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Original Paper

RESEARCH INTO THE DYNAMICS OF FIRE DEVELOPMENT AND THE EFFICIENCY OF THE FIRE ALARM SYSTEM IN A HIGH-RISE BUILDING

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Fires in high-rise residential buildings can lead to human casualties and significant property damage. Therefore, ensuring fire safety in these buildings is an urgent task. The results of the Fire Protection System simulation of the development of a fire in a residential apartment showed that open windows and doors of the room, as well as the wind speed outside the window, affect the dynamics of fire development and the spread of non-hazardous fire factors. However, when the wind speed outside the window is 7.0 m/s, due to draft and cooling, the hazardous factors of the fire do not reach critical indicators for humans. This makes the evacuation process safer for people. The impact of the position of windows and doors, and the wind outside the window on the time of detection or failure of fire detectors was determined. It was determined that even if the current regulatory requirements for installing fire detectors are met, when the wind speed outside the window is 7.0 m/s, only the smoke detector located in close proximity to the source of the fire and having increased sensitivity is triggered. The results demonstrate the need for an adaptive approach to the placement of detectors in high-rise residential buildings.

Keywords: *high-rise residential building, fire detectors, Fire Detection System, critical fire factors.*

INTRODUCTION

Modern high-rise buildings are complex engineering structures in terms of fire protection. The safety of people in a high-rise residential building is a matter of paramount importance, especially when it comes to fires. Fires in such buildings can lead to catastrophic consequences with numerous human losses and significant property damage. The fire hazard of tall buildings is caused by: complex construction, functional diversity, large number of people and high fire load. Their safe usage is extremely important.

Detecting a fire at an early stage and extinguishing it promptly is crucial to ensuring fire safety in high-rise buildings. Fire detection time is a critical indicator of the effectiveness of Fire Protection Systems (FPS) and the safe evacuation of occupants. Therefore, despite the rapid development of technology and the variety of fire detection methods, ensuring fire safety in tall buildings is an urgent task.

The complexity of planning high-rise buildings is due to the large number of stairwells, elevator and pipe shafts, air ducts, cable shafts and many other vertical shafts through which a fire can spread quickly and with high intensity. Inadequate arrangement of fire compartments contributes to the rapid spread of fire. Due to air convection, the horizontal speed of smoke diffusion is 0.3 m/s at the initial stage of a fire, and at the stage of a severe fire it can reach 3 to 4 m/s. After a high-rise building catches fire, smoke can diffuse through vertical shafts to the upper floors in 30 seconds, and its speed is more than 10 times faster than the

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speed in the horizontal direction. Fire development on the upper floors with the same fire load differs from fires on the lower floors due to differences in temperature and gas conditions, peculiarities of ventilation systems, and the influence of external factors such as wind and atmospheric pressure.

Fire protection of high-rise buildings is based on a set of measures that include: preventive measures, management solutions, training of maintenance personnel, fire load reduction, structural solutions, creation of fire barriers, FPS equipment and their maintenance, etc. This complex is regulated by the current regulatory documents in the construction industry. Despite the high fire safety requirements established by building codes (International Building Code (IBC), 2025; NFPA 72, 2025; NFPA 5000, 2024; NFPA 101, 2024; SBN V.2.2-15:2019; SBN V.2.2-41:2019), their practical application in high-rise buildings remains a serious problem. This is due to a number of factors that create significant obstacles to ensuring an adequate level of fire protection.

Ensuring the fire safety of tall buildings is a complex problem around the world. Statistics show that the number of fires in high-rise buildings is increasing significantly every year (Kodur *et al.*, 2020; Odynets *et al.*, 2020). Based on fire statistics in the United States and the United Kingdom, the main causes of fires in residential buildings are smoking, residential heating, electrical equipment malfunctions, and open flames (Kodur *et al.*, 2020). The authors' analysis of the statistics of fires in high-rise buildings in Ukraine (Odynets *et al.*, 2020) revealed an alarming trend of a 2.3-fold increase in their number over the past ten years. The study of fires showed that the number of fires in corridors and stairwells is decreasing, but the number of fires in kitchens, garbage chambers, technical rooms, and bathrooms, where many household appliances are concentrated, is increasing. The authors have identified a number of shortcomings in ensuring fire safety in high-rise buildings, in particular, in meeting the requirements for proper maintenance of FPS. The main problems are the failure of the fire detection systems and firefighting systems, untimely detection and extinguishing of fires.

In order to prove the effectiveness of the developed evacuation algorithms, technological solutions developed and used in FPS, and management and engineering decisions made, it is necessary to conduct research on fire development in high-rise buildings under various conditions. Comprehensive analysis and research of fire development is an important prerequisite for the development of fire protection measures and the creation of high-performance FPS. They are crucial in ensuring the fire safety of tall buildings; the absence or inoperability of these systems leads to large-scale fires, especially when the fire starts on the upper floors.

A previous study (Xiuyu *et al.*, 2012) analysed the features of fire occurrence and development in tall buildings in order to determine their course and to better understand the relationship between building characteristics and fire risks. In the course of the study, a partial event tree was formed, in which the main event was the direct losses caused by the fire. The structure of the fire safety system of a high-rise building was presented. The authors of that study aimed at addressing the issue of fire protection of tall buildings and providing some practical value for the design of tall buildings, fire safety assessment and the creation of a disaster prevention programme. However, the paper provides general recommendations that require further research in each specific area, including with regard to FPS.

In another study (Zhang *et al.*, 2024), the authors investigated the probability of a fire in tall buildings based on the analysis of risk factors. The study combined the event analysis method with fire codes for building design and identified eleven key risk factors that have a significant impact on fire prevention in tall buildings. Based on the identification of risk factors, a fire prevention tree for tall buildings was also created. Taking into account the uncertainty of fire occurrence in tall buildings, that study used an uncertainty-based method to model the risk of fire in tall buildings for early detection. The developed methodology was empirically validated by analysing empirical data on fire risks in nine representative high-rise buildings. However, the research was aimed only at determining the probability of fire, fire risks, and not at improving fire safety through technical solutions.

Fire load significantly affects the time of fire development. Its growth leads to an increase in fire spread, duration, and high temperatures. The analysis carried out in Džolev *et al.* (2021) and Ding *et al.* (2024) showed a large discrepancy and deviation in the fire load density from the standards for determining the fire load. According to the results of a previous study (Džolev *et al.*, 2021), the fire load density in residential apartments has doubled over the past 30 years. This has affected overall fire safety by increasing the energy released during combustion. The effect of fire load density on fire development was studied in a representative apartment using the OZone computer code. The growth of fire load and the number of fires in modern residential apartments was studied using the results of a survey of 50 high-rise buildings in Istanbul (Dundar *et al.*, 2024). The study was based on fire loads in living rooms, bedrooms, and kitchens. The results show that the average fire load density in living rooms ranges from 310 MJ/m^2 to 379 MJ/m^2, while for bedrooms it is from 518 MJ/m^2 to 650 MJ/m^2. The kitchen has an average fire load density of 552 MJ/m^2. The Fire Dynamics Simulator (FDS) software package modelled the development of the fire taking into account this fire load. The results of the FDS simulation show that the fire spread time ranges from 1 to 11 minutes, depending on the room. However, these studies (Džolev *et al.*, 2021; Dundar *et al.*, 2024) did not investigate how long it takes for FDS to detect a fire.

A comprehensive bibliometric analysis for research in the field of fire prevention and mitigation in tall buildings was conducted (Dabous *et al.*, 2024). The analysis covered the period between 2010 and 2023. The main purpose of the analysis was to classify and evaluate the effectiveness of fire prevention and mitigation technologies. The study promotes a methodological approach to analysing fire safety measures and emphasises the critical need for multidisciplinary approaches to improving fire safety protocols. Particular emphasis was placed on the integration of advanced technologies for fire detection, fire fighting and evacuation. The authors identified six passive technologies and 14 active technologies. Passive technologies are focussed on risk assessment and fire protection in terms of the use of fire sections and fire-resistant materials, and management solutions. The authors payed special attention to active fire detection technologies, automatic fire extinguishing, the use of unmanned aerial vehicles, artificial intelligence algorithms, and the Internet of Things (IoT). To reduce the time and accurately detect a fire, fire detection technologies such as intelligent fire detectors (FD) (Baek *et al.*, 2021; Kushnir *et al.*, 2021; Hitimana *et al.*, 2022; Kushnir *et al.*, 2023) and computer vision-based video systems (Abdusalomov *et al.*, 2022; Ahn *et al.*, 2023) are used. Many studies (Baek *et al.*, 2021; Kushnir *et al.*, 2021; Abdusalomov *et al.*, 2022; Hitimana *et al.*, 2022; Ahn *et al.*, 2023; Kushnir *et al.*, 2023; Dabous *et al.*, 2024) have found that FDS data can reduce fire detection time and false alarms. However, these works do not indicate how the location of the FD and different fire scenarios in tall buildings affect the fire detection time. This requires further research.

In Enaru *et al.* (2023), the process of fire development in a one-story building was modelled using the FDS software package, taking into account the real situation. The fire occurred in the kitchen; the probable source of ignition was the thermal effect of electric current on an electric cable, and the material that first ignited was plastic. The authors analysed the time of fire development, the degree of danger, temperature, and visibility. They also analysed architectural solutions that can be considered to prevent and manage fires in different situations. The results of the study create a real basis for improving evacuation conditions and limiting damage from fires in residential buildings.

In another study (Shnal *et al.*, 2020), the development of a fire in a three-story residential building was modelled using the FDS software package during full-scale fire tests. The nature of the fire and the time dependencies of its main parameters, such as the temperature distributions on the corresponding planes and the graphs of the dependencies of the average volume temperature on time and the corresponding variances of deviations for the room, were determined. This, in turn, made it possible to analyse the adequacy of the modelling results in FDS. The studies made it possible to determine the limits of this approach for predicting the behaviour of building structures in fire conditions. The FDS software package has been used (Yakovchuk *et al.*, 2021) to obtain numerical and graphical indicators characterising the process of fire initiation, spread, and development on the surface of the facade thermal insulation system. The obtained results were compared with experimental data to verify the possibility of using the appropriate software to reproduce real fire conditions in residential buildings. Other studies (Shnal *et al.*, 2020; Yakovchuk *et al.*, 2021) confirmed the possibility of using FDS to model fires in residential buildings. However, those studies did not investigate how long it takes for FDS to respond.

The FDS software package was used to model the dynamics of a fire in a high-rise office building, namely, the spread of smoke in the building, in order to track the evacuation time for each floor (Shu *et al.*, 2022). Smoke propagation on different floors was evaluated and compared through visibility and CO concentration at critical evacuation times. The study presented the results of a study of the evacuation of people from a building. However, determining the time from fire initiation to the moment of notification of people, taking into account the location of the FD and the location of the fire, requires further research.

Rapid fire detection and prompt extinguishing play an important role in protecting people's lives, property, and the building itself. Ensuring a high level of fire safety in such buildings, which can have dozens of floors, requires the implementation of highly efficient FDS. The speed and accuracy of fire detection depends on the FDS. The faster the FDS detects a fire, the faster it is possible to alert about the fire and organise the safe evacuation of people and start extinguishing the fire. These systems must be able to distinguish between a real fire and false alarms in order to take some measures to localise it, minimise the consequences, and prevent people from being exposed to the hazards of the fire.

A fire in a high-rise building will develop differently depending on the height of the floor. Wind speeds at greater heights may differ from those at ground level. If the windows and doors are open in the apartment, this will affect the operation of the FDS and thus the efficiency of the FDS. These factors must be taken into account when selecting and placing FDS.

The purpose of this study was to investigate the dynamics of fire development and the impact of fire hazards on a person during evacuation, as well as the effectiveness of the fire alarm system in a residential apartment of a high-rise building under various scenarios. The scenarios take into account the position of the windows and doors, as well as the impact of wind at different speeds, in order to further improve the level of fire protection.

To achieve this goal, the following objectives were made:

– to analyse the requirements of regulatory documents for the equipment of fire protection systems in high-rise buildings;

– to develop a model of a residential apartment located on the twentieth floor of a high-rise building with typical structural elements and fire load in the FDS software package;

– to simulate the dynamics of fire development in a residential apartment on the twentieth floor of a high-rise building under different scenarios and the impact of fire hazards on the process of evacuation of people in the FDS software package, based on the developed model of a residential apartment on the twentieth floor of a high-rise building;

– to study the effectiveness of FDSys, designed in accordance with regulatory requirements and additional conditions, during a fire under various scenarios in the FDS software package, based on a model of a residential apartment on the twentieth floor of a high-rise building.

MATERIALS AND METHODS

This study examined the dynamics (process) of the spread of fire hazards in a residential apartment of a high-rise building under different scenarios, modelled using a simulation computer model. We determined the effectiveness of the fire alarm system in a residential apartment of a high-rise building, depending on the location of the FDS installation under different scenarios. The scenarios take into account the position of windows and doors, and whether they are open or closed. The effect of wind outside the window at different speeds was also taken into account.

The hypothesis of the study was to estimate the time of fire detection by FDS depending on its location, the position of windows and doors, and the wind speed outside the window. This will provide data on the possible location of the FDS at the design stage. The assumptions made in the study are that the data obtained using the FDS software package under these scenarios will correspond to the real data that may be available during a fire with acceptable adequacy. The validation of the developed model in the FDS software package has been proven by similar studies (Shnal *et al.*, 2020; Yakovchuk *et al.*, 2021; Shu *et al.*, 2022; Dundar *et al.*, 2024).

FDS is fire development modelling software developed by the National Institute of Standards and Technology (NIST). FDS uses sophisticated mathematical models to describe combustion, heat transfer, and gas movement. The programme takes into account many factors, such as building geometry, material properties, location of the ignition source, and fire system operation. The programme is used to predict the spread of fire, smoke, temperature, carbon monoxide, and other hazards during a fire in buildings and other structures. Simulations can be used to check how FD will perform in different scenarios. The main capabilities of the FDS programme and the mathematical apparatus used for this purpose have been described in several papers (McGrattan *et al.*, 2013; Shnal *et al.*, 2020; Yakovchuk *et al.*, 2021; Enaru *et al.*, 2023; Shu *et al.*, 2023). The validity of the models developed in the software package depends on the scenario, the scale of the fire, the quality of the input data, the size of the grid, etc. However, FDS has high validity for engineering fire calculations. Publications of the NIST (McGrattan *et al.*, 2005; 2006; 2017) present the results of a large number of comparisons of simulations with experimental data. The typical error for key parameters is approximately 10–30%, which is considered high enough for fire modelling. For example, when studying temperature fields, the average relative error is 10–20% of the experimental values, and the deviation in the measured optical density is 25%.

The mathematical model underlying the calculations in the FDS software environment is based on simplified Navier–Stokes equations. It takes into account the transfer of mass, momentum, and energy, as well as combustion, smoke generation, and thermal radiation. This is the equation of energy (heat transfer):

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla} T = \alpha \nabla^2 T + \frac{\dot{Q}}{\rho c_p} \qquad (1)$$

where T is the temperature; $\vec{u}$ is the velocity vector of gases; $\alpha = \lambda / \rho c_p$ is the thermal diffusivity; $\dot{Q}$ is the heat source (rate of heat release due to combustion); c_p is the specific heat capacity; $\nabla^2 T$ is the temperature Laplacian describing thermal conductivity.

If a combustible material is specified, FDS can calculate the surface area:

$$\dot{Q} = HRRPUA \cdot A \qquad (2)$$

where HRRPUA is the Heat Release Rate Per Unit Area; A is the combustible surface area.

The activation of the heat detector (HD) in the FDS is determined by the equation (McGrattan *et al.*, 2013):

$$\frac{dT_l}{dt} = \frac{\sqrt{|u|}}{RTI}(T_g - T_l) \qquad (3)$$

where u is the gas velocity; RTI is the response time index; T_l is the temperature of the link, T_g is the temperature of the gas near the link.

A detailed model of a smoke detector (SD) is proposed in McGrattan *et al*. (2013). The model takes into account that smoke must first pass through the outer casing and then through a series of baffles before entering the sensing chamber. There is a time delay associated with the passage of smoke through the housing, as well as with the entry of smoke into the sensor chamber. The change in the mass fraction of smoke Yc in the sensor chamber SD can be found by solving the equation:

$$\frac{dY_c}{dt} = \frac{Y_e(t - \delta t_e) - Y_c(t)}{\delta t_c} \qquad (4)$$

where δt_e is the characteristic filling time of the entire volume confined by the outer enclosure; δt_c is the characteristic filling time of the sensor chamber; and Y_e is the mass fraction of smoke outside the FD in the free flow. A simple interpretation of the equation is that the concentration of smoke entering the sensor chamber at time t is equal to the concentration of the free flow at time $t - \delta t_e$.

An analytical solution to equation (4) can be found, but it is more convenient to simply integrate it numerically. The predicted mass fraction of smoke in the sensor chamber $Y_c(t)$ can be converted into an expression for the percentage of blackout per unit length using:

$$\text{Obscuration} = (1 - e^{-K_m \rho Y_c l}) \times 100\% \text{ per lenght } l$$

To simulate fire spread and FDS performance, a 22-storey residential high-rise building located in Lviv was selected. The building is a monolithic frame building with an underground parking lot, with a floor height (from floor to ceiling) of 2.7 m. The outer walls are brick, self-supporting with a fire resistance limit of 150 min and a fire spread limit of 0 min. This meets the requirements for external self-supporting walls REI90, M0 – the first degree of fire resistance. Internal partitions made of gas blocks with a fire resistance limit of 90 min. This meets the requirements for internal partitions EI30, M0 – the first degree of fire resistance. The facade of the building is ventilated and insulated with mineral wool. The roof of the building is combined. The entrance doors are metal fire doors with a fire resistance rating of EI60 min, interior doors are MDF on a wooden frame. The windows have single-glazed windows and a five-chamber profile. The layout corresponds to a typical residential high-rise building with 160 apartments and 62 parking spaces, one-room, two-room, three-room and 2-level penthouses.

We modelled the development of a fire when a fire broke out in the kitchen area of 28.5 m^2 of a three-room apartment (Fig. 1) on the 20th floor of a high-rise residential building. The following notations are used in the figure: HD1 and SD1 — HDs and SDs are located in the kitchen, HD2, HD3 and SD2, SD3 - HDs and SDs are located in the hallways, HD4 and SD4 - HDs and SDs are located in the common corridor. The kitchen can be classified as a medium fire risk category, according to its intended use. The initial conditions for FDS modelling are as follows: the cell size is 0.25 m × 0.25 m × 0.25 m, the ambient temperature is 20 °C, the relative humidity is 40%, and the atmospheric pressure is 101325 Pa. According to meteorological data, the average monthly wind speed in Lviv at ground level ranges from 2.6 m/s to 3.9 m/s. Taking into account approximate calculations using the Wind Profile Calculator, we model the development of a fire at a wind speed outside the window (V_w) on the 20th floor at 3.5 m/s and 7 m/s. Parameters of the fire centre: initial heat release 200 kW/m^2, fire centre area 0.25 m^2. The simulation time is 300 s.

The cell size of 0.25 × 0.25 × 0.25 m was chosen as a compromise between the required modelling accuracy and computation time. It is known that as the cell size decreases, the accuracy of calculations increases. However, excessive reduction of cell size does not significantly improve the results, but significantly increases the computational costs.

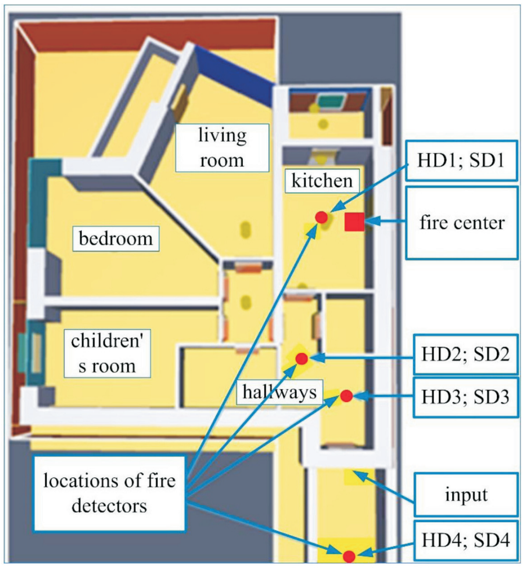

Fig. 1. Plan of a three-room apartment in which fire development is modelled.

The modelling is performed in 3D mode of the FDS software environment, which ensures high accuracy, more closely corresponds to a real fire and shows the actual distribution of smoke, heat and flows in space.

To detect fire, the point HD class A2 was used, which complies with the European standard EN 54-5:2017: minimum static response temperature 54 °C; maximum static response temperature 70 °C. Also, the optical SD with a sensitivity of 0.15 dB/m (3.43%/m) meets the requirements of the European standard EN 54-7:2018 from 0.05 dB/m (1.145%/m) to 0.2 dB/m (4.47%/m). These requirements ensure effective detection of a wide range of smoke types, including both smouldering and flaming fires. The American standard NFPA 72 does not set specific sensitivity values, but requires that each SD operate within its specified sensitivity range.

According to (IBC, 2025) section 9, SDs are installed: on the ceiling or wall outside each individual bedroom in the immediate vicinity of the bedrooms, in each room used for sleeping, and on each floor of a residential building, including basements, but not including uninhabitable attics, etc. SDs must not be installed in the following locations: ionisation SDs must not be installed less than 6096 mm horizontally from a permanently installed kitchen appliance; ionisation SDs with an alarm switch must not be installed less than 3048 mm horizontally from a permanently installed kitchen appliance; optical SDs must not be installed less than 1829 mm horizontally from a permanently installed kitchen appliance. SDs should be installed at least 914 mm horizontally from a door or opening of a bathroom with a bathtub or shower, etc. However, the IBC is not formally binding until it is adopted by a particular jurisdiction as its own document.

Clause 29.5.1 (NFPA 72, 2025) states that SDs are installed: in each bedroom (sleeping room), outside each group of bedrooms (in the corridor leading to the bedrooms), and on each floor, including basements.

With regard to these standards in Ukraine, clause 8.22 of SBN V.2.2-15:2019 states that the need to equip residential buildings, as well as built-in (attached) non-residential premises with FPS is determined in accordance with SBN V.2.5-56:2014. SBN V.2.2-56:2014 states that residential buildings with a nominal height of 26.5 m to 47 m, 47 m to 73.5 m, and 73.5 m to 100 m shall be equipped with FDS. FDS of the smoke protection system are installed in apartment hallways, off-apartment corridors and elevator halls using addressable components. Built-in rooms for various purposes are equipped with FDS regardless of the area.

RESULTS

Consider different environmental conditions that affect the development of a fire.

First scenario. All windows, kitchen doors and interior doors are closed.

Figure 2a shows the Heat Release Rate (HRR) during a fire. As one can see from the figure, HRR is characterised by three distinct stages: rapid growth, stabilisation, and a sharp drop. At the initial stage, there is a rapid increase in HRR from 0 to approximately 165 kW. This indicates rapid ignition and the initial phase of active combustion. Then the HRR stabilises at around 120–130 kW with small fluctuations. This indicates steady-state combustion, where the combustible materials are actively generating heat, the fire is spreading evenly and is being maintained by the available combustible materials and oxygen. The temperature in the kitchen reached about 170 °C, while the temperature in other rooms has hardly increased and there was full visibility due to the closed kitchen door. At the stage of 100–120 seconds, there was a sharp drop in HRR from 120–130 kW to almost 0 kW. Such a sharp drop is explained by a decrease in the concentration of oxygen, which is necessary for combustion. Because the kitchen door and window were closed and there was no oxygen supply, the entire fire was concentrated in the kitchen. Unlike a fire with an open window, where air flow supports combustion, in a closed room, the lack of ventilation leads to rapid fire extinguishment.

When the cell size was reduced from 0.25 × 0.25 × 0.25 m to 0.15 × 0.15 × 0.15 m, the HRR simulation results remained almost unchanged. When the cell size was increased from 0.25 × 0.25 × 0.25 m to 0.35 × 0.35 × 0.35 m, minor changes occurred (Fig. 2b). Therefore, as mentioned above, in further calculations we assume a cell size of 0.25 × 0.25 × 0.25 m.

Figures 3 and 4 show the change in temperature of the HDs sensing element and smoke obscuration at the sensitive element of a smoke detector (SD). HD2 and SD2, which were placed in the hallways of the apartment in accordance with the requirements of SBN V.2.5-56:2014, did not detect the fire. Thus, FDSys did not fulfill its functions. HD1 in the kitchen was triggered at 45.01 s (Fig. 3), and SD1 at 3.61 s.

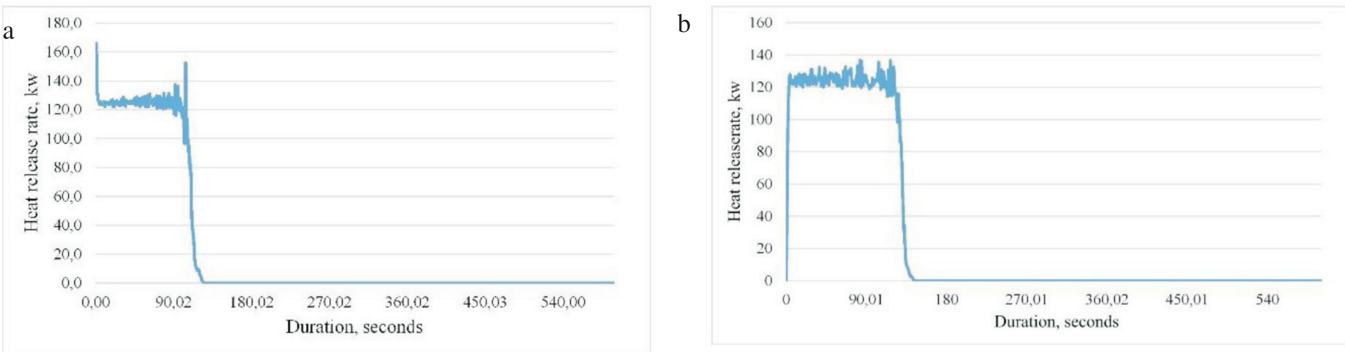

Fig. 2. Dependence of heat release rate on time: **a**, cell size 0.25 × 0.25 × 0.25 m; **b**, cell size 0.35 × 0.35 × 0.35 m.

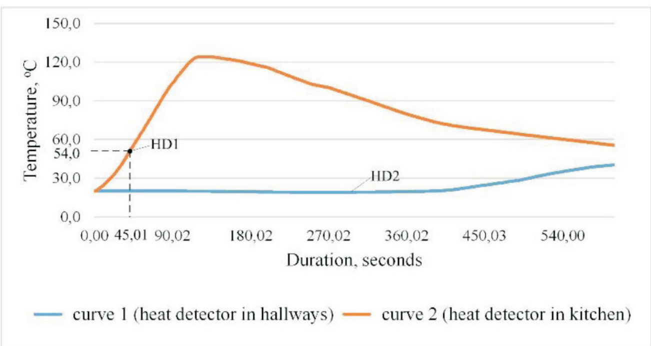

Fig. 3. Temperature change of the heat detector sensor element.

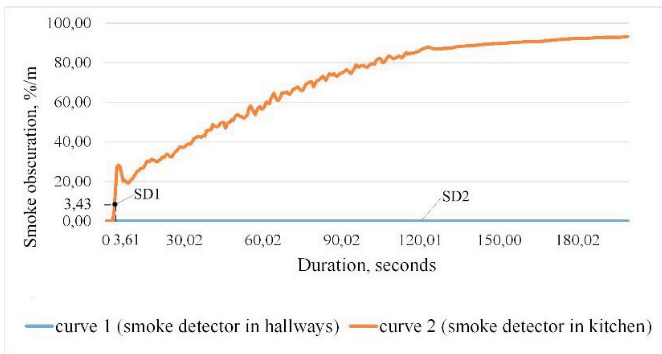

Fig. 4. Change in smoke obscuration at the sensitive element of a smoke detector.

Second scenario. A 0.6 × 1.5 m kitchen window is open, the kitchen door is closed and opened for 128 s, and the front door is closed. The fire was modeled at wind speeds outside the window (V_w) V_w = 3.5 m/s and V_w = 7 m/s.

Figure 5 shows the HRR during a fire when V_w = 3.5 m/s and V_w = 7 m/s. As can be seen from Figure 5, the bucket speed has almost no effect on HRR. The fire was characterised by rapid initial ignition and steady burning. The open window provided constant access to oxygen (air flow), which maintained stable combustion. A closed door prevented the creation of a draft. A stable HRR level indicates that the fire has reached a state where the burning rate is balanced with the air flow through the window. Small fluctuations may be due to: heterogeneity of combustible materials; small changes in the air flow through the window; and flame turbulence. At 128 s, the door opened, causing hot air and smoke to enter the apartment hallway and neighbouring rooms. However, the graph does not show any dramatic changes in HRR after this point. This may mean that the additional small influx of air from the hallways did not affect the combustion rate.

With the window open and the kitchen door closed, the temperature in the kitchen reached approximately 120 °C within 128 s. The temperature did not increase due to cooling, which occurred as a result of air flow through the open window. Visibility in the kitchen ranged from 0.5 to 3.4 m. Due to the fact that the kitchen door was closed, the fire was concentrated in the kitchen. The temperature in the other rooms hardly increased and there was full visibility. When the kitchen door was opened at 128 seconds, the fire hazards spread to the hallway of the apartment. Hot air entered the hallway and the temperature in the kitchen slightly decreased. Figures 6 and 7 show the temperature distribution and visibility at a height of 1.7 m during the fire for 180 s when V_w = 3.5 m/s. At 180 s, the temperature in the kitchen ranged from approximately 95 °C to 120 °C, and in the hallways from 60 °C to 80 °C. Visibility in the kitchen and hallways ranged from about 4 to 5.5 m (Fig. 7). When V_w = 7.0 m/s for 180 s, the temperature in the kitchen ranged from about 65 °C to 105 °C, and in the hallways from 40 °C to 48 °C. Due to the higher wind speed outside the window, visibility in the kitchen and hallways ranged from 6 to 18 metres. We can assume that there was full visibility. The temperature in the hallways exceeded 60 °C and made the process of evacuating people dangerous.

Figures 8 and 9 show the change in temperature of the HDs sensors and smoke obscuration at the sensitive element of a SDs when V_w = 3.5 m/s and V_w = 7 m/s. When V_w = 3.5 m/s, HD1 in the kitchen was triggered at 55.51 s (Fig. 8a), slightly faster than when V_w = 7 m/s (at 64.51 s) (Fig. 8b). When V_w = 3.5 m/s, SD1 was triggered at 5.6 s (Fig. 9a), and when V_w = 7 m/s, at 6.82 s. HD2, HD3, SD2, SD3, which were located in the hallways of the apartment in accordance with the requirements of SBH V.2.5-56:2014, did not detect a fire for 128 seconds (Fig. 8a, Fig. 9a). After the door was opened for 128 s, hot air and smoke entered the

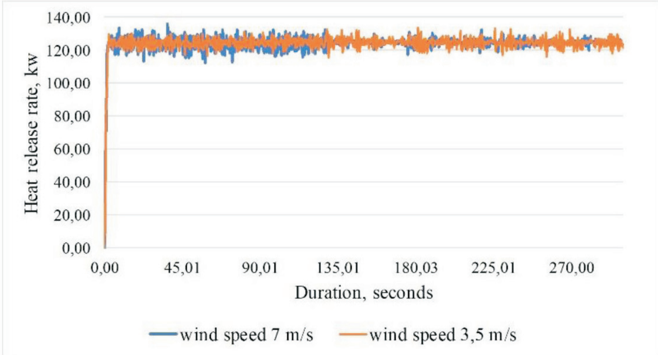

Fig. 5. Dependence of heat release rate on time.

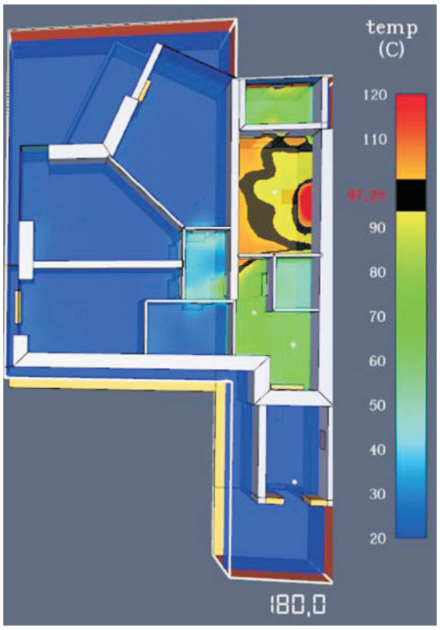

Fig. 6. Temperature propagation during fire development when V_w = 3.5 m/s

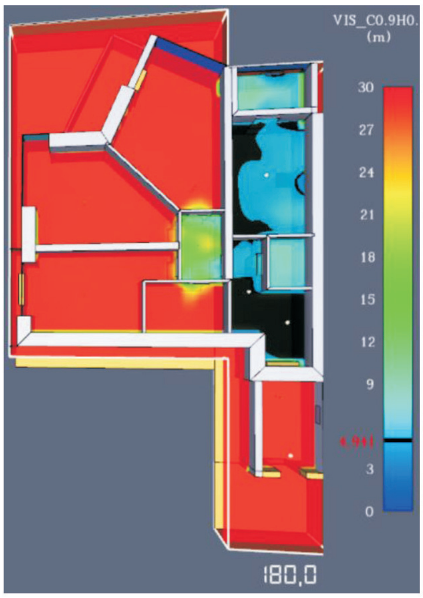

Fig. 7. Visibility at a height of 1.7 m during fire development when V_w = 3.5 m/s.

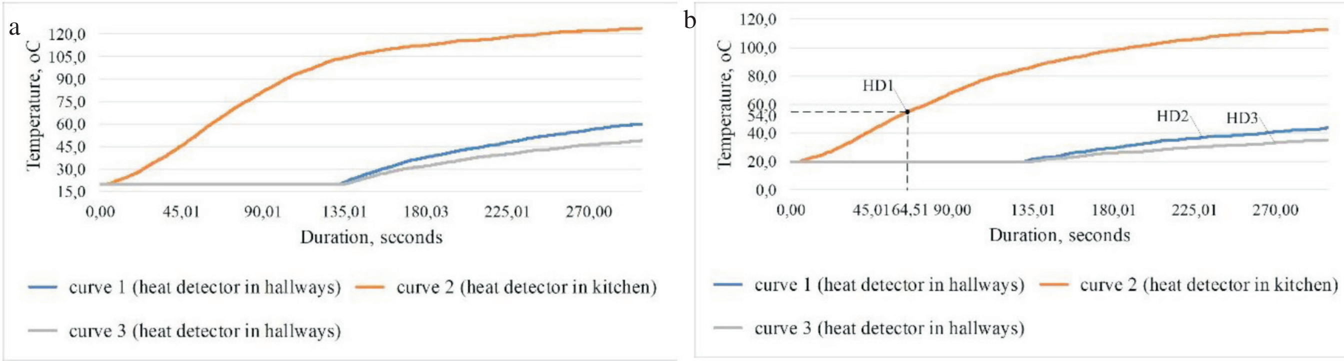

Fig. 8. Temperature change of heat detector sensing elements when: a, V_w = 3.5 m/s; b, V_w = 7.0 m/s.

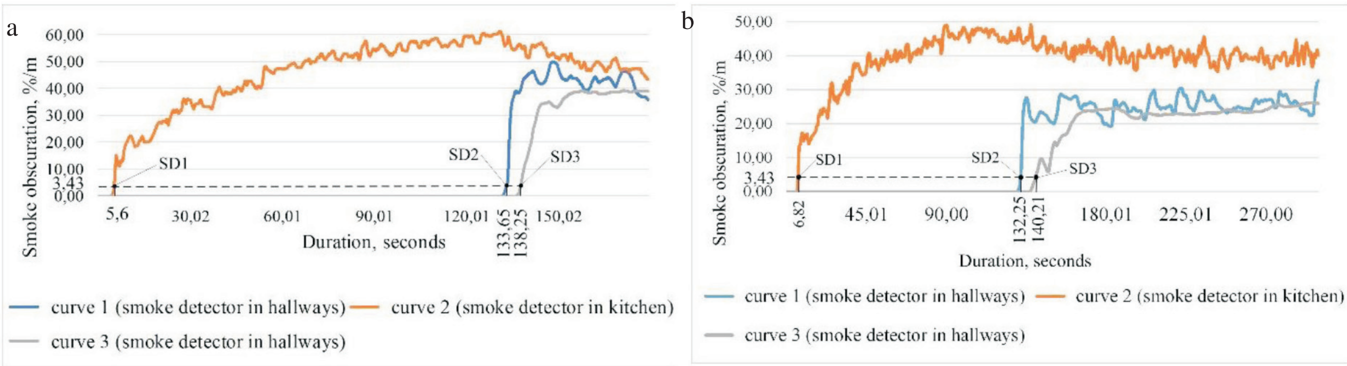

Fig. 9. Change in smoke obscuration at the sensitive element of a smoke detector when: a, V_w = 3.5 m/s; b, V_w = 7.0 m/s.

apartment hallways. When V_w = 3.5 m/s, HD2 was triggered at 258.92 s (Fig. 8a), and after the door was opened, at 130.92 s. HD3 was not triggered at all. When V_w = 7 m/s, HD2 and HD3 did not trigger during the modulation time of 300 s. The temperature of the HD2 sensor increased faster than that of HD3 (Fig. 8). When V_w = 3.5 m/s, SD2, which was located closer to the exit from the kitchen, was triggered at 133.65 s, and SD3 at 138.25 s (Fig. 9a); after the door was opened, SD2 was triggered at 5.65 s, and SD3 at 10.25 s (Fig. 9). When V_w = 7.0 m/s, the results were almost similar. SD2 was triggered at 132.25 s, and SD3 at 140.21 s. Thus, the wind speed outside the window in this scenario did not significantly affect the time of fire detection by SDs in the hallways of an apartment. The location and type of FD affected the fire detection time.

Third scenario. The kitchen window and the window in the children's room are open, all interior doors are open, and the front door is closed. The fire was modelled (with a draft) when the wind speeds outside the window were V_w = 3.5 m/s and V_w = 7 m/s.

As can be seen from Figure 10, the HRRs when V_w = 3.5 m/s and V_w = 7 m/s were almost the same. As in the previous scenario, the HRR was characterised by a rapid initial increase and stabilisation with small fluctuations. At the initial stage, there was a sharp increase in HRR from 0 to about 140 kW. This indicated rapid ignition and the initial phase of active combustion. Later, the HRR stabilised within the range of 125–130 kW with small fluctuations. Open windows and interior doors created a draft. The draft

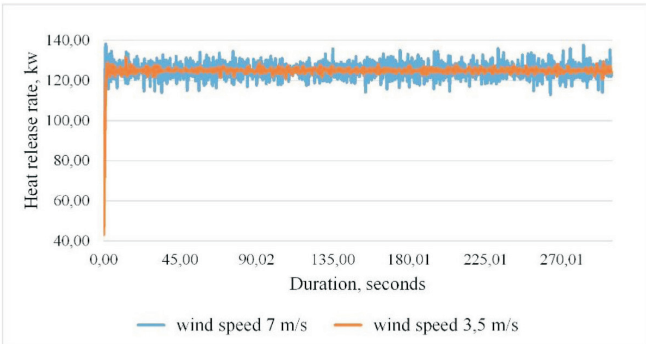

Fig. 10. Dependence of heat release rate on time.

provided a constant and intense flow of oxygen, which supported stable combustion. A stable HRR level indicates that the fire has reached a state where the burning rate is balanced with the intense air flow through the draft.

Figures 11 and 12 show the temperature distribution during the fire and visibility when V_w = 3.5 m/s. As can be seen from Figure 11, due to the draft, the temperature in the kitchen ranged from about 70 °C to 120 °C, in the hallways from about 60 °C to 80 °C, and in other rooms from about 20 °C to 45 °C. Due to the draft, the smoke was removed from the children's room, and visibility in the kitchen and hallways ranged from approximately 3 to 6.7 m (Fig. 12). The high temperature in the hallways made the evacuation process dangerous for people.

Figure 13 shows the temperature distribution during the fire and visibility when V_w = 7.0 m/s. As can be seen from Fig-

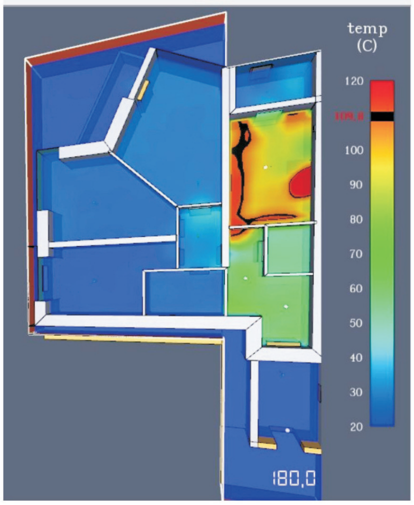

Fig. 11. Temperature propagation during a fire when V_w = 3.5 m/s.

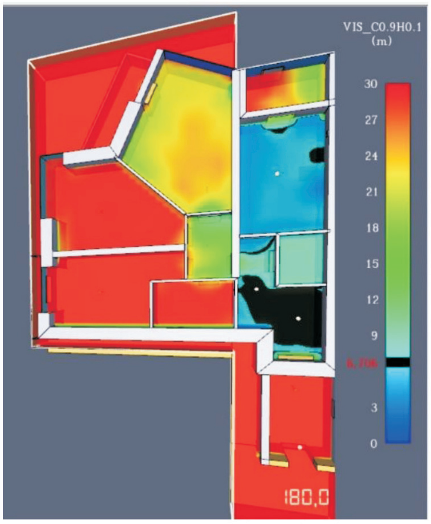

Fig. 12. Visibility at a height of 1.7 m during fire development when V_w = 3.5 m/s.

ure 13, due to the significant draft, the temperature in the kitchen ranged from about 26 °C to 35 °C, in the hallways from about 24 °C to 26 °C, and in other rooms from about 23 °C to 26 °C. Thanks to the considerable draught, there was full visibility in all rooms. When V_w = 7.0 m/s, the evacuation process was less dangerous for people.

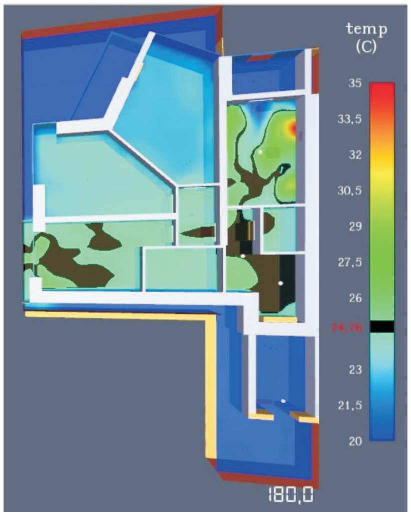

Fig. 13. Temperature propagation during a fire when V_w = 7.0 m/s

Figure 14 shows the temperature change of the HDs sensors, and Figure 15 shows the change in smoke obscuration at the sensitive element of a SD. When V_w = 3.5 m/s, HD1 in the kitchen was triggered at 60 s (Fig. 14a), and SD1 at 6.1 s (Fig. 15a). HD2 and HD3, which were located in the hallways of the apartment in different places, were triggered at 124.5 and 258.41 s, respectively. The response time between HD2 and HD3 differed by almost two times. SD2 was triggered at 16.9 s, and SD3 was triggered at 30.75 s (Fig. 15a). As can be seen from the modelling results, FDs placed in the hallways of an apartment in accordance with the requirements of SBN V.2.5-56:2014, but in different locations, detect fire at different times.

When V_w = 7.0 m/s, HD2, HD3, SD2, SD2, located in the hallways of the apartment did not trigger (Fig. 14b and Fig. 15b). HD1, which was located in the kitchen, did not trigger (Fig. 14b); SD1 was triggered at 5.5 s (Fig. 15b). Thus, even the placement of FDs in accordance with the regulatory requirements of SBN V.2.5-56:2014 does not ensure the operation of FDSys, and thus the fulfillment of their functions. If the FDs are placed in accordance with the IBC requirements, then the FDSys is triggered.

Fourth scenario. The window in the kitchen and the window in the children's room are open, all interior doors and the front door to the apartment are open. The fire was mod-

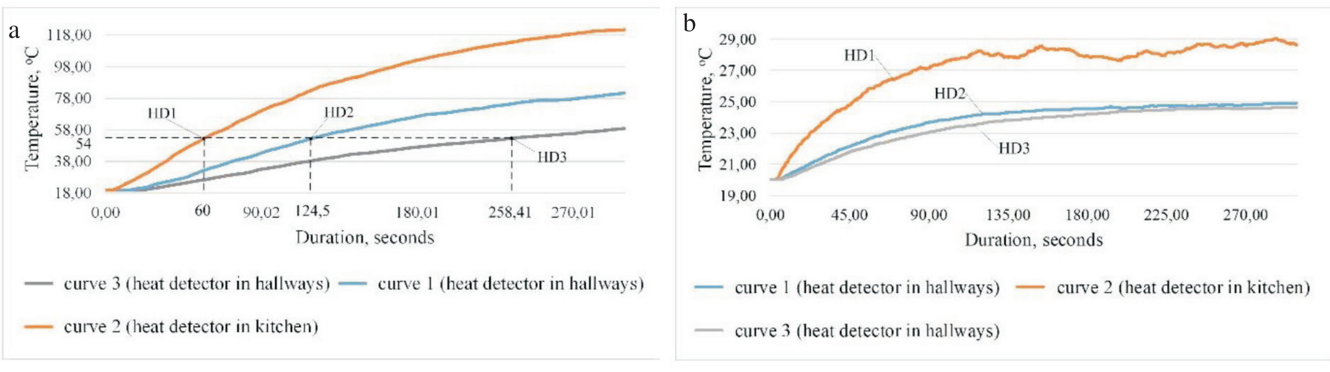

Fig. 14. Temperature change of heat detector sensing elements when: a, V_w = 3.5 m/s; b, V_w = 7.0 m/s.

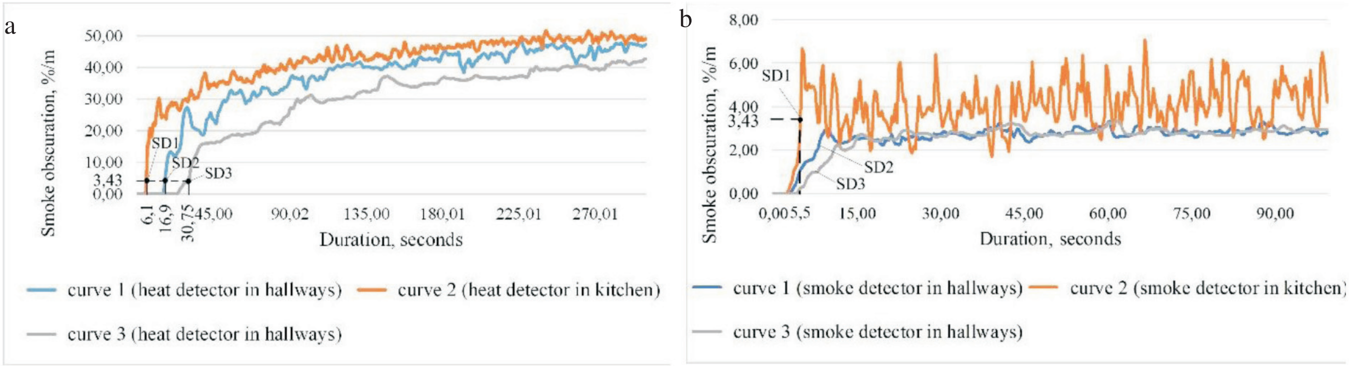

Fig. 15. Change in smoke obscuration at the sensitive element of a smoke detector when: a, V_w = 3.5 m/s; b, V_w = 7.0 m/s

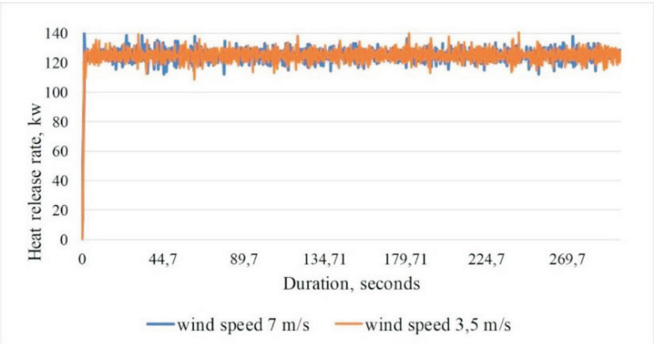

Fig. 16. Dependence of heat release rate on time.

elled when the wind speed outside the window was V_w = 3.5 m/s and V_w = 7 m/s.

Figure 16 shows the HRR when V_w = 3.5 m/s and V_w = 7 m/s. As can be seen from Figure 16, the HRR when the front door to the apartment was open was almost the same as in the third scenario, when the front door was closed. The only difference was the frequency of HRR oscillation when V_w = 3.5 m/s.

Figure 17 shows the temperature distribution during a fire when V_w = 3.5 m/s. As can be seen from Figure 17, due to the draft, the temperature in the kitchen ranged from about 23 °C to 35 °C, and in other rooms — from about 21 °C to 24 °C. As in the third scenario, due to the significant draft, when V_w = 3.5 m/s and V_w = 7 m/s, the smoke was blown out and good visibility was achieved.

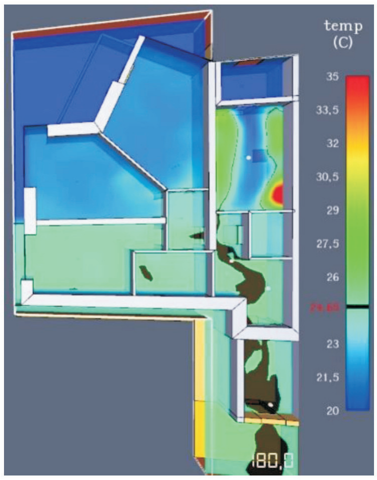

Fig. 17. Temperature propagation during the fire when V_w = 3.5 m/s.

Due to the draft, HDs located in the kitchen, in the hallways of the apartment, and in the common corridor did not trigger when V_w = 3.5 m/s and V_w = 7 m/s (Fig. 18). Only SD1 in the kitchen was triggered (Fig. 19).

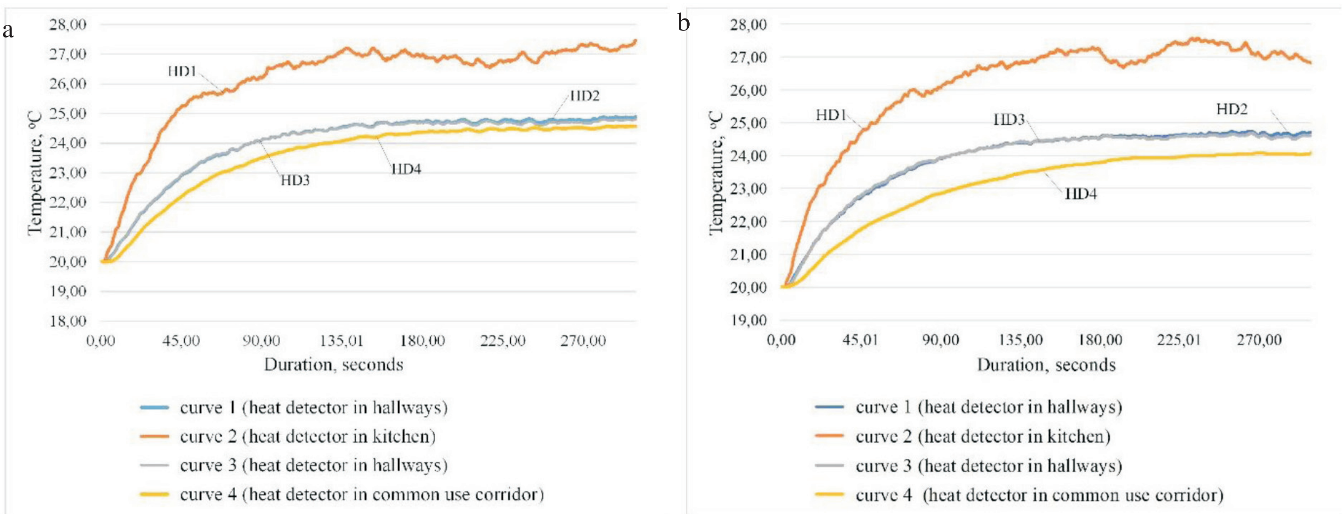

Fig. 18. Temperature change of heat detector sensing elements when the wind speed outside the window: a, V_w = 3.5 m/s; b, V_w = 7.0 m/s.

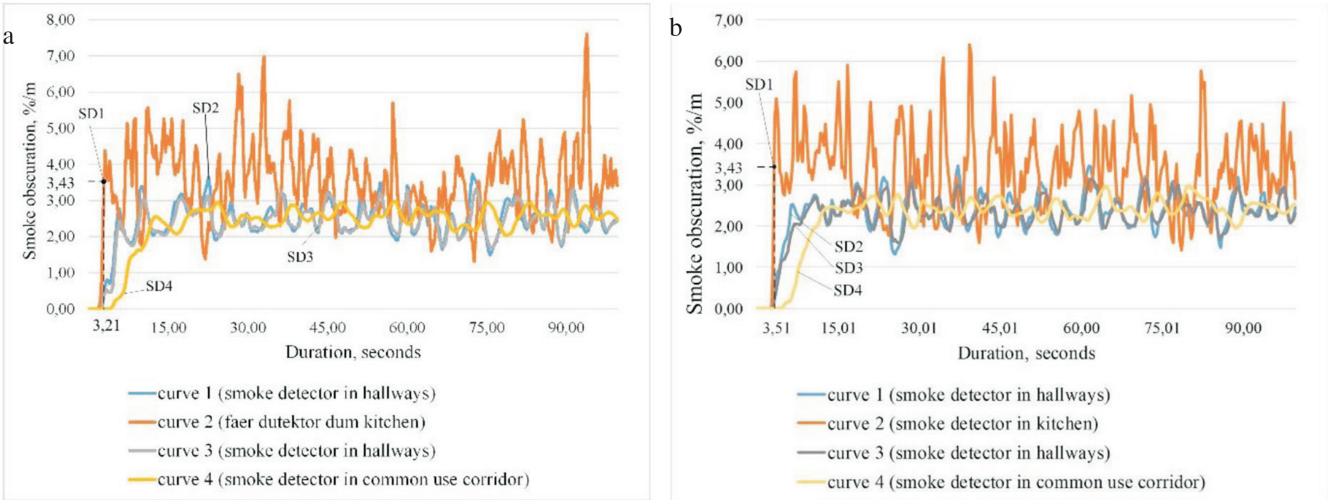

Fig. 19. Change in smoke obscuration at the sensitive element of a smoke detector when: a, V_w = 3.5 m/s; b, V_w = 7.0 m/s.

DISCUSSION

As can be seen from Figure 2, if the kitchen window and door are hermetically sealed, the fire in the kitchen quickly begins to develop and reaches approximately 170 °C, stabilises, and almost goes out by 120 s. The air entering through the leaks in the door frame is not enough to sustain the fire. The hallways have full visibility and the temperature is about 21 °C. This makes it possible for people to safely evacuate the apartment. With the 0.6 × 1.5-metre kitchen window open and the kitchen door closed, the fire is also concentrated in the kitchen. However, the inflow of air through the open window allows the fire to stabilise and burn steadily (Fig. 5). Due to cooling, the temperature does not exceed 120 °C. At 128 s, the door opens and the fire hazards spread to the apartment hallways. The high temperature in the hallways (from 60 to 80 °C (Fig. 6), with a wind speed of V_w = 3.5 m/s) makes the evacuation process dangerous for people. However, we can assume that there is full visibility (approximately 4 to 5.5 m) (Fig. 7). At higher wind speeds outside the window (V_w = 7.0 m/s), the temperature in the kitchen and hallways decreases due to cooling. In the kitchen, the temperature is approximately 65 °C to 105 °C, and in the hallways from 40 °C to 48 °C. This makes the evacuation process safer for people.

If a window is open in the kitchen, children's room, or interior doors are open, a draft is created and fire hazards spread throughout the apartment. However, due to the draft and cooling, the fire hazards do not reach critical levels for humans. The greater the wind outside the window, the more smoke is blown out of the apartment, the greater the visibility and the lower the temperature (Figs. 11 and 12). When V_w = 7.0 m/s, the evacuation process becomes safer for people. The temperature in the kitchen ranged from about 26 °C to 35 °C, in the hallways from about 24 °C to 26 °C, and in other rooms from about 23 °C to 26 °C (Fig. 13). Thanks to the considerable draft, there is visibility in all rooms.

With the window in the kitchen, children's room and interior and exterior doors open, the temperature in the kitchen is low, approximately 23 °C to 35 °C, due to cooling. In other rooms, the temperature is approximately 21 °C to 24 °C. There is also good visibility due to the considerable draft.

Consequently, the air flow is conducive to fire development. However, due to cooling, the temperature decreases. Due to the significant draft, the smoke is removed and there is good visibility. This makes the evacuation process safer for people. The wind speed outside the window when the windows are open affects the spread of fire hazards.

Table 1 shows the data on the operation of FDs under different scenarios of fire modelling up to 300 s. With the kitchen window and door closed, HD2, HD3, SD2, and SD3, which are located in the hallways of the apartment in accordance with the requirements of SBN V.2.5-56:2014, do not trigger (Figs. 3 and 5). Thus, FDS has not fulfilled its functions. If the FDS are placed in accordance with the IBC, HD1 in the kitchen was triggered at 45.01 s (Fig. 3) and SD1 at 3.61 s (Fig. 5).

With the kitchen window open and the kitchen door closed, HD1 (Fig. 8) and SD1 triggered (Fig. 9). HD2 and HD3, which are located in the hallways of the apartment, are not triggered. After the door is opened for 128 s, hot air and smoke flow into the hallways of the apartment. When V_w = 3.5 m/s, only SD2 (at 133.65 s), SD3 (at 138.65 s), and HD2 (at 258.92 s), which is located closer to the entrance interior door to the kitchen, are triggered (Table 1). When the wind speed outside the window is higher, HD2 and HD3 no longer trigger. Therefore, when the windows are open and the wind speed outside the window of a high-rise residential building is high, it is likely that HD will not trigger and SD will trigger with a certain delay. In addition, the location of the FD affects the time of fire detection, which is very important.

During the scenario with the window open in the kitchen and room, the interior doors are open, a significant draft is formed, which significantly affects the dynamics of fire development. As a result, the air in the room is cooled and the smoke is blown out. Only FDS are triggered when V_w = 3.5 m/s. At the same time, HDs were triggered with a sig-

Table 1. FD response time in different scenarios and placement

Location of FD	First scenario	Second scenario		Third scenario		Fourth scenario	
		wind speed		wind speed		wind speed	
		3.5 m/s	7.0 m/s	3.5 m/s	7.0 m/s	3.5 m/s	7.0 m/s
	Response times of FD, s						
HD1	45.01	55.51	64.51	60	–	–	–
SD1	3.61	5.6	6.82	6.1	5.5	3.21	3.51
HD2	–	258.92	–	124.5	–	–	–
SD2	–	133.65	132.25	16.9	–	–	–
HD3	–	–	–	258.41	–	–	–
SD3	–	138.25	140.21	30.75	–	–	–
HD4	–	–	–	–	–	–	–
SD4	–	–	–	–	–	–	–

nificant delay (Table 1). With the front door to the apartment still open, and with such wind values outside the window, only the SD in the kitchen was triggered. All other FDS did not trigger. Thus, when the windows and doors are open, the value of the wind speed outside the window significantly affects the detection of fire by FDS.

According to the simulation in FDS, in the fourth scenario, only SD1 in the kitchen was triggered. In order to avoid false alarms, the physical SD has a time delay for triggering. The SD is triggered only after some time. According to its operation algorithm, the fire will be confirmed within some time. In our case, the smoke obscuration fluctuates, so the SD may not trigger in real conditions.

Thus, even the placement of FDS in accordance with regulatory requirements does not provide a certain level of fire protection for high-rise buildings. In addition, even with the recommended selection and placement of SDs, it does not guarantee timely detection of a fire by FDS. However, if you use a smoke detector with a blackout threshold of 2 %/m (0.088 dB/m) or lower, it can detect a fire. The performance of FDS is affected by the position of doors and windows, whether they are closed or open, and the wind speed outside the window. Therefore, it is recommended to choose SD or multisensor FD.

CONCLUSION

A model of a residential apartment located on the twentieth floor of a high-rise building with typical structural elements and fire load was developed in the FDS software package. Based on the developed model, the results of numerical simulation of fire development in a residential apartment showed that when windows and doors are open and there is a significant wind outside the window, a significant draft is formed, which significantly affects the dynamics of fire development and the spread of non-hazardous fire factors. The air flow contributes to the development of the fire, and the hazardous factors of the fire spread throughout the apartment. However, when the wind speed outside the window is 7.0 m/s, due to draft and cooling, the fire hazards do not reach critical indicators for humans. The temperature drops, and the smoke is blown out and good visibility sets in. This makes the evacuation process safer for people.

Based on numerical modelling in the FDS software package, a complex effect on the time of operation or failure of FDS, with windows and doors open or closed, as well as the wind speed outside the window, was established. It was determined that even if the current regulatory requirements for the installation of FDS are met, when the wind speed outside the window is 7.0 m/s, only the SD that which is located in close proximity to the source of fire and has increased sensitivity, is triggered. All other FDS are not triggered. Therefore, the wind speed outside the window affects the movement of convective flows of combustion products and the ability of FDS located at a greater distance than those located in close proximity to the source of ignition to detect fires. The results demonstrate the need for an adaptive approach to the placement and type of detectors in high-rise residential buildings. It has been established that it is necessary to set requirements for the sensitivity of smoke detectors used in residential buildings in order to trigger them. The use of SD or multisensor FD with a smoke sensor with increased sensitivity to smoke allows for reliable detection of fire at an early stage of fire in high-rise buildings.

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UGUNSGRĒKA ATTĪSTĪBAS DINAMIKA UN UGUNSDROŠĪBAS SIGNALIZĀCIJAS SISTĒMU EFEKTIVITĀTE DAUDZSTĀVU ĒKĀ

Ugunsgrēka attīstības modelēšana parādīja, ka atvērtie logi un durvis, kā arī vēja ātrums ārpusē ietekmē uguns attīstības dinamiku dzīvoklī. Tika noteikta logu un durvju novietojuma, kā arī vēja ietekme uz uguns detektoru aktivizēšanu. Tika noskaidrots, ka, pat ja tiek izpildītas esošās normatīvās prasības par uguns detektoru uzstādīšanu, gadījumos, kad vēja ātrums ārpusē pārsniedz 7.0 m/s, tie nedarbojas un tiek aktivizēti tikai augstas jutības dūmu detektori, kas atrodas tuvu uguns izcelsmes vietai. Rezultāti parāda nepieciešamību pēc padziļinātas pieejas detektoru izvietošanai daudzstāvu dzīvojamās ēkās.