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NUMERICAL STUDY OF CONDITIONS ON THE STAIRCASE DURING A FIRE IN A PUBLIC BUILDING

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Abstract
Fire is one of the most common risks to the environment and human health. Fire, depending on the conditions of combustion and the type of fuel, can emit many toxic products. The paper presents numerical analyzes of the conditions that can occur in a building during a fire. The conditions were analyzed in terms of the safety of the occupants and possible emissions of pollutants into the atmosphere. The temperature, propagation of smoke, and emission of pollutants were analyzed. A numerical model was created using Fire Dynamics Simulator (FDS) software. The model represents a staircase and a corridor in a real building located at the Silesian University of Technology in Poland. The results show that safe conditions are only ensured for a limited time, and emissions can also be harmful to occupants and the environment.

Keywords: **Fire; FDS; Numerical study; Staircase.**

1. INTRODUCTION

Fire in a building is one of the greatest risks to occupants. Fire, due to its characteristics, can cause numerous dangerous conditions that can affect occupants and the safety of the building. Fire is an unpredicted and uncontrolled process of heat propagation [1]. Products, such as high temperature, smoke and fire emissions, can be harmful to occupants, firefighters, and the environment. In general, fire contributes to the air many contaminants, either from the plume or from the water runoff or releases from burned materials. The deposition of these contaminants on land and water can lead to further contamination. The schematic impact of fire on the environment is presented in Fig. 1. A significant number of studies have been conducted on the emissions from burning materials. Many of them are cited in the NFPA report [2]. The authors also indicate a list of fires that have a significant potential to have an immediate and lasting impact on the environment.

Smoke contains a mixture of toxic combustion products and, depending on fuel and fire conditions, its composition may be different [3]. Smoke is dangerous because it can contain various toxic species, has a high temperature, can contain unburned particles, and most of all, it can partially or completely limit visibility and therefore slow or prevent evacuation [4, 5]. Considering the safety in the indoor environment, the main threat to the occupants in the case of a fire in a building is exposure to smoke and toxic products of combustion. Statistics show that more fire deaths are caused by smoke inhalation than by burns [6]. Fire, analyzing human exposure, can cause acute (by acute toxicants) or long-term (by carcinogens, mutagens) impact [2]. Many studies have been conducted to analyze emissions from combustion. Reisen et al. presented a list of particle and volatile organic emissions from furnishing materials [7]. Blomqvist et al. presented a study on emissions from fires with specific materials [8] and in simulated room fires [9].

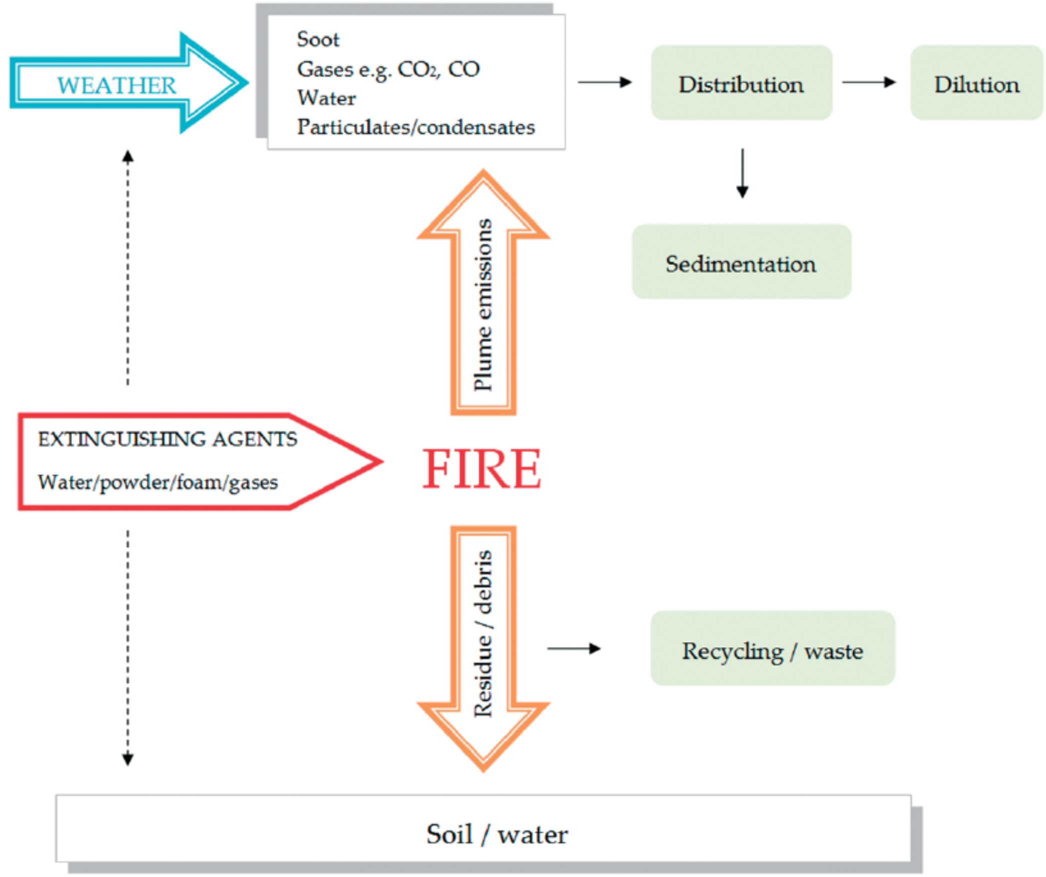

Figure 1.
Impact of fire on the environment (based on [2])

To prevent escape routes from being filled with smoke or to remove existing smoke, smoke ventilation systems are used. Depending on the building and regulations, natural or mechanical ventilation should be used. In general, the main objective is to extract smoke at a rate sufficient to prevent the smoke layer from descending to an elevation where people reside [10]. The control of fire and smoke in naturally ventilated buildings was described by Short et al. [11]. They provided a case study for the Lanchester Library building. Smoke movement mechanisms and temperature distribution in a staircase were described by Shi et al. [12].

Due to many fire incidents that have occurred in the past, it is crucial to test and predict conditions, such as smoke movement and temperature distribution, in corridors and stairs, which are the main escape routes. Smoke movement is one of the most important aspects of a fire risk analysis [13]. To predict these conditions, numerical analysis is used.

2. MATERIALS AND METHODS

In this study, numerical simulations of fire in a public building are presented. Simulations were carried out using Fire Dynamics Simulator (FDS) software [14]. The model represents the geometry of a staircase and a section of a corridor in an actual building located at the Silesian University of Technology in Poland.

Simulations were carried out to check the conditions that can occur in the stairwell during the fire. A fire scenario was defined and set in the model.

The paper presents the analyzes of conditions such as temperature, visibility and emission of pollutants.

2.1. Description of the simulated facility

The facility is located at the Silesian University of Technology in Gliwice, Poland. The simulated part of the facility contains a stairwell, a part of the corridor, and a room where the fire starts. Only part of the corridor was modeled because at the end of the actual corridor there is a fire door ((1) in Fig. 2a) that sep-

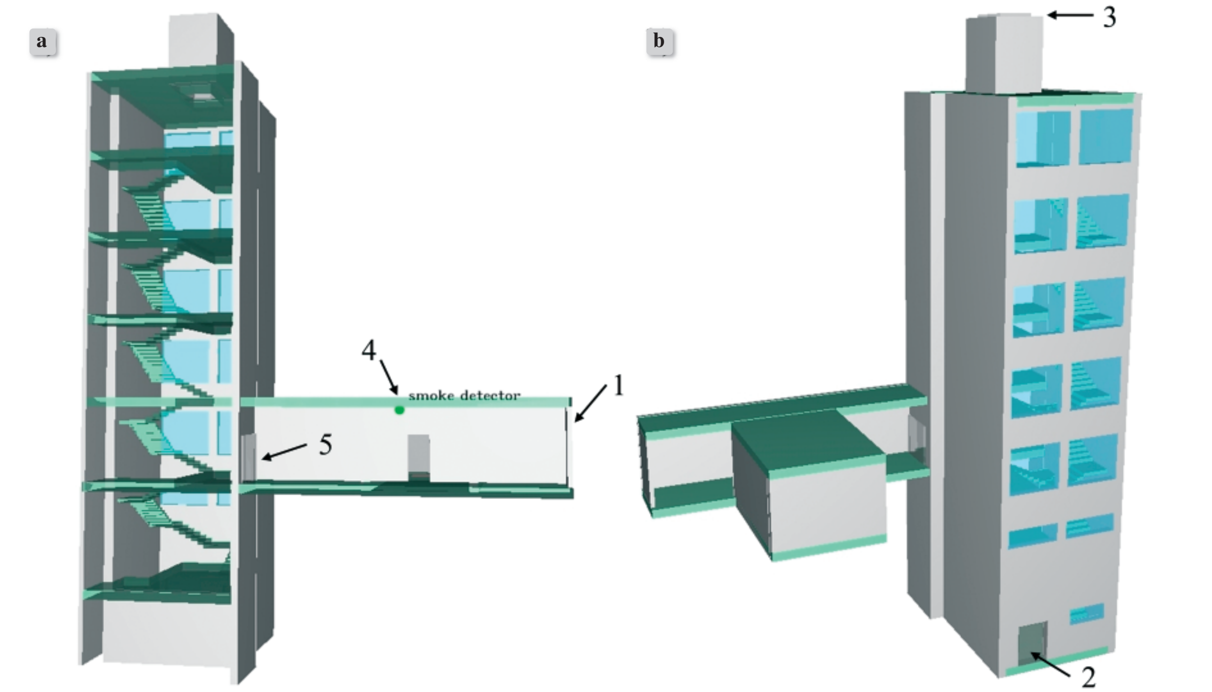

Figure 2.
The layout of the staircase and corridor model: a) front view; b) back view

arates the fire zone from the rest. The model was prepared to recreate the actual facility in the best way possible. The stairwell contains the basement, a ground floor, and five floors. The ceiling height of the basement is 2.75 m, the ceiling height of the ground floor is 4.18 m, the ceiling height of the fifth floor is 3.12 m, and of all other floors is 3.18 m. The layout of the model is presented in Fig. 2.

In this stairwell, there is a natural smoke exhaust system installed. The system contains an inlet air opening ((2) in Fig. 2b) in the basement – an exit door from the building, where fresh air enters, and a smoke damper ((3) in Fig. 2b) in a skylight on the roof, where the smoke exits. Smoke movement is dictated by the laws of physics. The smoke exhaust system was modeled according to the actual system. The Polish standard PN-B-02877 [15] (based on the German standard DIN 18232 Part 2 [16]) describes design principles for natural ventilation. Ventilation was designed according to NFPA regulations [17]. The smoke detector ((4) in Fig. 2a) is located in the corridor, near the room where the fire starts. The fire detector activates the smoke exhaust system in the stairwell – activates opening of the inlet air door and the smoke damper. At the end of the corridor there is a door that leads to the staircase ((5) in Fig. 2a).

2.2. The numerical model

The building model was created in the FDS program. The walls were modeled as gypsum plaster surfaces and the roof, stairs, and floors were modeled as concrete surfaces. All windows were modeled as PVC surfaces. The thickness of the model components represents the actual state-of-the-art. The material properties used in the model are shown in Tab. 1.

Polyurethane fire tests were conducted to study the movement of smoke through the corridor and staircase in a public building. The toxic properties of combusting polyurethane foam were described by McKenna et al. [18].

The fire was located in the room on the first floor. The fire compartment is 4.2 x 5.9 x 3.18 m high. A 1 x 1 m vent was set to model the fire. The fire source was modeled as a polyurethane burner with HRRPUA 0.5 MW/m^2 with a t-squared fire ramp. The medium rate of fire development was modeled.

Table 1.
Material properties

Properties	Material		
	Gypsum plaster	Concrete	PVC
Density, kg/m^3	1440	2280	1380
Specific Heat, kJ/(kg·K)	0.84	1.04	custom
Conductivity, W/(m·K)	0.48	1.8	custom
Emissivity	0.9	0.9	0.95

The assumptions set in the model are presented in Tab. 2. The combustion properties of polyurethane were established as shown in Tab. 3.

Table 2.
Assumptions set in the model

Assumption	Value
Door to the room where fire ignites	Open
Door to stairwell (5)	Open
Smoke detector	Cleary Ionization I1
Fire ventilation	Natural – inlet air opening in the basement and smoke damper on the roof
Fire ventilation activation	Activates via smoke detector

The heat release rate of the fire is shown in Fig. 3.

The pollutants' emission are given in a form of mass yield per a mass unit of combusted material [7]. These values can be applied almost directly in the FDS numerical model taking into account the assumed HRR curve and the known effective combustion heat (EHC) of polyurethane foam (PUR), which is the burning material.

Table 3.
Fuel properties

Fuel Type	HRRPUA, kW/m^2	Composition, atoms			
Simple Chemistry Model	500	Carbon	Hydrogen	Oxygen	Nitrogen
		6.3	7.1	2.1	1.0

Since the fire was modeled as a surface source with the determined heat release rate per area (HRRPUA) and commonly adopted t^2 type fire growth rate was assumed, the pollutants' source was set in the same way. It consisted of a surface emitting the selected species with the mass flux of *i*-th specie expressed as follows (Y_i denotes mass yield of *i*-th specie):

$$F_i = \frac{HRRPUA}{EHC} Y_i \tag{1}$$

The same parameters as for fire growth were set for the growth of pollutants' emissions.

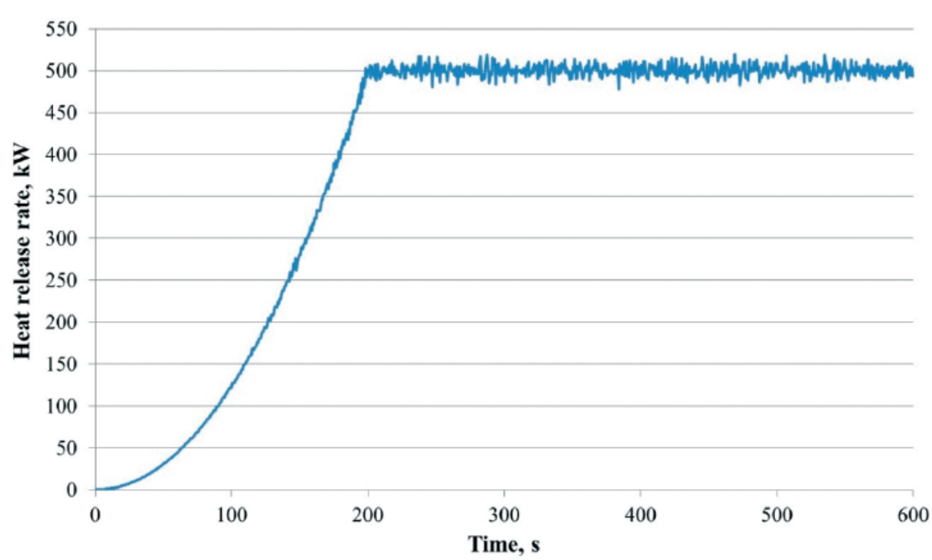

Figure 3.
Heat release rate

Table 4.
Mass yields [7] and calculated mass fluxes for selected pollutants

HRRPUA = 500 kW/m^2		
EHC (PUR) = 21 MJ/kg		
	Y_i, kg/kg	F_i, kg/m^{2}s
Benzene	$4.897 \cdot 10^{-3}$	$11.70 \cdot 10^{-5}$
Toluene	$0.459 \cdot 10^{-3}$	$1.09 \cdot 10^{-5}$
Formaldehyde	$9.30 \cdot 10^{-4}$	$2.21 \cdot 10^{-5}$
Acetaldehyde	$1.21 \cdot 10^{-3}$	$2.88 \cdot 10^{-5}$
Phenol	$4.30 \cdot 10^{-4}$	$1.02 \cdot 10^{-5}$
Benzoic acid	$7.65 \cdot 10^{-3}$	$1.82 \cdot 10^{-4}$

To record the conditions in a stairwell, the thermocouples were modeled. The layout of the thermocouples is presented in Fig. 4a. To record smoke movement and emissions, the 2d slice output was set. Its location is presented in Fig. 4b. To record the mass fraction of the pollutants considered, gas phase devices were set. Its location on the staircase is presented in Fig. 4c. The gas phase devices are located at the following heights: 1 – 2 m; 2 – 6.5 m; 3 – 10.2 m; 4 – 13.7 m; 5 – 17.3 m; 6 – 21 m; 7 – 23.5 m.

The computational domain in the FDS model contains 704128 cells. The domain was divided into three meshes to optimize the calculations.

The most important numerical parameter in FDS is the mesh cell size. To verify how well the flow field is resolved, the non-dimensional expression D*/δx was calculated. According to McGrattan, the quantity D*/δx represents the number of computational cells spanning the characteristic diameter of the fire [4]. D* is a characteristic fire diameter defined through the HRR of a fire and the thermal properties of ambient conditions and δx is the nominal size of a mesh cell. In general, the smaller the characteristic fire diameter, the smaller the cell size should be in order to adequately resolve the fluid flow and fire dynamics. It is suggested that the D*/δx value has to range from 4 to 16.

$$D^* = \left(\frac{\dot{Q}}{\rho \cdot c_p \cdot T \cdot \sqrt{g}} \right)^{\frac{2}{5}} \tag{2}$$

where:

$\dot{Q}$ – Heat Release Rate, kW,

ρ – Air density (≈1.2), kg/m^3,

c_p – Air thermal capacity (≈1), kJ/kg K,

T – Ambient air temperature, K,

g – Gravitational acceleration, m/s^2

D*/δx for the grid size of 0.15 m is 4.86. Due to that, the grid size of all meshes was adopted 0.15 x 0.15 x 0.15 m.

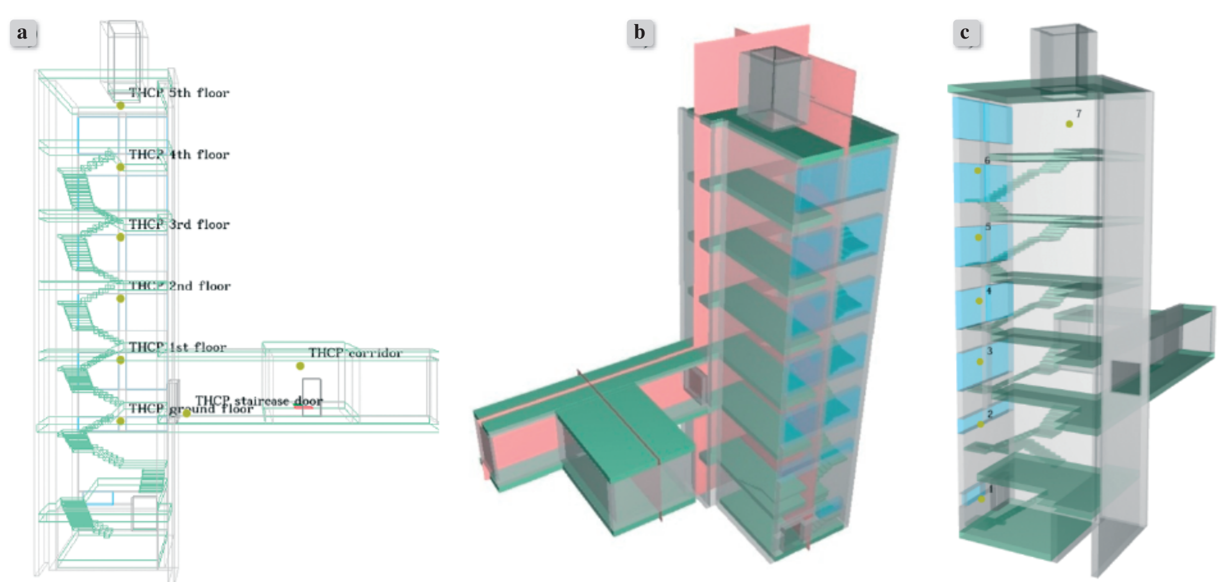

Figure 4.
The layout of: (a) the thermocouples in the model; (b) the 2d output slices; (c) the gas phase devices

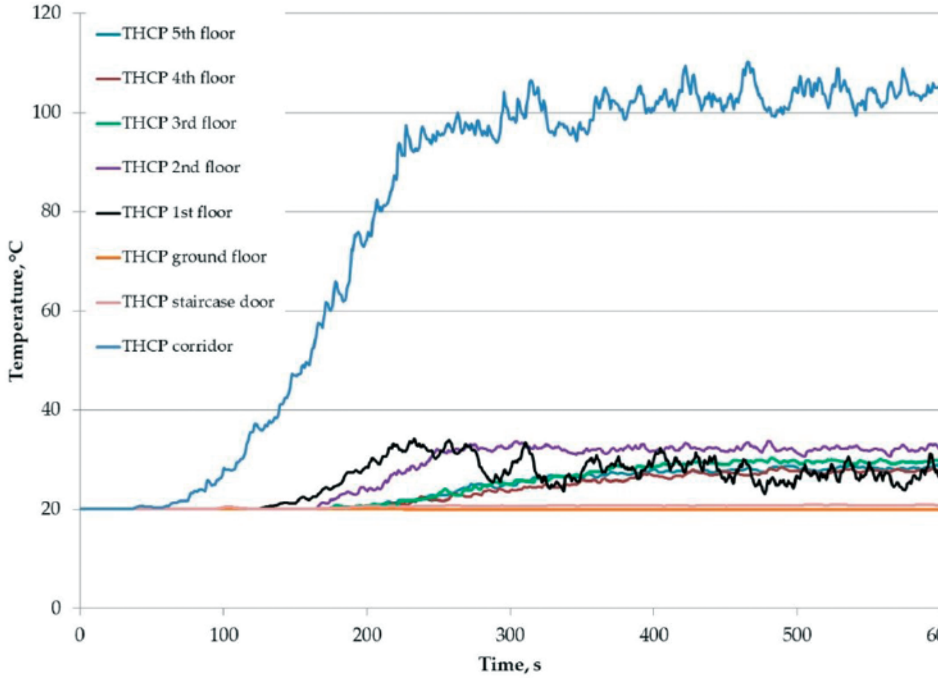

Figure 5.
Temperatures at the measurement points

3. RESULTS

The numerical model was built to analyze the conditions that may occur during the fire. Fig. 5 shows the temperatures at the measurement points.

The highest temperature values were measured by the thermocouple located in the corridor. The temperature reaches nearly 100°C there in just 4 minutes. Safe conditions in the corridor during an evacuation are provided for about 3 minutes from the start of the fire, until the moment when the temperature reaches 60°C. The remaining temperature values were below 40°C and these values are considered safe conditions for the occupants.

The Polish regulations define the maximum allowed concentrations of pollutants depending on the exposure time, the values are given in Tab. 5.

The numerical analyzes allowed to observe the dispersion of pollutants in the corridor and staircase. The concentration of the pollutants measured is presented in the following figures (Fig. 6 and Fig. 7). Each plot shows the time changes of a specific pollutant concentration at each measuring point (Fig. 4c). The maximum permitted concentrations are also marked in the plots.

In each plot, the concentration values of pollutants at points 1 and 2 are relatively low. At other points, the increasing trend can be observed. The instantaneous maximum allowed concentration (NDSCh) was exceeded only for formaldehyde at points 3–7 (Fig. 6c). Occupants located on the first and upper floors are exposed the most. It can be concluded that the conditions on the staircase, in terms of exposure to formaldehyde, can be harmful to the occupants. Only in the basement and on the ground floor is the potential evacuation possible because the concentration there is lower than the NDSCh. Possible effects of formaldehyde contamination include, among others, eye irritation and respiratory system, cough, dyspnea, headache, chemical burns, and many others.

Table 5.
The maximum permitted concentrations of pollutants [19]

	Maximum permissible concentration during a work shift (NDS), mg/m^3	Instantaneous maximum allowed concentration, not longer than 15 min (NDSCh), mg/m^3	Concentration value that must not be exceeded in the working environment at any time (NDSP), mg/m^3
Benzene	1.6	-	-
Toluene	100	200	-
Formaldehyde	0.37	0.74	-
Acetaldehyde	-	-	45
Phenol	7.8	16	-
Benzoic acid	-	-	-

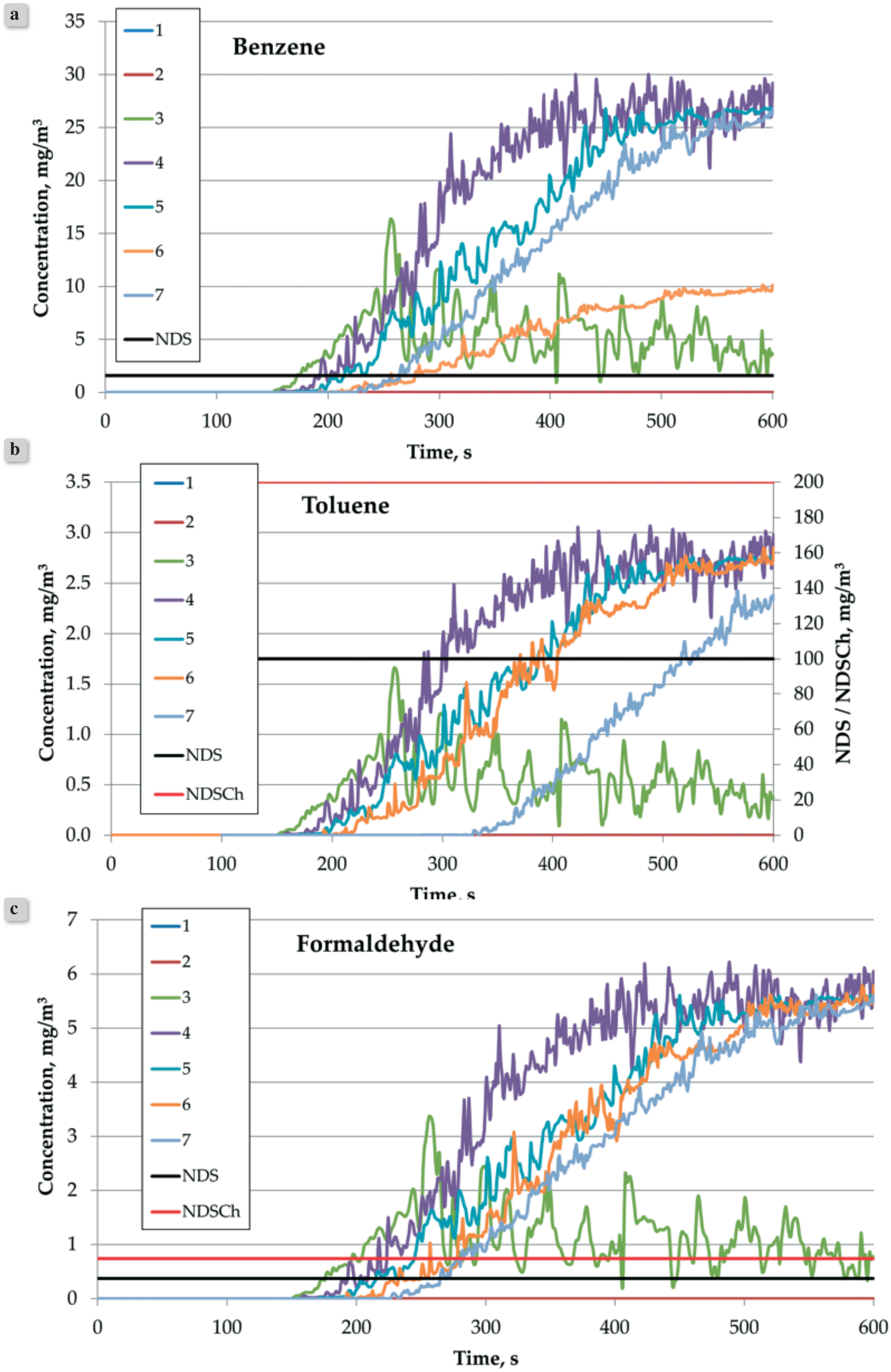

Figure 6.
Concentration of: (a) benzene; (b) toluene; (c) formaldehyde

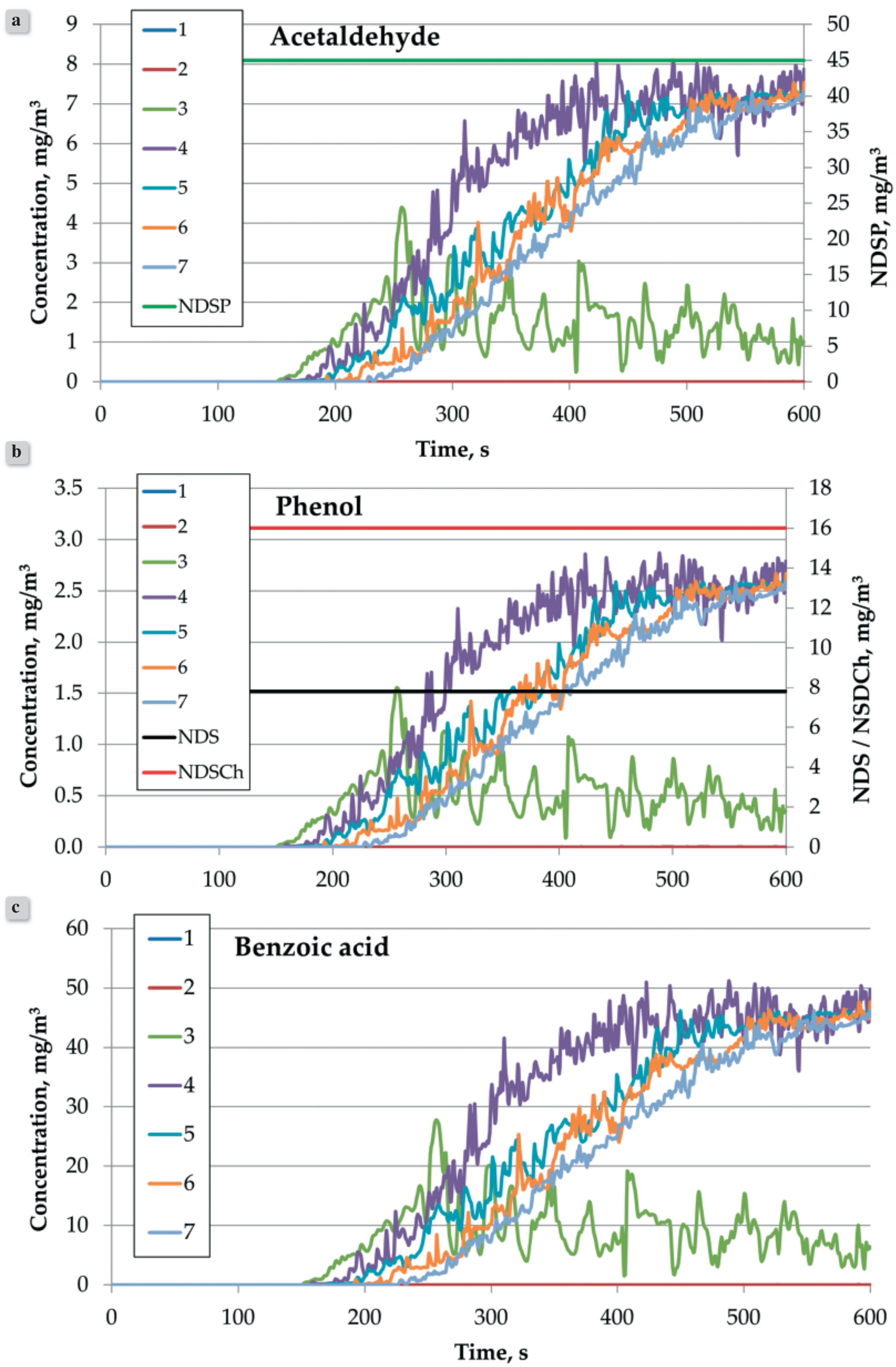

Figure 7.
Concentration of: (a) acetaldehyde; (b) phenol; (c) benzoic acid

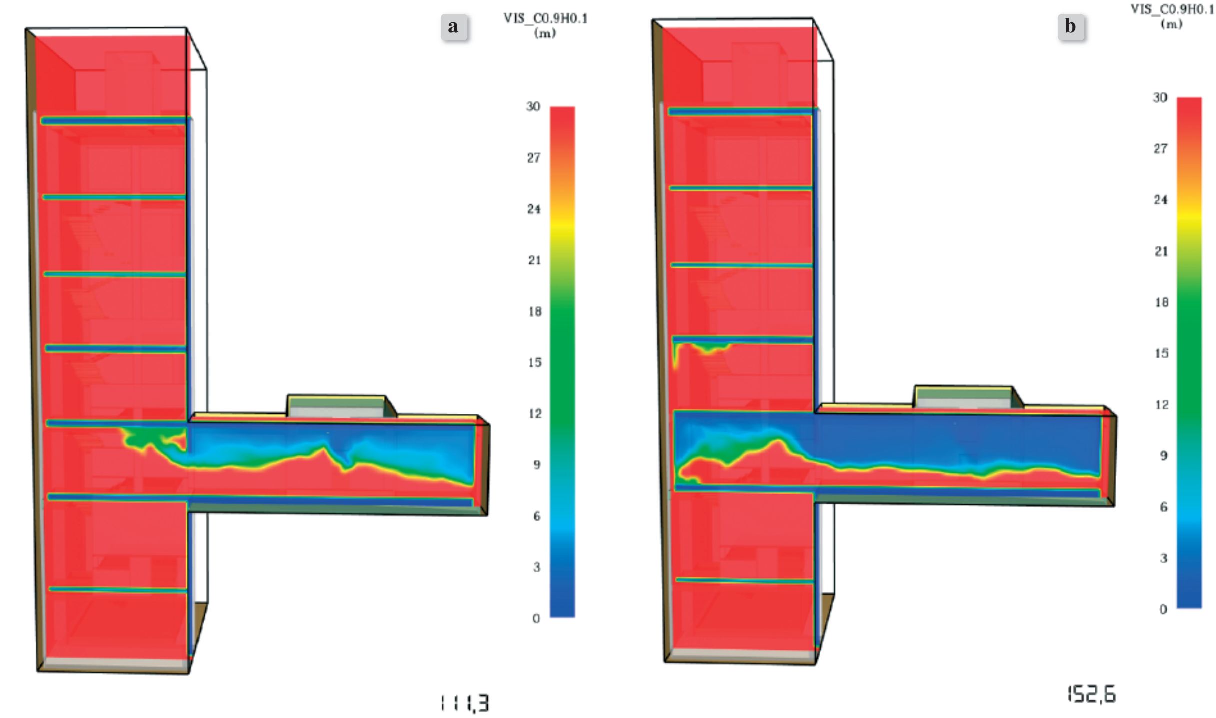

Figure 8.
Visibility in the corridor: (a) after 111 seconds; (b) after 152 seconds

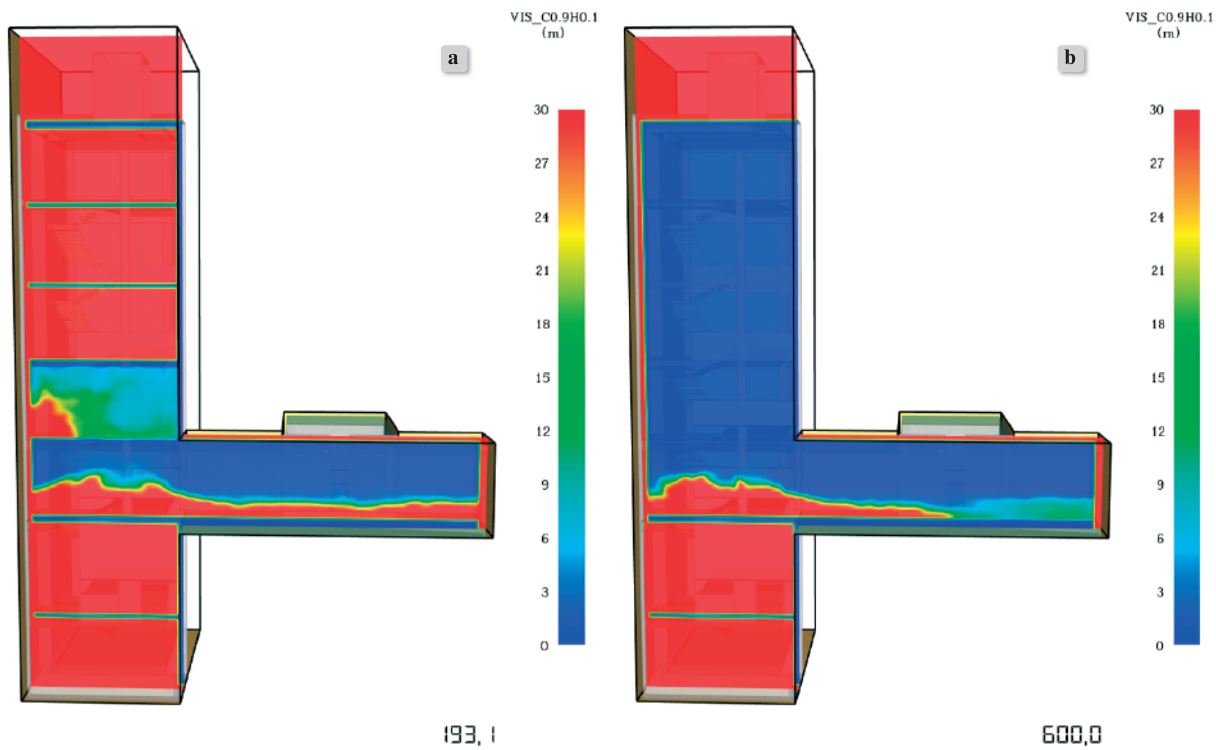

Figure 9.
Visibility in the staircase in: (a) 193 seconds; (b) 600 seconds

Table 6.
Door opening activation time

	Time, s	
Event	V1	V2
Closing	When the smoke detector activates	
Opening	60	55
Closing	90	70
Opening	150	80
Closing	180	90
Opening	200	110
Closing	215	125

Besides benzene, concentrations of other pollutants considered are lower than NDS and NDSCh in the analyzed total time of 10 minutes. It is important to remember that fires emit a large number of pollutants to the environment and their influence can be harmful to the environment.

The analysis shows that after about 200 seconds, there are no safe conditions for evacuation due to dangerous concentrations of benzene and formaldehyde.

Considering the conditions in terms of smoke and limited visibility, the safe conditions in the corridor are provided for only about 110 seconds. After that, the smoke layer is lower than the high where people move and visibility is less than 10 meters (Fig. 8a). After about 152 seconds, visibility in the corridor drops to almost 0 meters, and evacuation through this corridor is impossible.

When the smoke spreads to the staircase, evacuation from the upper floors may be limited and finally impossible. When visibility drops, the movement of the occupants is slower, people lose orientation, and are more exposed to the inhalation from toxic products of combustion. Fig. 9a shows that in 190 seconds the visibility in the second floor staircase is less than 12 meters and, under these conditions, people cannot use this staircase to evacuate. Smoke spreads upward and exits through the smoke damper located on the roof. Due to the inlet opening located in the basement, fresh air enters, and a smoke-free layer is provided, but only in the basement and up to the height of the ground floor (Fig. 9b). It means that the occupants located under the floor where the fire is, can use this staircase to evacuate during the entire analyzed time.

To indicate how important automatically closed doors are, two additional simulations were performed (V1 and V2). In these simulations, the door to the stairwell ((5) in Fig. 2a) is automatically closed when the smoke detector is activated. The door opens a few times to simulate people's escape. The timing is presented in Tab. 6.

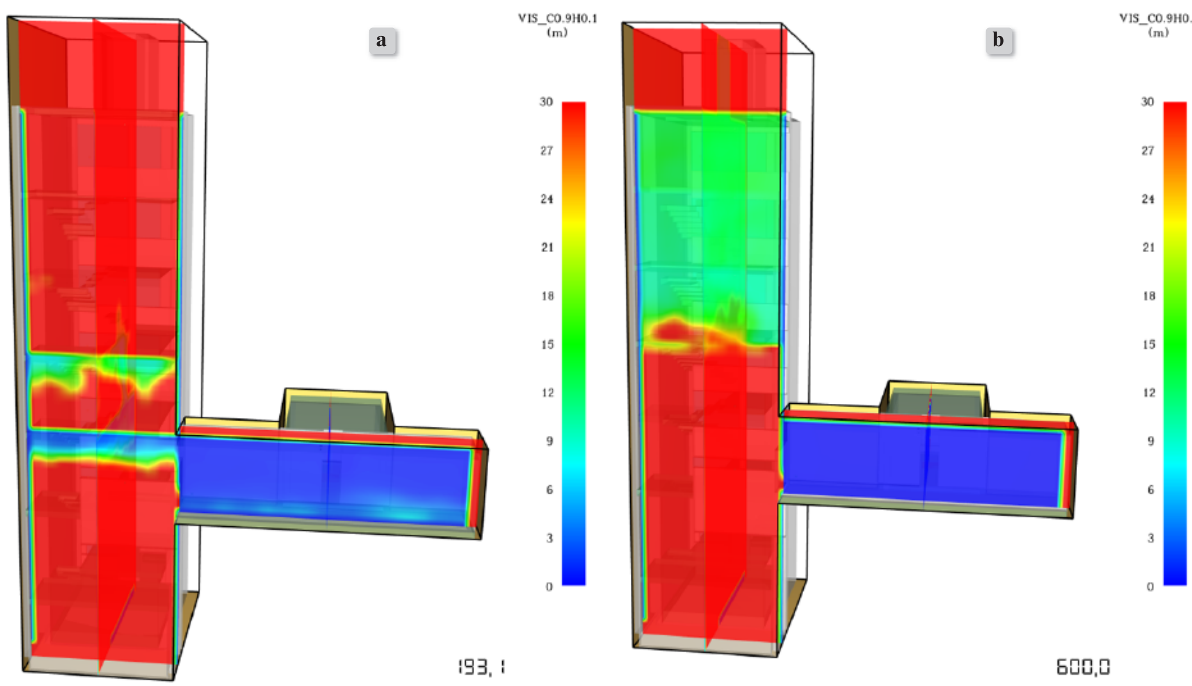

Figure 10.
Simulation V1 – Visibility in the staircase in: (a) 193 seconds; (b) 600 seconds

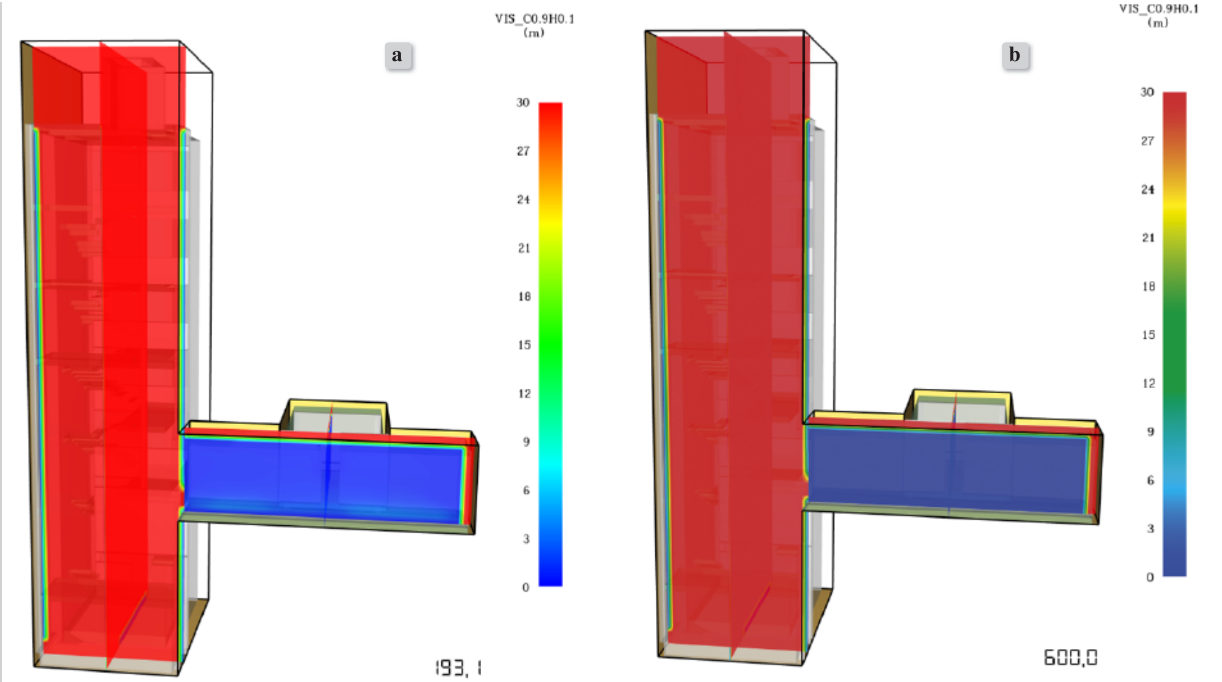

Figure 11.
Simulation V2 – Visibility in the staircase in: (a) 193 seconds; (b) 600 seconds

When comparing the results, some differences can be observed. The main difference between the simulation with an open and a closed door can be noticed at the end of the simulation. When the door to the staircase is closed, there is almost no smoke in the staircase (Fig. 9b, Fig. 10b and Fig. 11b). Depending on the frequency and timing of the door event, the amount of smoke can differ. That can be observed in Fig. 10 and Fig. 11. The role of these doors in evacuation is substantial, as confirmed by the results from simulations with door open and closed.

4. CONCLUSION

The paper presents numerical analyzes of a fire in a public building. The aim was to examine the conditions that can occur in the corridor and the staircase during a fire. Analyzes of the following parameters, such as temperature, smoke propagation, visibility, and pollutants concentration, have shown that fire develops quickly and safe conditions for the occupants are provided only for a limited time. The presented study has proved that the concentrations of the harmful components may quickly reach the level, which may seriously affect humans' health or even pose a threat to people' lives. Since the conditions were getting worse very quickly, it is extremely important to make people aware of potential danger and to teach them how to behave and react in a case of fire.

The crucial role of automatic door-closers was also highlighted. In cases when they were activated the concentrations of the harmful components at the staircase were significantly lower than for the case with door permanently opened. So it was shown that such relatively low-cost solution was able to ensure the safe condition on the escape route for a long time.

Fires emit many pollutants to the environment. It is also important to remember that pollutants emitted can contaminate the environment directly but also can interact with extinguishing agents and that can lead to further contamination.

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