting of smoke detectors in fire compartments with ceiling irregularities is one of the problems faced by designers of fire detection systems. This is due to differences or lack of rules within standards pertaining to planning and design of fire detection systems. Concealed spaces formed by beams and joists affect stratification and, consequently, the response of smoke detectors. It is crucial to detect fire as quickly as possible, so the location of a smoke detector beneath the beams or on a structural slab in the cells in-between is not a matter of aesthetics. In most standards used in the world, there are no unique regulations for smoke detector siting on ceilings with parallel or cross-bracing beams or joists. Therefore, there is a problem of determining the optimal distance between detectors and the resulting problem of delayed fire detection. The European standard is mandatory for most countries in Europe, but it does not contain rules that apply to this problem. The investigation presented in this paper is based on a combination of requirements set by different standards for smoke detector siting so as to find a rule that is applicable according to the European standard. A fire compartment and beams subdividing the ceiling with dimensions that affect stratification were chosen for simulations in the Fire Dynamics Simulator (FDS). The aim of the investigation is to identify a proper location of smoke detectors in a beamed ceiling as well as the optimal distance between them.

Key words: *smoke detector, stratification, ceiling, parallel beams, simulation, obscuration threshold*

1. Introduction

Smoke detector performance in ceilings that contain a beam structure or other types of obstructed ceilings has not been widely investigated. When there are sufficiently deep parallel beams in the ceiling, no smoke flow enters the adjacent channels. This can result in earlier sensor activation times under a beamed ceiling than under a smooth ceiling, provided that a sensor is located in every channel [1].

The variables dependent on ceiling height, such as smoke flows, ceiling jets, ambient airflows, and the heat release rate of a fire influence smoke detector performance. In the case of a beam ceiling, flow trapping and the existence of “dead air” spaces may occur; as a result, the question arises as to how the detector spacing needs to be changed when the ceiling is not smooth but interrupted by beams or joists. There is no significant difference in temperature rise or optical density between detectors located on the bottom of the beam or the ceiling of an adjacent beam bay when detectors are properly arranged [2]. The distance between individual detectors affects fire detection at an early stage and the total number of detectors in the fire compartment. Consequently, the arrangement of detectors affects the response of the fire detection system as well as the cost of the system as a whole. The major areas of investigation concerning detector performance are based on the influence of ceiling type (e.g., smooth, waffled, flat, sloped, beamed, beam orientation, narrow corridor), ventilation conditions (e.g., mechanical ventilation, orientation, flow rate), ceiling height (e.g., high ceilings, temperature gradient), and combinations thereof [3]. All the above factors affect the stratification and, consequently, the response time of the detector. The flow of combustion products is altered by the presence of beams, joists, walls, or sloped ceilings. Stratification is likely to be a factor and should be taken into consideration with a relatively small fire and a relatively high ceiling [4]. The presence of beams and obstruction makes both modelling and detector placement difficult not only because of the smoke distribution dependency on the relation between beam depth and ceiling height, but also the temperature distribution within the bays of the beamed ceiling [5].

Taking into account that smoke detection is based on smoke reaching the detection chamber, stratification is an important factor to consider when determining detector placement. The position of smoke detectors in compartments with ceiling irregularities mostly depends on stratification effects. Consequently, the initial motives and hypotheses for this kind of investigation are as follows:

- With beams and joists on the ceiling, it appears logical that the smoke will first reach the bottom of the beam and then the space inside the beam due to the effect of stratification. Most standards recommend that smoke detectors should be sited on the ceiling rather than the bottom of the beam. However, where stratification can be expected, the location and spacing of smoke detectors must be adjusted.
- The rules related to the coverage radius and coverage area of an individual smoke detector are defined in the standards as a starting point for determining the optimal distance between the detectors. However, these rules cannot be applied when there are parallel beams on the ceiling in the fire compartment. By means of simulation, it is possible to check the response time of the detectors and, based on that, determine the optimal distance between them.

These facts, especially the second one, may raise concerns during the design of fire detection systems for these kinds of fire compartments. The key parameters to be considered are shown in Figure 1. Besides height H of the room, the crucial parameters that affect stratification are labelled in Figure 1: the depth of a joist denoted by h and the distance between joists denoted by D. In order to solve the problem related to the position of smoke detectors in the case of this type of ceiling irregularity, world-leading standards offer different rules.

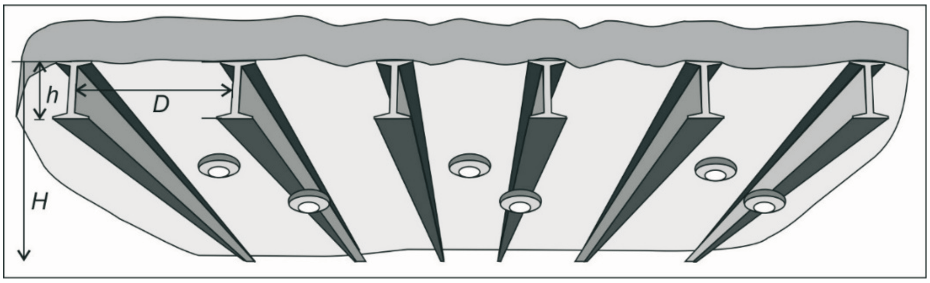

Fig. 1 Example of possible positions of detectors on the ceiling with parallel beams

There are two starting points to be considered within the theoretical background before carrying out the simulation: rules and recommendations from standards, and parameters for the simulation based on the previously mentioned hypotheses. The investigation described in this paper is a part of ongoing investigations related to smoke detector response in compartments with ceiling irregularities [6].

2. Rules for smoke detector position in the case of an obstructed ceiling

In order to set up an appropriate scenario for the simulation, rules for the described problems from five world standards – European standard EN 54-14, German standard VDE 0833-2, British standard BS 5839-1, American standard NFPA 72, and Russian standard SP 5.13130 – were analysed.

The European standard considers all three parameters shown in Figure 1 as follows [7]: Any ceiling irregularity (such as a beam) having a depth greater than 5% of the ceiling height should be treated as a wall, and the following requirements shall apply:

- $D > 0.25\times(H\text{-}h)$: detector in every cell.
- $D < 0.25\times(H\text{-}h)$: detector in every second cell.
- $D < 0.13\times(H\text{-}h)$: detector in every third cell.

According to the German standard, one smoke detector may be used for monitoring several ceiling bays formed by subdividing elements if the surface of the ceiling bays is less than or equal to 0.6 times the maximum monitoring area of 60 m^2 (for room height up to 6 m) or 80 m^2 (for room height above 6 m) [8]. Also, the maximum area monitored by one smoke detector is not more than 1.2 times the size of the maximum monitored area providing a horizontal distance of 7.1 m and 8.2 m for 60 m^2 and 80 m^2, respectively.

The British standard states that if the longer dimension of the cells is less than 10.6 m for point smoke detectors, then, across the shorter cell dimension, the spacing, M, between the detectors should be maximum 5 m for a ceiling height of 6 m or less and beam depth less than 10% H [9].

The American standard points out that for ceilings with beam depths equal to or greater than 10% H the following shall apply (with standard spacing for smoke detectors) [10]:

- Where beam spacing is equal to or greater than 40% H, point type detectors shall be located on the ceiling in each beam pocket.
- Where beam spacing is less than 40% H, the location of detectors either on the ceiling or on the bottom of the beams shall be permitted.

Finally, the Russian standard states that point smoke detectors should be installed in each section of the ceiling 0.75 m wide or more, limited by building structures (beams, girders, plate ribs, etc.) protruding from the ceiling at a distance of more than 0.4 m. The maximum distance between the detectors along the line beams is 8.5 m. If the distance between the linear beams is less than 3 m, this distance between the detectors can be increased by 1.5 times. [11]

3. Simulation model

The setup of the simulation parameters was based on the fact that depending on the beam depth and the distance between the beams, hot gases generated by a fire will be channelled by the beams. Many experiments showed that the beams tend to isolate or channel the smoke flow [12]. The height of 6 m of the fire compartment and the depth of the beam of 10% of the room height are the limit values in all the abovementioned standards. Furthermore, data based on an investigation shows that the velocity and temperature of the ceiling jet flowing over an obstruction are reduced by almost 80% when compared to the case of a smooth unconfined ceiling, for a beam depth equivalent to roughly 15% of the fire-to-ceiling height [13].

As a result, the specifications for the fire compartment and the placement of the detectors for the simulation in this study were determined by combining the previously listed guidelines from the five international standards. Dimensions of the room are 21.2 m × 21.2 m; therefore, one smoke detector with a coverage radius of 7.5 m is enough for a quarter of the room according to the European standard (a total of four smoke detectors for the whole room). According to the German standard two detectors are required for the observed quarter of the room. The distance between them is 4.8 m, which is less than the maximum distance M allowed by the British standard. Finally, according to the American standard it is allowed to locate a detector on the ceiling or on the beam.

Detectors shown in Figure 2, in a quarter of the fire compartment, are denoted C on the ceiling, and B on the beams as follows: detectors C2 and B2 are sited according to the European standard, whereas detectors C1, C3, B1 and B3 on the ceiling and the bottom of the beams are sited according to the VDE standard. The radii of covering for all detectors are also shown in Figure 2. The burner – the centre of fire – is located in the middle of the room at the intersection of the diagonals.

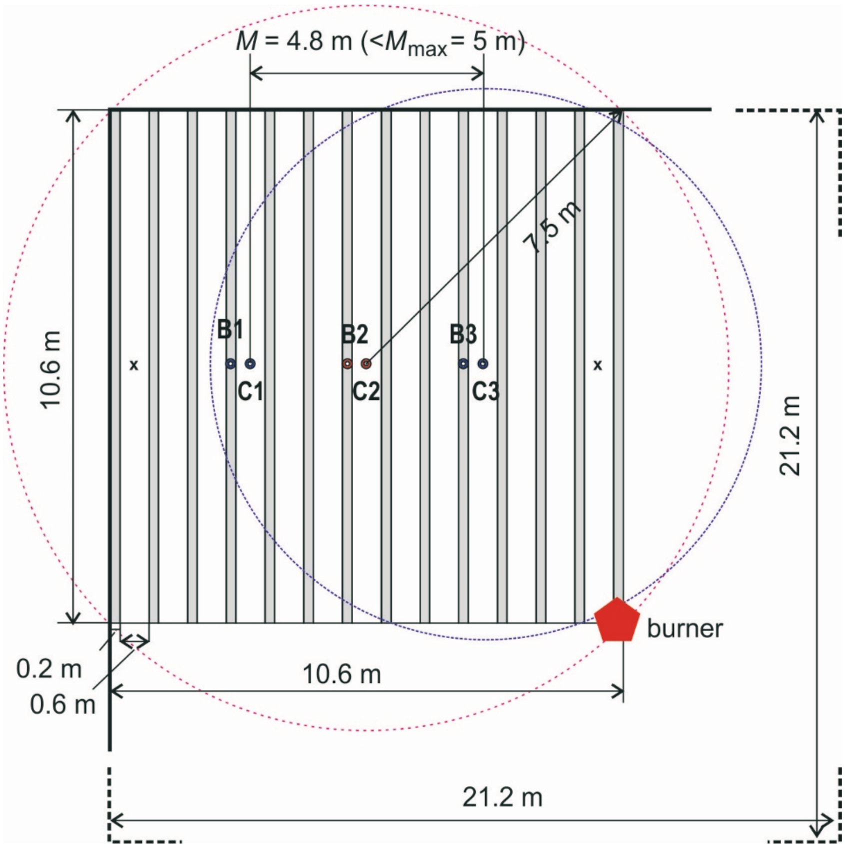

Fig. 2 Illustration of rules for detector siting used for the simulation

3.1 Simulation set-up

Since the focus of this paper is on the thermal flow of smoke, which is affected by its "buoyancy", the Fire Dynamics Simulator (FDS) Large Eddy Simulation (LES) method was used for numerical simulations.

FDS is a model of the fire-driven fluid flow and it numerically solves a form of the Navier-Stokes equations approximated for low-speed and thermally-driven fluids. The governing equations are [14], Eq. (1) – Eq. (4):

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = \dot{m}_b''' \tag{1}$$

which is often written in terms of the mass fractions of the individual gaseous species:

$$\frac{\partial}{\partial t}\left(\rho Y_\alpha\right)+\nabla\cdot\rho Y_\alpha\mathbf{u}=\nabla\cdot\rho D_\alpha\nabla Y_\alpha+\dot{m}_\alpha'''+\dot{m}_{b,\alpha}''' \tag{2}$$

Conservation of momentum:

$$\frac{\partial}{\partial t}\left(\rho\mathbf{u}\right)+\nabla\cdot\rho\mathbf{u}\mathbf{u}+\nabla p=\rho\mathbf{g}+\mathbf{f}_b+\nabla\cdot\tau_{ij} \tag{3}$$

Transport of sensible enthalpy:

$$\frac{\partial}{\partial t}\left(\rho h_s\right)+\nabla\cdot\rho h_s\mathbf{u}=\frac{Dp}{Dt}+\dot{q}'''-\dot{q}_b'''-\nabla\cdot\dot{q}''+\varepsilon \tag{4}$$

where ρ is the density, **u** is the three components of velocity, $\mathbf{u}=[u,v,w]^T$, T is the temperature, D_α is the diffusion coefficient, Y_α is the mass fraction of α^{th} species, $\dot{m}_{b,\alpha}'''$ is the production of species α by the evaporating particles, p is the pressure, **g** is the acceleration of gravity, $\mathbf{f}_b$ is the external force vector, τ_{ij} is the stress tensor, h_s is the sensible enthalpy, $\dot{q}'''$ is the heat release rate per unit volume from a chemical reaction, $\dot{q}_b'''$ is the energy transferred to the evaporating droplets, $\dot{q}''$ is the conductive and radiation heat fluxes, ε is the dissipation rate, and t is the time. The governing equations can be treated as an LES or a Direct Numerical Simulation (DNS).

This study was carried out using the FDS open-source software package, developed by the National Institute of Standards and Technology [14].

In the past few years, LESs have become increasingly popular in computational fluid dynamics (CFD) because of the increasing computational power of the new computers [15]. Also, in the past decade, significant improvements have been made in the development of CFD models. At the moment, this approach is less expensive than field tests and it provides flow features at every point in space simultaneously [16].

The fire compartment was designed for CFD LESs within a computational domain that was 21.6 m long, 6.2 m wide, and 6.2 m high. The fire compartment ceiling was located on parallel beams. The width of the beams was 0.2 m, the depth was 0.6 m (10% H) and the distance between the beams was 0.6 m.

In order to check the hypotheses mentioned above and, consequently, to determine the best detector arrangement for this type of ceiling irregularity, numerical simulations were carried out for four scenarios based on the growth phases of the fire specified by the t^2 fire growth models: slow, medium, fast and ultrafast fire with growth coefficients that are specified by the t^2 fire growth model.

Since the detector distances from the fire source for all scenarios are known, it is necessary to take the recommended alarm thresholds from UL 268 into consideration [17], more precisely, the acceptance standards for various coloured smokes in smoke detector tests. According to this, the acceptable response range of a detector is 1.6-12.5 %/m and 5.0-29.2 %/m for grey and black smoke, respectively [10].

4. Results and discussion

Two obscuration thresholds have been observed: 20 %/m and 7 %/m. The obscuration threshold of 20 %/m is typical for smoke generated by smouldering combustion but relatively high for flaming combustion [16]. Also, the flaming tests require the response of the detector within 4 minutes, while the smouldering test requires a smoke detector response prior to smoke obscuration per meter reaching 20 %/m within 15±3 minutes [2]. As a result of these factors, an obscuration threshold of up to 25 %/m was observed during the analysis.

The first step in the analysis described at the beginning is to analyse the detector responses sequence for all four t^2 fire growth models. It is also interesting to estimate time instances for reaching some of the characteristic obscuration threshold values measured on each detector.

The slow growth fire detector C3, which is located on the ceiling and closest to the centre of the fire, achieves a value of 19.83 %/m in 231 s (Figure 3). Time instances and the order of reaching the obscuration of 7 %/m on all detectors are shown in Table 1.

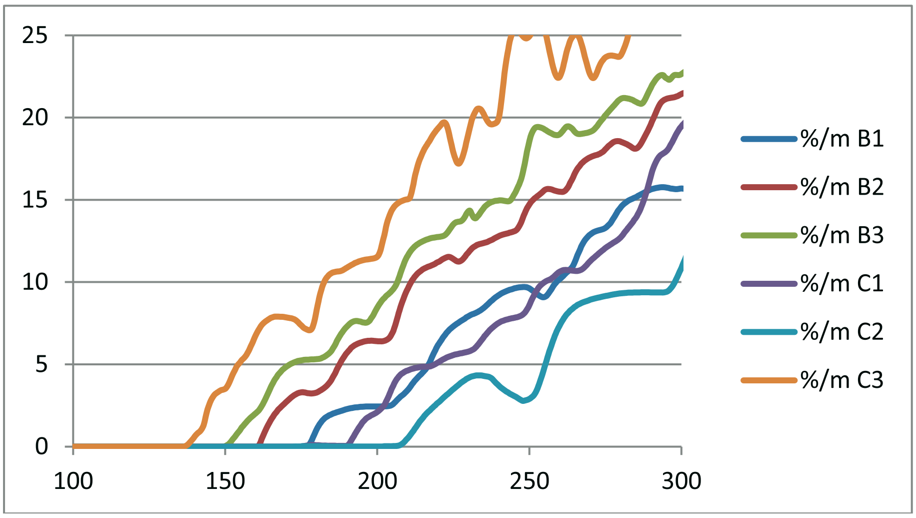

Fig. 3 Obscuration – slow growth fire

Table 1 Slow growth fire – order of reaching the obscuration of 7 %/m

Order	Detector	Time [s]	%/m
1	C3	160.28	6.87
2	B3	187.83	6.81
3	B2	204.66	6.59
4	B1	222.65	6.89
5	C1	235.85	6.84
6	C2	258.65	6.87

Detectors C3 on the ceiling and B3 on the bottom of the beam detect fire first since they are located closest to the fire centre, while detectors B2 and B1 almost simultaneously reach similar values of obscuration as do the detectors on ceilings C1 and C2, which reach the last obscuration threshold close to 7 %/m.

The curves of obscuration in the scenario with medium growth fire are shown in Figure 4. Detector C3, located on the ceiling and closest to the centre, is again the first to reach the value of obscuration close to 20 %/m, i.e., the value of 19.88 %/m is reached in 96.63 s. Afterward, the order of achieving similar obscuration values on other detectors is as follows: B3 and B2 on the beam, C2 on the ceiling, B1 on the beam, and C1 on the ceiling, Table 2.

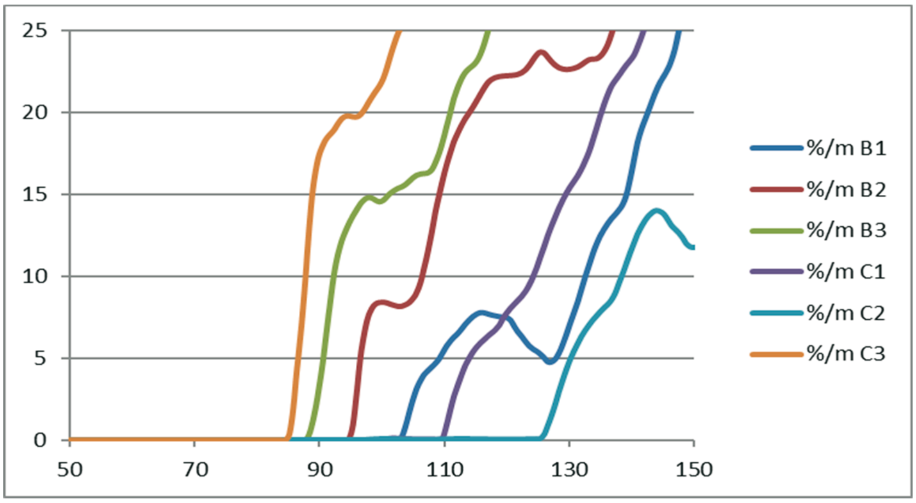

Fig. 4 Obscuration – medium growth fire

Table 2 Medium growth fire – order of reaching the obscuration of 7 %/m

Order	Detector	Time [s]	%/m
1	C3	117.02	6.95
2	B3	129.63	6.57
3	B2	136.22	6.92
4	C2	149.45	6.97
5	B1	151.88	6.69
6	C1	163.28	6.96

Obviously, the order of obscuration values on detectors is very similar to the case of the slow growth fire and identical to the order of obscuration for three detectors that are located closest to the centre of the fire.

The development of obscuration in the case of the fast growth fire is shown in Figure 5. The value 19.74 %/m is reached in 95.43 s, and the order of reaching the obscuration of 7 %/m on the detectors is given in Table 3.

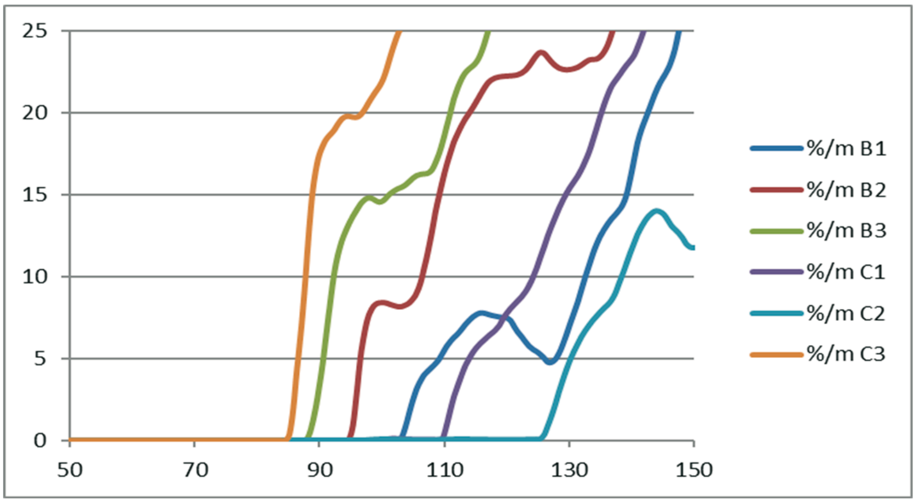

Fig. 5 Obscuration – fast growth fire

Table 3 Fast growth fire – order of reaching the obscuration of 7 %/m

Order	Detector	Time [s]	%/m
1	C3	87.04	6.46
2	B3	91.21	6.68
3	B2	97.26	6.59
4	B1	112.86	6.82
5	C1	118.86	7.00
6	C2	133.25	7.02

The order of obscuration on the detectors is the same as in the case of the slow growth fire.

Finally, the curves of obscuration in the case of ultrafast growth fire are shown in Figure 6. The value of obscuration of 20.05 %/m is reached in 69.63 s, and the ascending order of obscuration values on the detectors is given in Table 4.

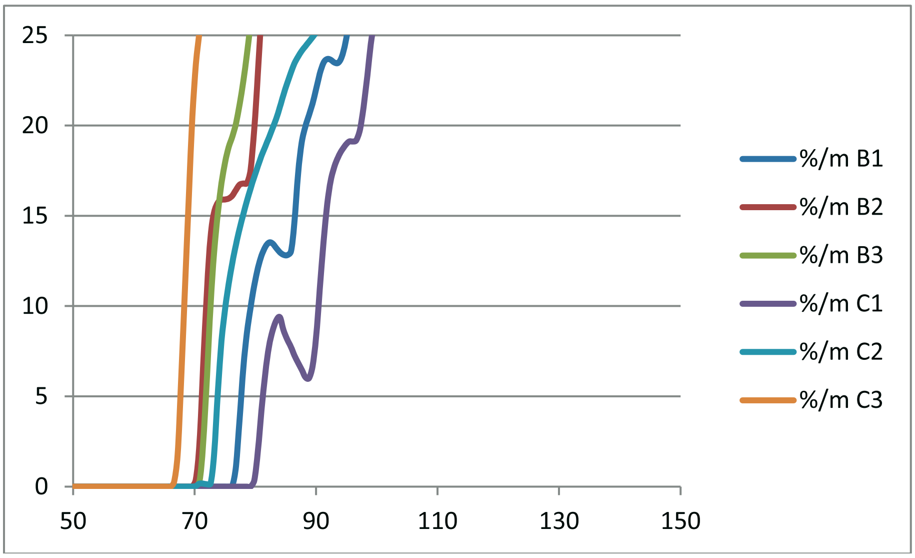

Fig. 6 Obscuration – ultrafast growth fire

Table 4 Ultrafast growth fire – order of reaching the obscuration of 7 %/m

Order	Detector	Time [s]	%/m
1	C3	67.81	6.13
2	B2	71.4	6.61
3	B3	72.04	6.17
4	C2	73.84	5.32
5	B1	78.03	6.61
6	C1	81.63	6.27

The order of obscuration on the detectors is the same as in the case of the medium growth fire.

The above findings demonstrate that the values of obscuration set by this simulation reach the detectors located on the beams for all types of fires more quickly. More precisely, the order of reaching obscuration values near 7 %/m for each t^2 fire is given in Table 5.

Table 5 Order of reaching obscuration of 7 %/m for all detectors and fire growth models

Detector	Slow fire	Medium fire	Fast fire	Ultrafast fire
C1	5	6	5	6
B1	4	5	4	5
C2	6	4	6	4
B2	**3**	**3**	**3**	**2**
C3	**1**	**1**	**1**	**1**
B3	2	2	2	3

Based on the presented graphs and data in the tables above, three facts are obvious:

- Detector C3 located nearest to the fire centre is the first to have reached the values of obscuration required for the fire detection.
- The order of obscuration is the same for slow growth and fast growth fires as well as for medium growth and ultrafast growth fires.
- With the exception of ultrafast fires, the value of obscuration on detector B2 is always the third in order.

Consequently, it is necessary to assess time delays between the values of obscuration on detectors C3 and B3, which are located in accordance with the VDE standard, and detector B2 which is located in accordance with the European standard. This type of testing is necessary not only for verifying the hypotheses presented at the beginning of the paper, especially the one related to the detector location on ceilings or beams, but also for economic reasons. If the detectors are placed in accordance with the European standard, for a room under consideration with the dimensions of 21.2 m × 21.2 m only four detectors are needed, and if the detector arrangement is in accordance with the German standard, twice as many detectors will be required.

The difference between reaching similar values of obscuration in the pair of detectors C3 and B3 that is close to the fire centre is very small and it is approximately as follows: for slow growth fire – ~ 17 s, for medium growth fire – ~ 12 s, for fast growth fire and for ultrafast growth fire – ~ 4 s. Therefore, it is interesting to determine the time delay in the obscuration values between detectors C3 and B2. Table 6 contains data on time delays of obscuration between detector C3, which is located closest to the fire, and detector B2 for the value of about 7%/m of obscuration.

Table 6 Time delays for achieving obscuration values near 7 %/m on detectors B2 and C3 for all stages of fire development

Fire growth type	Detector	Time [s]	Obs. [%/m]	Detector	Time [s]	Obs. [%/m]	Delay [s]
Slow	B2	**204.66**	6.81	C3	**160.28**	6.87	**44.38**
Medium	B2	**136.22**	6.92	C3	**117.02**	6.95	**19.20**
Fast	B2	**97.26**	6.59	C3	**87.04**	6.46	**10.22**
Ultrafast	B2	**71.40**	6.61	C3	**67.81**	6.13	**3.59**

5. Conclusions

Based on all the data presented in the previous analysis, it is possible to draw certain conclusions regarding the position of the detector and to set a course for further investigation.

The presented study was motivated by the discordance between the leading world standards in defining the rules for siting smoke detectors on a beamed ceiling.

The researchers sought to find a generalized correlation between the variables of the environment and the fire conditions (i.e. fire growth rate and ceiling height). The results do not give an indication as to the time the detectors activate, but only whether or not the detectors activate. Slow growth fires result in more variability in terms of spacing. Fast growth fires show that the radial spacing is more dependent on the ceiling height. Overall, as long as devices are able to recognize lower than standard obscuration levels, they may be used at higher elevations than what is currently standardised, with accordingly reduced spacing.

The four t-squared fire growth models were used in this study and the time delays for achieving obscuration thresholds were thereby established according to the position of the detector and fire growth types.

Starting from the initial hypotheses, the simulation results revealed that, undoubtedly, the obscuration threshold required to activate the smoke detector is achieved first on the detectors sited at the bottom of the beam and then on the detectors between the beams, due to the stratification process.

However, there was no relevant difference in the values of obscuration between adjacent detectors located on the bottom of the beam and the ceiling in the beam bay. Siting of smoke detectors according to the rules from the European standard leads to a more economic fire detection system design without considerable delay of detection, especially in the case of larger areas to be protected.

Although the presented study considered the case of a room with boundary dimensions that match all the standards, the time delay in reaching the obscuration thresholds required to activate the detector is not long, so this supports the previous conclusion. Smoke detectors positioned on the ceiling in accordance with the European standard would be perfectly acceptable in rooms with a greater height and a greater distance between the beams. The placement of detectors on ceilings also serves an aesthetic purpose, because detectors within the field are hidden from view and do not interfere with the interior appearance of the room.

In the case of rooms with a high fire risk, the arrangement of smoke detectors in accordance with the German standard should be considered in terms of reliability and allowable redundancy.

In addition, the use of linear smoke detectors should also be taken into consideration because the simulation demonstrated that any type of ceiling irregularity significantly affects smoke stratification. By using linear smoke detectors, it is possible to detect fire at the very beginning of stratification formation. Therefore, further investigation should focus on quantifying each of those factors.

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