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CONFINED SPACE FIRE SIMULATION IN CFAST

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Review article

Abstract: The Consolidated Fire and Smoke Transport Model computer program is a two-zone fire simulation model that gives each layer a uniform room temperature and gas concentration. The paper highlights two model scenarios that differ in the use of fire protection equipment. the first model scenario features a smoke detector that influences the course of the fire by detecting and signalling its occurrence. In the second model scenario, there is no smoke detector and therefore the course of the fire is not affected by detection and signalling and subsequent intervention. This paper aims to compare the results between the temperature of the upper and lower smoke layer, and the height of the smoke layer in the two simulations.

Keywords: Fire, Simulations, Consolidated Fire and Smoke Transport Model, Smoke layer temperature, Smoke layer height.

Introduction

Fire models are designed fires based on a bounded domain of application of specific physical parameters. These models are used for designing fire safety of buildings, assessing the possibility of evacuation of the building, creating designs for smoke and heat extraction facilities and selecting the location of fire detectors. They can also be used in the investigation of the causes and progression of fires. The distribution of fire models is shown in Figure 1 (STN EN 1991-1-2, 2007; Kačíková, 2013).

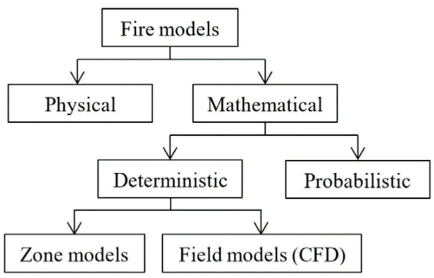

Figure 1 Division of fire models (Cote, 1986)

Zone models

The building environment in which a fire is located is complex and knowledge of fire behaviour is obtained using zonal models. These models idealize the space by dividing rooms into single or multiple zones with unique conditions. Single-zone models represent each room as a zone and model the movement of smoke throughout the room structure. A two-zone model divides the space into two layers, where the upper layer is filled with combustion gases and the lower layer is filled with ambient fresh air. Each of these layers is characterised by its average temperature and smoke concentrations. The plane that divides these two layers is called the hot layer interface (Mózer, 2015).

CFAST

The CFAST program is a two-zone fire model designed for modelling fires and tracking the movement of combustion products in a enclosure space. Each room of the model is divided into two layers, an upper and lower layer, where each layer has a uniform temperature and smoke concentration. The evolution of these phenomena is described by a set of differential equations that are derived from the fundamental laws of conservation of mass and energy. CFAST includes NIST's Smokeview program, which simulates the propagation and flow of smoke and cold air in a room and can specify the temperatures in the layers and color-code these during the simulation (Peacock, 2015).

Similar research and case studies

In the field of enclosure fire modelling with CFAST, a number of researches and case studies have been carried out around the world, not only on

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the use of CFAST itself, but also on the comparison of several types of models with CFAST.

One of the studies was conducted at the University of California, Department of Mechanical Engineering, in which Guillermo Rein and his team dealt with a topic *A comparison of three firemodels in the simulation of accidental fires* (Rein, 2004). In this study, three model scenarios of single-family house, small apartment and one-story house fires were created to analyze the use of three fire modelling approaches in CFAST, FDS and a simplified analytical model of fire growth. Based on the results of the study, it was found that the results of the three approaches were in relatively good agreement, especially in the early stages of the fires. The conclusion of the study was that even simpler models such as CFAST can be used as one of the first steps to approximate the behaviour of fires in enclosure spaces or to validate orders of magnitude larger and more complex results from other models.

The second example in which CFAST was used is a study from the Department of Mechanical Engineering, Yuan Ze University, Taiwan, entitled *Using the CFAST/FDS software to simulate the performance safety verification of the building* (Cherng-Shing, 2012), in which Cherng-Shing Lin and his team looked at the application of CFAST and FDS+Evac to the analysis of a fire case of a four-storey building, with a focus on the assessment of evacuation and fire resistance of the building. This study was intended to develop Taiwan's regulations to help plan and design fire safety protection for buildings. The simulation itself was based on an actual fire case.

In another example, the research *Configuration approaches of CFAST for prediction of smokeand heat detector activation times in corridor fires* from the Department of Disaster Prevention, Daejeon University, Republic of Korea, where Hyon-Yeon Jang and Cheol-Hong Hwang (Hyo-Yeon, 2023) investigated the use of CFAST in evaluating its predictive performance of smoke and heat detector activation times in comparison with the Fire Dynamics Simulator (FDS). The research compared the simulation results of CFAST and FDS in models with the same computational domain. A number of factors that may affect the results were also observed in the research, such as the number of computational domains in the simulations, where in CFAST the flow velocity is fixed in several computational domains depending on the presence of a fire source in the same space. In addition, the two programs use different methods of predicting temperatures and concentrations, therefore when considering the activation of individual fire detectors in the programs, particular attention should be paid to the partitioning between the fire source and the areas of interest, asa constant velocity is applied according to the presence of a fire within

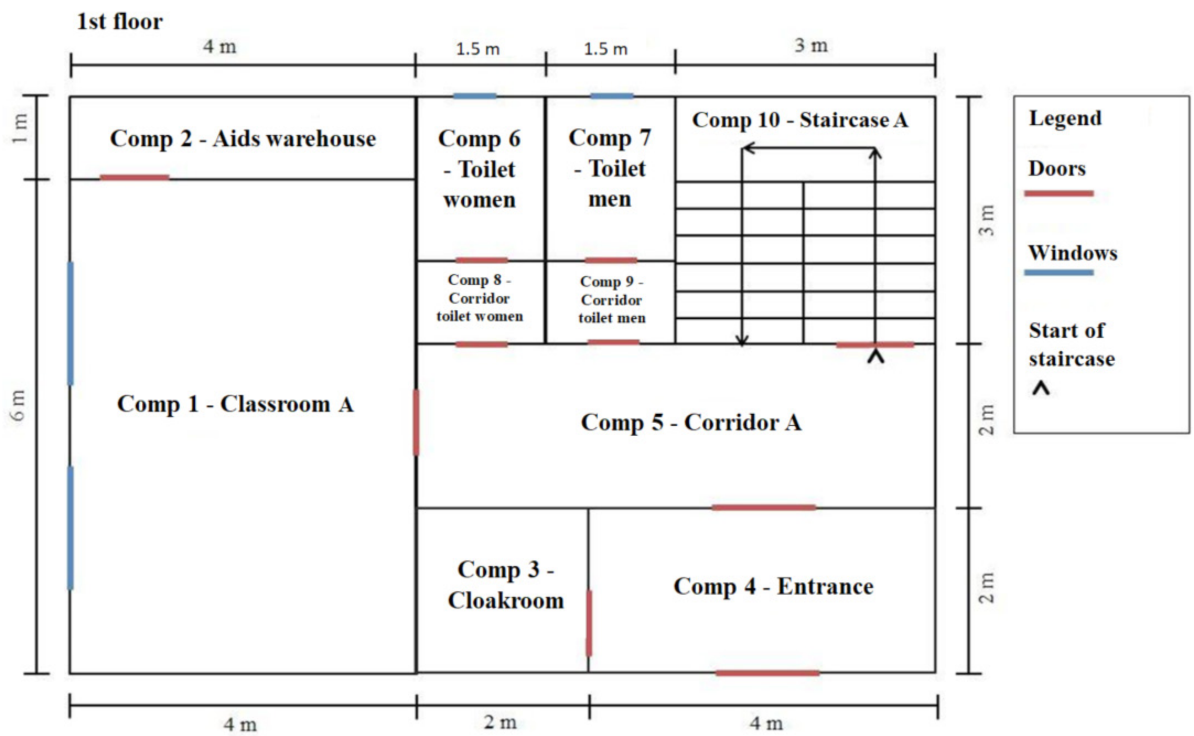

Figure 2 Floor plan of the first floor

the designatedcomputational region. Based on the research, it is concluded that the CFAST program is feasible in estimating the activation time of smoke and heat detectors in building fire risk assessment.

This paper aims to compare the results between the upper and lower smoke layer temperatures, and the smoke layer height in two simulations, and to determine the effect of fire engineering equipment and building ventilation on the final results.

Materials and methods

The simulated space was a primary school building consisting of two floors. The first floor consists of 10 rooms and the second floor consists of 8 rooms. On the first floor, there is an entrance to the building, which is connected to a cloakroom and a corridor. From the corridor, it is possible to access classroom A, which includes storage of utilities and sanitary facilities, consisting of a corridor and a toilet. The first floor also includes a staircase leading to the second floor. The staircase leads to a corridor on the second floor, which gives access to the headmaster's office, the assembly room, the staff toilets and Class B, which contains the storage of supplies. Floor plan of the first floor is shown in Figure 2. The floor plan of the second floor is shown in Figure 3.

Simulation space creation

Creating a simulation space in CFAST requires the definition of several parameters, including simulation parameters, thermal properties of materials, room design, natural and artificial ventilation, and fire and fire engineering equipment. The following section of the paper deals with the description of each parameter in the space and fire simulation process.

Simulation parameters

The simulation parameters were set as follows:

Time data

- Simulation length: 3600 s.
- Output recording interval: 60 s.
- Output recording interval to Excel: 15 s.
- Output interval for Smokeview: 15 s.
- Largest accessible time interval: Default.

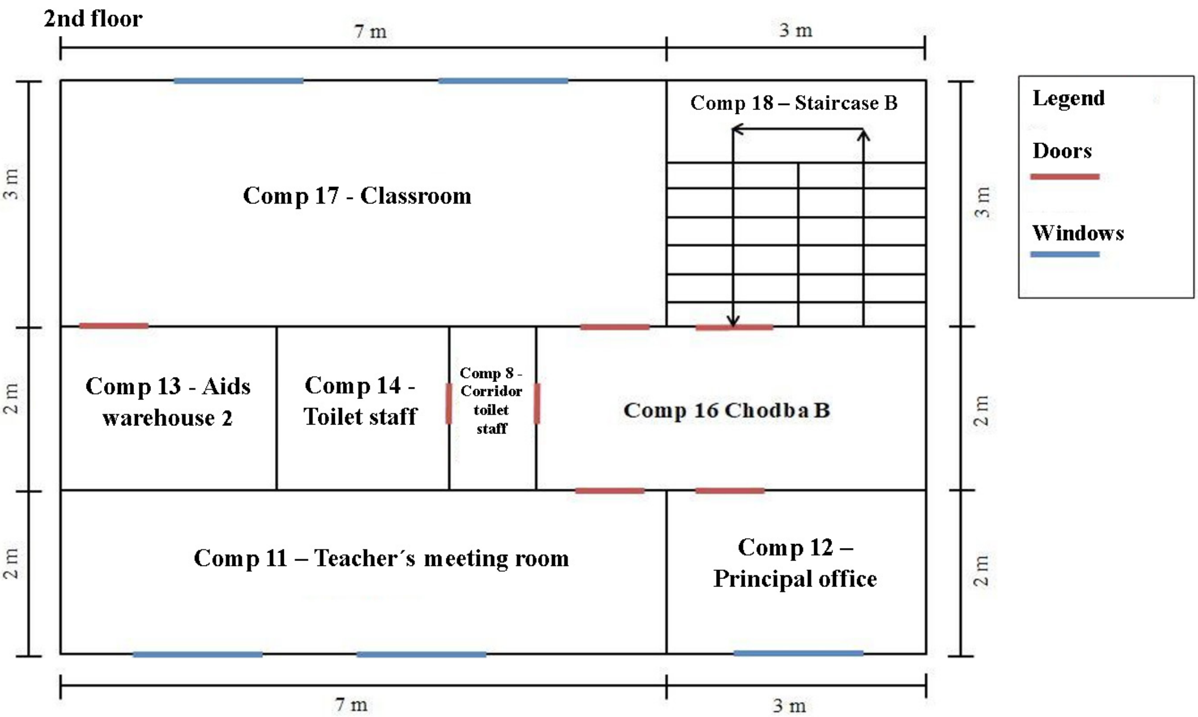

Figure 3 Floor plan of the second floor

Simulation conditions

- Interior temperature: 25 °C.
- Interior humidity: 50 %.
- Outdoor temperature: 35 °C.
- Ambient pressure: 101 325 Pa.
- Insulated surfaces in the enclosure: Not used.
- Lower limit of oxygen content in air: 0.15.

Thermal properties of materials

Two predefined materials were chosen for the construction of the room - brick and concrete. Concrete was used as the base for the 0.2 m thick ceilings and floors, and brick was used as the material for the 0.15 m thick perimeter walls of the room.

Creation of rooms

The building is made up of 18 rooms. Ten rooms are situated on the first floor and the remaining eight on the second floor. A description of the individual rooms is given in Table 1 in Annex.

Natural ventilation

Vertical openings

Vertical openings in the building are divided into doors and windows. There are a total of 17 doors in the building and they are described in Table 2 in Annes and a total of 9 windows in the building and they are described in Table 3 in Annex.

Horizontal openings

There is a single horizontal opening in the building, which serves as a staircase. Table 4 describes this opening.

Fires

There are 2 fires in an elementary school after school hours that follow each other. Both of these fires are located in classroom A on the 1st floor. The first fire will be initiated by a short circuit of the teacher's computer in the classroom, as this equipment is always on and rarely shuts down completely. The second fire will be caused by the first fire of the teacher's computer spreading to the electrical wiring substation at the point of maximum fire output of the computer. The input data needed to define the fires was obtained from the CFAST program itself, which contains an accessible database of selected fires. The input data defining both fires are shown in Table 5 and Table 6 shows the heat release rates over time for both fires.

Fire-technical means

There is one classroom A smoke detector in the building. The parameters of the smoke detector are given in Table 7.

Table 4 Horizontal openings of building

Floor	Opening	Location		Hole area	Shape	Offset	
		Top compartment	Bottom compartment			X	Y
Between floors	Stairs	Staircase B	Staircase A	4 m^2	Square	1.5	1.5

Table 5 Input data for defining fires (Wald, 2017)

Fire parameter	Computer fire	Cable substation fire
Ignition time (s)	30	195
Position X (m)	3.5	2.7
Position Y (m)	5.5	5.5
Max HRR (kW) in time (s)	238.8 kW in 171.6 s	380.4 kW in 40.4 s
Fuel	Polyurethane - $C_{6.3}H_{7.1}O_{2.1}N$	Polyurethane - $C_{6.3}H_{7.1}O_{2.1}N$

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Table 6 Heat release rate data over time for fires (Wald, 2017)

Computer fire		Cable substation fire	
Time (s)	**HRR (kW)**	**Time (s)**	**HRR (kW)**
44	0	0.4	0
83.6	6.9	4.8	36.5
110	51.3	6.6	75.5
145.2	122.4	10.3	80.8
171.6	238.8	16.5	70.6
202.4	151	20.2	153.8
237.7	211.2	23.5	177.3
255.3	125.3	28.7	239.8
272.9	111.5	36	320.5
360.9	161.8	40.4	380.4
440.1	137.2	42.2	281.7
836.2	88.8	48.9	165
1166.3	44.4	60.2	90.1
1602	31.6	76	30.8
1800	14.8	89.6	0

Table 7 Fire-technical means

Room	Type of means	Position			Blackout (%)
		X	Y	Z	
Classroom A	Smoke detector	2	3	2.4	23.93

Modelling of fire scenarios

Using CFAST, 2 fire scenarios were created. These fire scenarios differ in the use of fire protection equipment.

In the first scenario, no fire engineering equipment was used to detect the accompanying physical and chemical phenomena of the fires. The computer fire originated at 30 seconds into the simulation and spread to the electrical cable substation at 195 seconds. This fire was not monitored by equipment that would have signalled its occurrence. Due to this fact, the temperature in the room started to rise and a smoke layer formed, which had nowhere to escape, as there were no windows or doors open in Class A during the entire simulation. Figure 4 shows classroom A at 135 sec with the computer fire starting and Figure 5 shows both fires in the room with a gradually decreasing smoke layer.

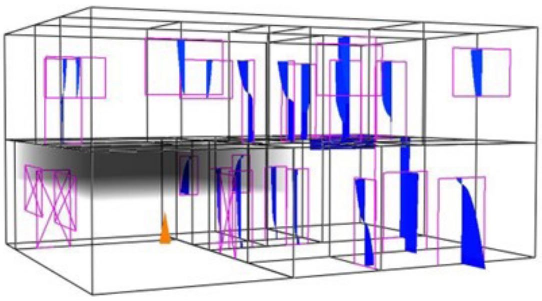

Figure 4 Starting a fire in classroom A

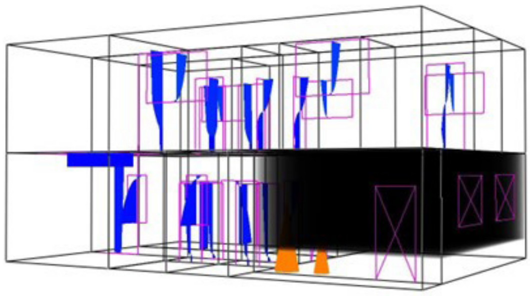

Figure 5 Both fires in a classroom with a gradually decreasing smoke layer

In the second scenario, a smoke detector was used to detect smoke as a concomitant of fire with an obscuration value of 23.93 %. This smoke detector was activated at 135 seconds based on which the alarm device was triggered. The school principal was in the building and after the alarm was triggered, he tried to locate the scene of the fire. At 156 seconds, the principal entered classroom A where he spotted the fire, he then evacuated the building leaving the door ajar behind him, thus providing an air supply to the fire. The second source of oxygen supply and exhaust of combustion products was an open window in the second floor principal's office with an opening fraction of 0.5. Figure 6 shows the school building at the 210 second mark with smoke gradually spreading through the rooms, and Figure 7 shows the building smoke at the end of the simulation.

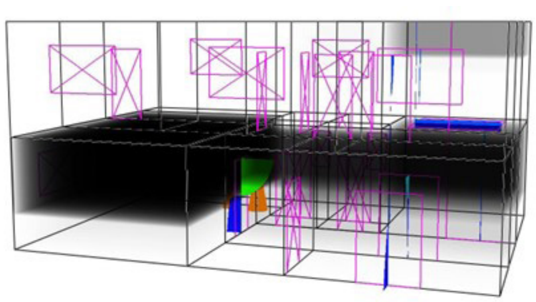

Figure 6 Gradual smoke expansion in the building in 210 second

Results and discussion

The creation of the individual scenarios produced outputs from the simulations that were used to compare smoke layer temperatures, and smoke layer heights, and to determine smoke detector activation.

Following the initiation of the fires in the no smoke detector scenario, the upper smoke layer temperature in classroom A rose rapidly to its maximum value of 191.06 °C, which it reached at the end of phase III (phase III of IV: phase III - fully developed fire, phase IV - flame retardancy) of the fire at 255 seconds. Gradually, the temperature of the smoke layer in the room decreased, reaching

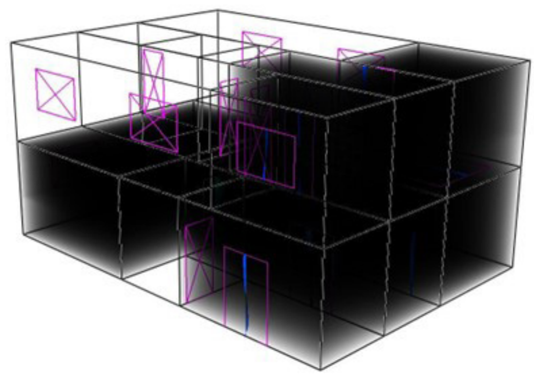

Figure 7 Smoke in the building at the end of the simulation

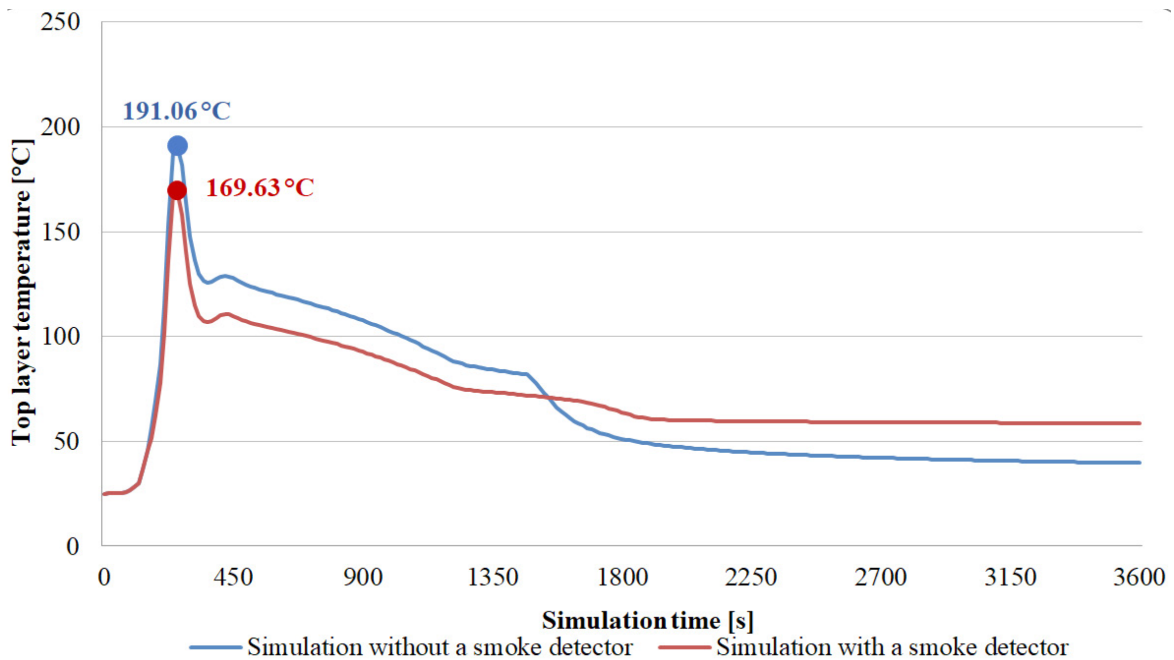

Figure 8 Graph of top layer temperatures in classroom A

39.64 °C at the end of the simulation. In the fire scenario with the smoke detector, the upper layer temperature increased rapidly but due to the rapid fire detection and the fresh air supply, the maximum upper layer temperature was only 169.63 °C at the end of phase III of the fire.

By comparing the temperatures, we can see that the early response and venting of combustion products cause the maximum upper layer temperature to drop by 21.43 °C. The second observation is that the fresh air supply to the room promotes combustion which causes the final temperature in the smoke detector scenario to be 19.16 °C higher than in the non-smoke detector scenario. Figure 8 shows a plot of the evolution of the upper smoke layer temperature in classroom A in both scenarios.

The evolution of the lower smoke layer temperatures is similar in both scenarios to the evolution of the upper smoke layer. The lower layer in the scenario without a smoke detector reached a maximum temperature of 69.28 °C and then decreased to 36.49 °C. In the scenario with the smoke detector, the maximum temperature of the lower layer was 52.48 °C, which decreased slightly and held approximately constant at 40 °C from the middle of the simulation.

Based on the graph, it can be concluded that the lower layer is more sensitive to changes in fresh air supply to the simulation during the fire. This is evidenced by the sudden 2.5 °C drop in temperature due to the opening of the door in classroom A, which provided a fresh air supply and cooled the lower layer. Figure 9 shows a graph of the temperature evolution of the lower layer in classroom A in both scenarios.

The development of the height of the smoke layer depends on the ventilation of the space in which the fire is located. In the first scenario, there was no smoke detector, so there was no door opening and the smoke had nowhere to escape, it started to accumulate under the ceiling and form a smoke layer that gradually decreased, reaching the floor of the room in 540 seconds and thus the whole room was filled with smoke. In the second model scenario, a smoke detector was present in the room during the fire, which meant that the door was open and the room was ventilated. The smoke layer formed in classroom A gradually dropped to its lowest value of 0.59 m, at which point the air supply began to displace the combustion products through the open door, causing the smoke layer to gradually increase until the amount of smoke formed and the amount of smoke vented equilibrated and the smoke layer height stabilized at approximately 1 m. Figure 10 shows a plot of the evolution of the height of the smoke layer in classroom A in both scenarios.

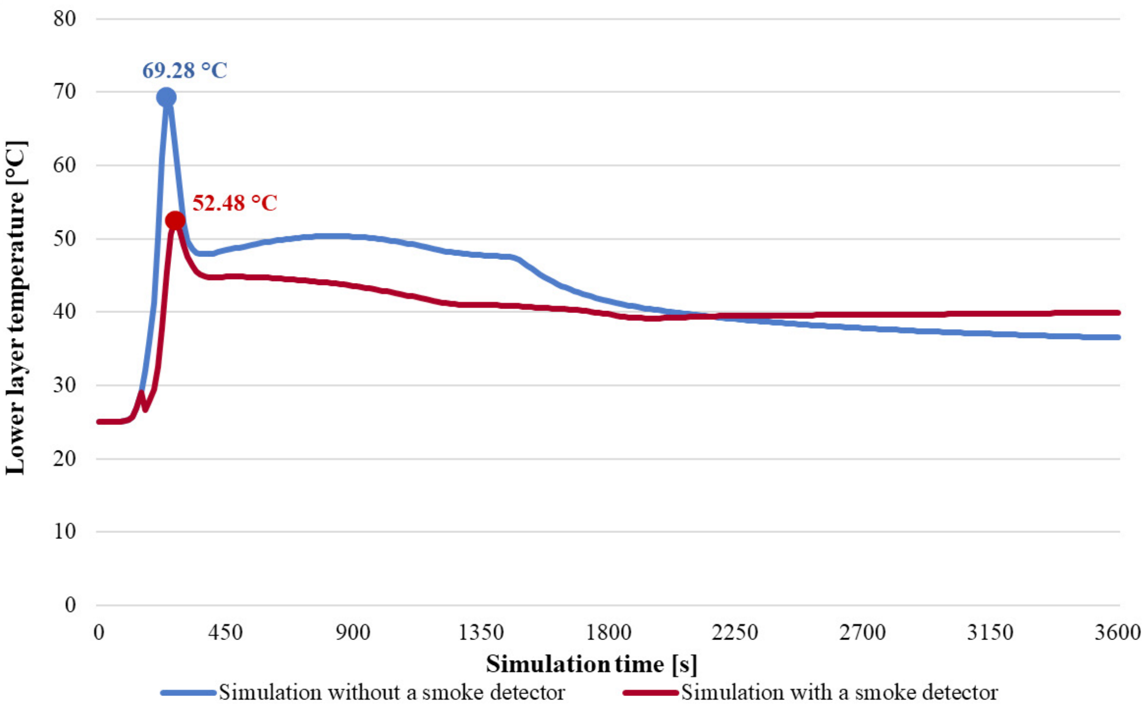

Figure 9 Graph of the temperature evolution of the lower layer in classroom A

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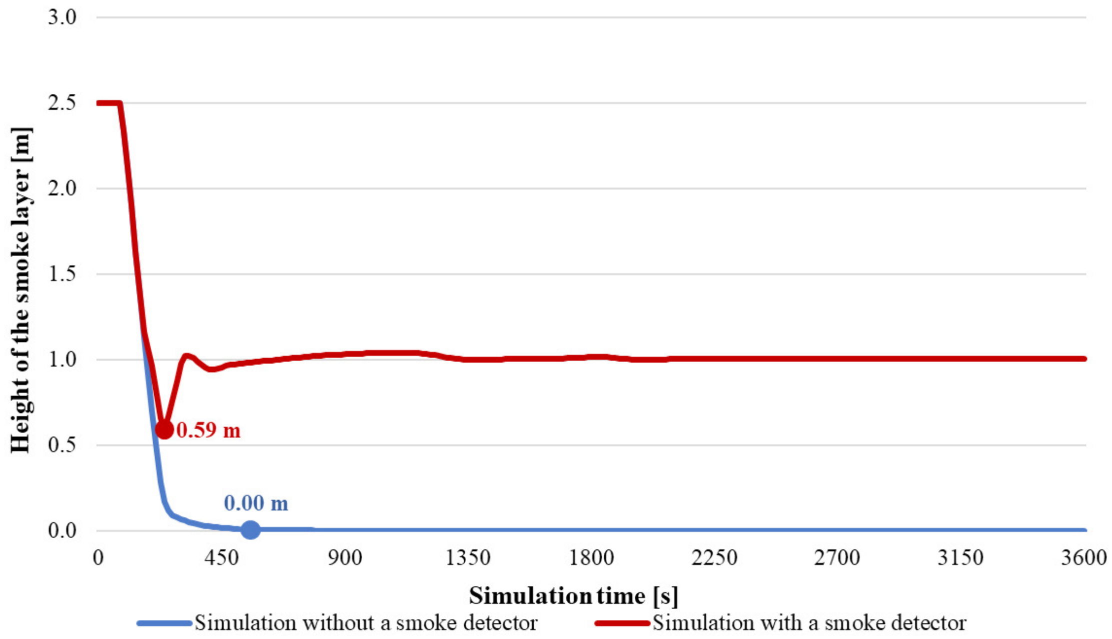

Figure 10 Graph of the smoke layer height evolution measured from the floor in classroom A

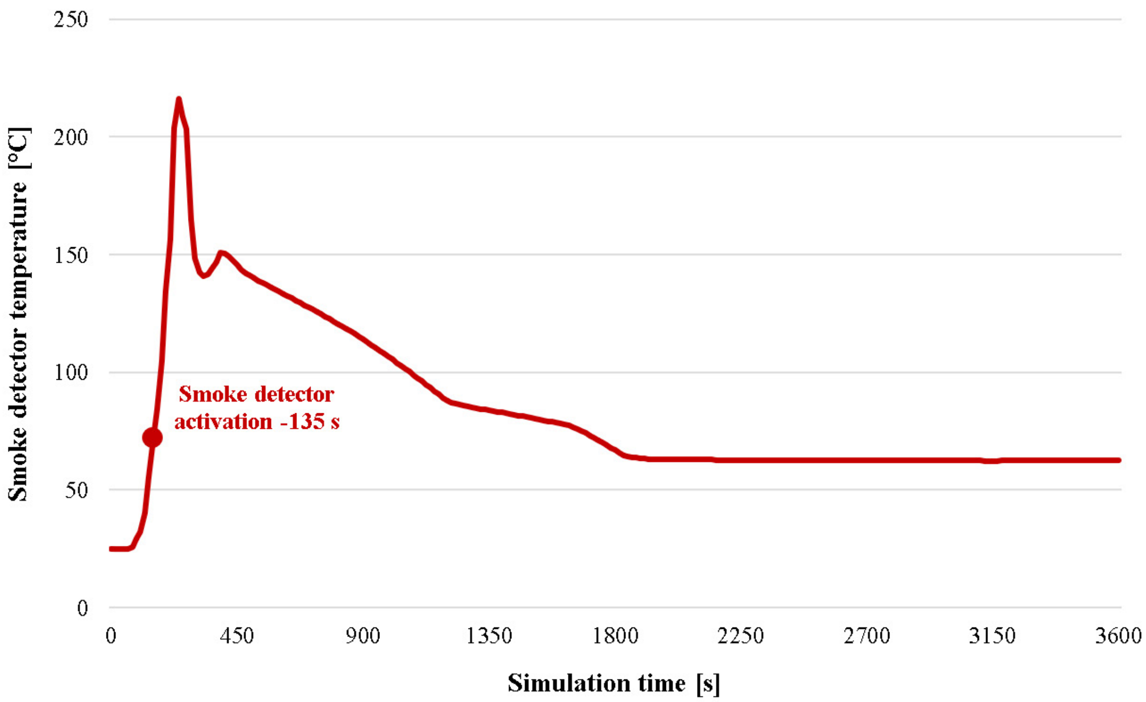

Figure 11 Smoke detector activation

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Figure 11 shows that the activation of the smoke detector occurred at 135 seconds, i.e. in the incipient phase of the fire. The ventilation of the room affects the obscuration of the smoke detector, due to the combustion products escaping from the room.

Conclusion

Based on the simulation results of the case study, it was found that if there are no fire detectors in the fire area, the occupants of the building would not be alerted to the fact of the fire, therefore there would be no opening of the openings in the room with the fire, causing the smoke layer to drop to floor level, reducing the temperature and oxygen content of the room, which in this case also results in a reduction in the intensity of combustion. Alale no one will know about the fire, and if the room temperature rises above 400 °C and the windows are vented, non-linear forms of fire spread will occur which can spread the fire to the whole building. If there are people in the building who are unaware of the fire, not only their health but also their lives may be at risk.

The smoke detector is used to detect the presence of a fire and to inform all persons in the building of its occurrence by means of signalling devices. These occupants can then decide to start extinguishing the fire until the fire brigade arrives or evacuate. However, if the fire is not extinguished and the occupants are subsequently evacuated from the building, fresh air may enter the building, causing an exchange of gases that will promote the combustion process and increase the temperature, as was the case in the second simulation of the case study. By comparing the scenarios, we concluded that the use of fire detection is not only beneficial in this case study simulation, but also in general.

References

CFAST - Consolidated Fire and Smoke Transport (Version 7) [online]. Nist.gov, 2015 [cit. 2023-08-24]. Available at: https://nvlpubs.nist.gov/NISTPUBS/TECHNICALNOTES/NIST.TN.1889V1.PDF

Cote, A. E., Linville, J. L. 1986. Fire protection handbook. 16th edit. Quincy: National Fire Protection Association - NFPA.

Fire dynamics [online]. Gitech.sk, 2013 [cit. 2023-08-24]. Available at: www.gitech.sk/fire/images/dokumenty/Dynamika_poziaru.pdf

Hyo-Yeon, J., Cheol-Hong, H. 2023. Configuration approaches of CFAST for prediction of smokeand heat detector activation times in corridor fires. Applied Sciences, 13 (24): 13161.

Cherng-Shing, L., Chun Chan, Y., Te-Chi, Ch., Shih-Cheng, W. 2012. Using the CFAST/FDS software to simulate the performace safety verification of the buildings. In Proceedings of the 2012 International Conference on Electronics, Communications and Control, 3443-3446.

Mózer, V. 2015. Fundamentals of fire safety in buildings. 1st edit. Zilina: University of Zilina (in Slovak).

Rein, G., Bar-Ilan, A., Farnandez-Pello, A. C., Alvares, N. 2004. Comparison of Three Fire Models in the Simulation of Accidental Fires. Journal of Fire Protection Engineering, 17 (1): 1-26.

STN EN 1991-1-2:2007. Loads on structures, Part 1-2: General loads - Loads on structures subjected to fire.

Wald, F., Pokorný, M., Cábová, K., Hejtmánek, P. 2017. Modelling fire dynamics in buildings. 1st edit. Prague: Czech Technical University in Prague (in Czech).

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ANNEX

Table 1 Rooms of the building

Floor	Room	Room name	Dimensions (m)			Position		
			Width	Depth	Height	X	Y	Z
1st floor	Compartment 1	Classroom A	4	6	2.5	0	0	0
	Compartment 2	Aids warehouse 1	4	1	2.5	0	6	0
	Compartment 3	Cloakroom	2	2	2.5	4	0	0
	Compartment 4	Entrance	4	2	2.5	6	0	0
	Compartment 5	Corridor A	6	2	2.5	4	2	0
	Compartment 6	Toilet women	1.5	2	2.5	4	5	0
	Compartment 7	Toilet men	1.5	2	2.5	5.5	5	0
	Compartment 8	Corridor toilet women	1.5	1	2.5	4	4	0
	Compartment 9	Corridor toilet men	1.5	1	2.5	5.5	4	0
	Compartment 10	Staircase A	3	3	2.5	7	4	0
2nd floor	Compartment 11	Teachers meeting room	7	2	2.5	0	0	2.5
	Compartment 12	Principal office	3	2	2.5	7	0	2.5
	Compartment 13	Aids warehouse 2	2.5	2	2.5	0	2	2.5
	Compartment 14	Toilet staff	2	2	2.5	2.5	2	2.5
	Compartment 15	Corridor toilet staff	1	2	2.5	4.5	2	2.5
	Compartment 16	Corridor B	4.5	2	2.5	5.5	2	2.5
	Compartment 17	Classroom B	7	3	2.5	0	4	2.5
	Compartment 18	Staircase B	3	3	2.5	7	4	2.5

Table 2 Vertical construction openings - doors

Floor	Opening	Location		Dimensions (m)		
		First compartment	Second compartment	Doorstep	Height	Width
1st floor	Door 1	Classroom A	Aids warehouse 1	0	1.8	0.8
	Door 2	Classroom A	Corridor A	0	1.8	0.8
	Door 3	Entrance	Corridor A	0	1.8	1.2
	Door 4	Entrance	Outside	0	1.8	1.2
	Door 5	Cloakroom	Entrance	0	1.8	0.8
	Door 6	Corridor A	Corridor toilet women	0	1.8	0.6
	Door 7	Corridor A	Corridor toilet men	0	1.8	0.6
	Door 8	Toilet women	Corridor toilet women	0	1.8	0.6
	Door 9	Toilet men	Corridor toilet men	0	1.8	0.6
	Hole in the staircase downstairs	Corridor A	Staircase A	0	2.5	1.5
2nd floor	Door 10	Principal office	Corridor B	0	1.8	0.8
	Door 11	Teachers meeting room	Corridor B	0	1.8	0.8
	Door 12	Corridor B	Classroom B	0	1.8	0.8
	Door 13	Aids warehouse 2	Classroom B	0	1.8	0.8
	Door 14	Corridor toilet staff	Corridor B	0	1.8	0.6
	Door 15	Toilet staff	Corridor toilet staff	0	1.8	0.6
	Hole in the staircase upstairs	Corridor B	Staircase B	0	2.5	1.5

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Table 3 Vertical construction openings - windows

Floor	Opening	Location		Dimensions (m)		
		First compartment	Second compartment	Doorstep	Height	Width
1st floor	Window 6	Toilet men	Outside	1	1	0.5
	Window 7	Toilet women	Outside	1	1	0.5
	Window 8	Classroom A	Outside	1	1	1.5
	Window 9	Classroom A	Outside	1	1	1.5
2nd floor	Window 1	Classroom B	Outside	1	1	1.5
	Window 2	Classroom B	Outside	1	1	1.5
	Window 3	Teachers meeting room	Outside	1	1	1.5
	Window 4	Teachers meeting room	Outside	1	1	1.5
	Window 5	Principal office	Outside	1	1	1.5