Dušica J. Pešić, Milan Đ. Blagojević, Darko N. Zigar*

HEAT FLUX AS A PARAMETER OF VULNERABILITY OF MULTI-STOREY BUILDING STRUCTURES EXPOSED TO FIRE – A NUMERICAL STUDY

TOPLOTNI FLUKS KAO PARAMETAR UGROŽENOSTI KONSTRUKCIJA VIŠESPRATNIH OBJEKATA IZLOŽENIH POŽARU – NUMERIČKA STUDIJA

Originalni naučni rad / Original scientific paper
UDK /UDC:

Rad primljen / Paper received: 12.12.2021

Adresa autora / Author's address:
University of Niš, Faculty of Occupational Safety of Niš, Niš, Serbia email: dusica.pesic@znrfak.ni.ac.rs

Keywords
- multi-storey buildings
- numerical simulations
- heat flux
- temperature
- structure vulnerability

Abstract

A multi-storey building fire in a densely built-up urban area can easily spread into its neighbourhood. The aim of this study is to analyse the impact of fire in a multi-storey building on adjacent high buildings. For simulation of fire inside an office building and possibility of its spread to residential buildings, computational fluid dynamics large eddy simulation method has been used. Fire Dynamics Simulator software package with its graphical user interface PiroSym is used to numerically investigate the vulnerability of residential building structures. Since the ignition due to fire radiation is the most frequent way of fire spread from one building to another, the radiation levels at the façade surface of certain floors of exposed buildings to fire are investigated. The results show that the intensities of heat fluxes and temperatures on the façades of residential buildings depend on the quantity of flammable material burned during the fire as well as on the distance of exposed buildings from the fire-affected office building. These results can be used in spatial planning of cities and in the design of buildings to determine the safe separation distance between buildings in the function of fire protection.

Ključne reči
- visoki objekti
- numeričke simulacije
- toplotni fluks
- temperatura
- ugroženost konstrukcije

Izvod

U gusto izgrađenom urbanom području požar nastao u zgradi može se lako proširiti na okolinu. Zbog toga je cilj ovog istraživanja analiza uticaja požara višespratnog objekta na susedne visoke objekte. Za simulaciju dinamike požara u poslovnom objektu i mogućnost njegovog širenja na stambene zgrade korišćen je metod simulacije velikih vrtloga računarske dinamike fluida. Softverski paket Fire Dynamics Simulator sa grafičkim interfejsom PiroSym je korišćen za numeričko istraživanje ugroženosti građevinskih konstrukcija stambenih zgrada. S obzirom da je paljenje usled zračenja požara najčešći način širenja požara sa jednog objekta na drugi, istraživani su nivoi zračenja na površini fasada pojedinih spratova zgrada izloženih dejstvu požara. Rezultati pokazuju da intenziteti toplotnih flukseva i temperature na fasadama stambenih objekata zavise od količine zapaljivog materijala sagorelog tokom požara, kao i od rastojanja zgrada od požarom zahvaćenog poslovnog objekta. Dobijeni rezultati se mogu koristiti pri prostornom planiranju gradova i projektovanju zgrada za određivanje bezbednosnog rastojanja između objekata u funkciji zaštite od požara.

INTRODUCTION

Urbanisation brings with it a set of advantages but also many problems due to the concentration of a large number of inhabitants in a relatively small area. In order to use the area efficiently, high buildings are designed and built in cities which increases the risk of fire that could result in human casualties and serious damages. In a high-rise building, the fire rapidly develops due to many internal flammable items and flammable exterior insulation materials. Since the fire inside multi-storey buildings is a major concern in dense build-up urban areas, in recent decades, modelling of fire spread in them is a key factor of a fire risk analysis used for fire safety design. With the development of Computational Fluid Dynamics (CFD) techniques, a Fire Dynamics Simulator (FDS) open-source software package has become a commonly used CFD code for fire dynamics modelling in high buildings.

Many numerical studies have been conducted to investigate fire spread in both horizontal and vertical directions inside high buildings. The stairwells and elevator shafts are considered the main route of vertical movement of smoke during the fire. Ahn et al. /1/ performed theoretical, experimental and numerical investigation of smoke dynamics in high-rise buildings. Turbulent fires of various heat release rates in a confined space were simulated numerically using FDS, which was verified against experimental data. The agreement between experimental and numerical results was good. Gawad and Ghulman /2/ investigated the important aspects of fire dynamics such as smoke propagation and temperature distribution. The study aimed to decrease the fire hazards by computationally predicting the expected smoke movement in high-rise buildings in real-life conditions. He et al. /3/ carried out a numerical simulation of smoke spread process through the elevator shafts. The result showed that the process in the shafts can be divided into two phases: the smoke gradually fills the shafts, and the gas temperature and pressure are transient; the smoke fully fills the shafts, the temperature and pressure are almost steady, which suggests that the smoke inflow rate equals the outflow rate.

There is also much research on the flame ejecting behaviour from window and their extension on the façade of the building. Asimakopoulou et al. /4/ numerically investigated the key factors influencing external venting flames in order to identify its heat impact on façades. The predicted gas temperatures and heat fluxes were analysed and compared with experimental data. The results indicate that FDS generally predicts accurately the heat flux intensity on façades. Duny et al. /5/ performed FDS simulation of the behaviour of flame ejecting from compartment fire and its spread on building façade. The effect of increasing the distance from building façade surface on the intensity of the radiation heat flux was investigated. The numerical results show that a reduction in distance will significantly enhance the fire spreading rate and its size due to the increasing contribution by radiation.

Besides of the risk of fires inside tall buildings, there is a risk of fire spreading from one building to another because buildings are very often at an insufficient distance apart. Namely, if two buildings are located in the immediate vicinity, in certain cases, the burning of a neighbouring building can occur due to flying embers from the building in flames or due to convection of fire heat. However, the spread of fire between buildings is most often caused by ignition due to the thermal radiation of the flame. Bearing in mind these facts, it is necessary to notice that a small number of studies have been performed that analyse the possibility of fire spreading between buildings due to thermal radiation of the fire flame. Based on results of twelve full-scale experiments, Cheng and Hadjisophocleous /6/ proposed a numerical model of radiation heat flux on target wall from post-flashover compartment fire. Numerical investigations of fire spread possibility described in Pešić et al. /7/ between two-storey residential houses are based on the intensity of the critical thermal fluxes of the curtain ignition on the window of the building exposed to thermal radiation of the fire.

However, according to the authors' findings, there is no numerical study of the possibility of spreading the fire that takes place in a multi-storey building to buildings in the immediate vicinity. Therefore, in order to assess the vulnerability of neighbouring building structures due to the fire, in this study the Large Eddy Simulation (LES) method is employed. The FDS software package and its graphical user interface PiroSym are used to simulate intensities of heat fluxes on the façades of endangered high-rise buildings.

NUMERICAL SIMULATION

In order to perform numerical experiment of fire spreading between neighbouring buildings, it is necessary to define a model of building structure affected by fire, as well as building in the vicinity, certain fire scenarios and to calculate corresponding input parameters.

In this study, the model of a multi-storey office building affected by fire and two residential high-rise buildings A and B exposed to flame radiation is defined (Fig. 1).

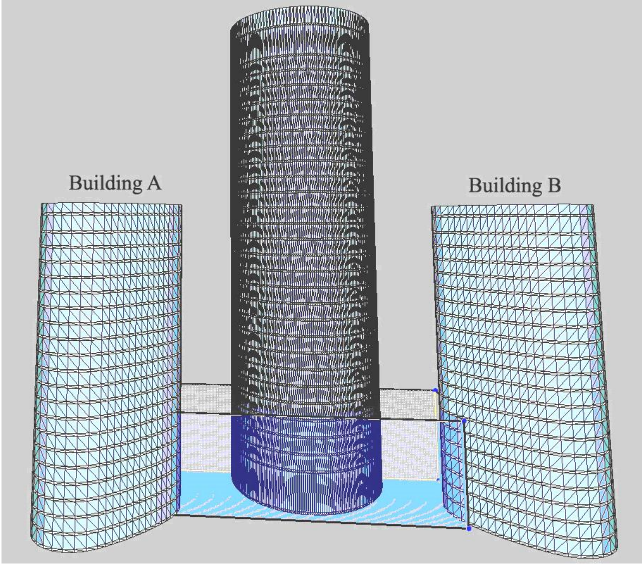

Figure 1. Building 3D model in Pyrosim.

In order to determine the intensity of heat fluxes on the façades of residential buildings exposed to effects of fire flames in the office building, it is assumed that residential buildings are at different distances from the fire affected building. At the same time, the most unfavourable scenario is hypothesised, which envisages a fire of a wider scale. Namely, it is assumed that the fire affects the entire fire sector of about 454 m^2 on the first floor of the office building, so that both residential buildings are exposed to the fire. The numerical experiment is performed in two cases:

- Scenario I: burned out 80 % of flammable material in the fire sector during the fire;
- Scenario II: all flammable material in the fire sector burns out during the fire (100 %).

Theoretical background

For the purposes of the numerical experiment, it is necessary to calculate the appropriate input parameters such as specific fire load, equivalent fire duration and heat released during the fire.

The calculation of the specific fire load includes the fixed (immobile) and mobile fire load of twelve offices, common space and communication corridors affected by fire. Based on TRVB A 100, the office building is classified in the type of building 03 whose fixed fire load is 100 MJ/m^2, /9/. Based on TRVB A 126, the value of mobile fire load of 700 MJ/m^2 is adopted for office space /10/. Considering that the area of all offices is 141.4 m^2, the total fire load of office space is 98966 MJ. The calculated fire load of the common space and communication corridors with a total area of 312.6 m^2, which includes various moving elements of the interior and equipment, is 91249 MJ. The specific fire load of the fire sector is calculated based on standard SRPS U.J1.030 /11/:

$$P_i = \frac{P_{im}}{S_p} + P_{in}\,, \qquad (1)$$

where: P_{im} - mobile fire load; P_{in} - immobile fire load; S_p - fire sector area.

In order to analyse the fire dynamics, the model of equivalent fire given in Eurocode EN 1991-1-2 /12/ is used. Equivalent fire duration is calculated based on the expression:

$$t_e = k_c (P_i k_b w_f), \quad (2)$$

where: k_c and k_b - conversion factors; w_f - ventilation factor.

The t^2 fire model is used to design the heat release curve during the adopted fire scenarios /12/. The quantity of heat released in the fire is calculated using the equation:

$$Q = \chi S_p \frac{P_i}{t_e}, \quad (3)$$

where: χ is incomplete combustion coefficient.

For adopted scenarios I and II, input parameters are:
- specific fire load of the fire sector calculated by Eq.(1) is 518.96 MJ/m^2;
- equivalent fire duration calculated by Eq.(2) is 21.75 min;
- quantities of heat released during the fire calculated by Eq.(3) are 144440 kW and 180550 kW, respectively.

Simulation set-up

In order to optimise computing time, in a computational domain with dimensions of 51×49.5×22.5 m, the fragments of office building and adjacent residential buildings are designed. Distances between the office building and residential buildings are 15.5 m (building A) and 14.5 m (building B). All buildings are built of reinforced concrete while the façades are of glass and aluminium. The thermodynamic properties of building materials at normal temperature are shown in Table 1.

Table 1. Properties of building materials.

Material	Thickness (m)	Density (kg/m^3)	Heat conductivity (W/mK)	Specific heat (J/kg°C)
Concrete	0.025	2100	1.0	880
Aluminium	-	2710	225	900
Glass	0.006	2500	0.76	840

Mobile fire load of the fire sector in the burning office building consists of flammable materials, such as work tables, chairs, filing cabinets, chest of drawers, upholstered armchairs, computer equipment, etc. Office floors are covered with synthetic carpets. The properties of the used materials are shown in Table 2.

Table 2. Properties of flammable materials.

Material	Thickness (m)	Density (kg/m^3)	Heat conductivity (W/mK)	Ignition temperature (°C)	Mass burning rate (kg/m^{2}s)
Wood	0.020	450	0.18	360	0.06
Upholstery	0.002	100	0.1	350	0.03
Memory foam	0.025	30	0.034	350	0.03
Carpet	0.008	750	0.16	290	0.05

To investigate the exposure of a building to fire, it is very important to determine the severity of the fire, that depends on the intensity of flame thermal radiation. Therefore, in accordance with the provisions of standard NFPA 80A, in this research it is assumed that the fire is of moderate severity, i.e. a medium speed fire /13/.

For simulation purposes the worst fire spread scenario through window openings of the burning building assumes that the doors and all the windows of offices, as well as all windows of adjoining residential buildings exposed to fire are closed at the start of simulation. In order to obtain the maximal value of flame heat flux on the façade of fire-exposed buildings, it is assumed that all the windows in the offices affected by fire break at the same time. Incident heat flux gauges and temperature gauges are placed on the façades of certain floors of residential buildings A and B, i.e. at heights of 8.34, 11.6, 14.75, 17.75 and 21.1 m.

When applying LES simulation, grid size is the key parameter which has to be considered very carefully. In general, a relatively high resolution of numerical grid is necessary, because the finer mesh obtains more accurate numerical solutions of equations. However, the smaller grid size needs more computation resources and longer computing time. Therefore, in accordance with the accepted fire intensity, the optimal grid size is determined. The size of a cell in a uniform grid is 0.4 m in three spatial directions (x, y, and z), and consequently, the number of grid cells is 622080 (180×64×54 in the x, y and z direction, respectively).

According to the calculated equivalent duration of the fire, duration of numerical simulations is 1305 seconds.

RESULTS AND DISCUSSION

Fire dynamics in office building

Maximum values of radiation heat flux of fire flame and hot combustion products from a burning building occur during the fully-developed fire phase. Therefore, for the investigation of fire spreading, it is very important to predict the dynamics regime of the fire. Fire dynamics simulation results inside and outside of the office building after the breakage of glazed window openings are shown in Fig. 2.

The obtained results show that after the fire spreads through window openings to the outside environment, fire flame and plume are carried by strong buoyancy force. Buoyancy force arises as a result of high temperature and low density of fire products compared to fresh air. It forces the gaseous products with high velocity directly upwards along the façade of the office building.

Also, it can be seen in Fig. 2, the fire very quickly reaches a stationary fully developed phase with flaming combustion of flammable materials at a constant rate. Consequently, fire flame flows along the façade wall of the second building floor. It should be noted that in scenario II, the flame reaches the façade of the fourth building floor in specific time intervals.

Heat release rate

Heat released during the fire is a key parameter that determines its severity, and consequently intensity of the thermal radiation of flame. The simulation results of heat release rate quantities in the office building affected by fire are shown in Fig. 3.

As can be seen in Fig. 3, the heat release rates in scenarios I and II are 162000 kW and 210000 kW, respectively. Comparing the simulation results and corresponding values of 144400 kW (scenario I) and 180550 kW (scenario II) calculated by using Eq.(3), it is obvious that the values obtained by numerical experiment are 16 and 12 % higher, in respect. The fact that the numerical experiment is performed at a higher quantity of fire heat indicates that the worst-case scenarios of the impact of office building fire on the structures of neighbouring residential buildings are considered.

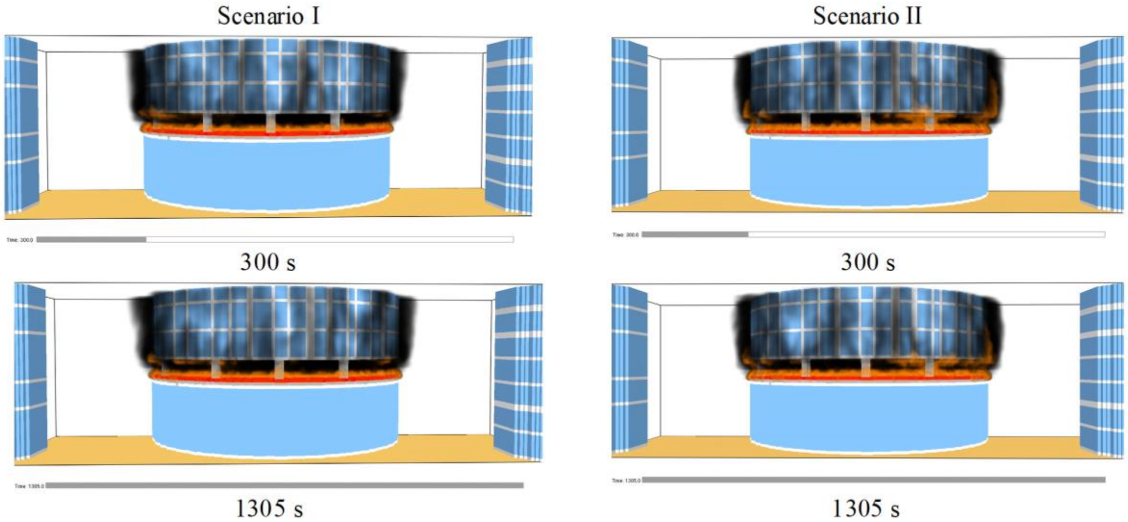

Figure 2. Fire dynamics in office building.

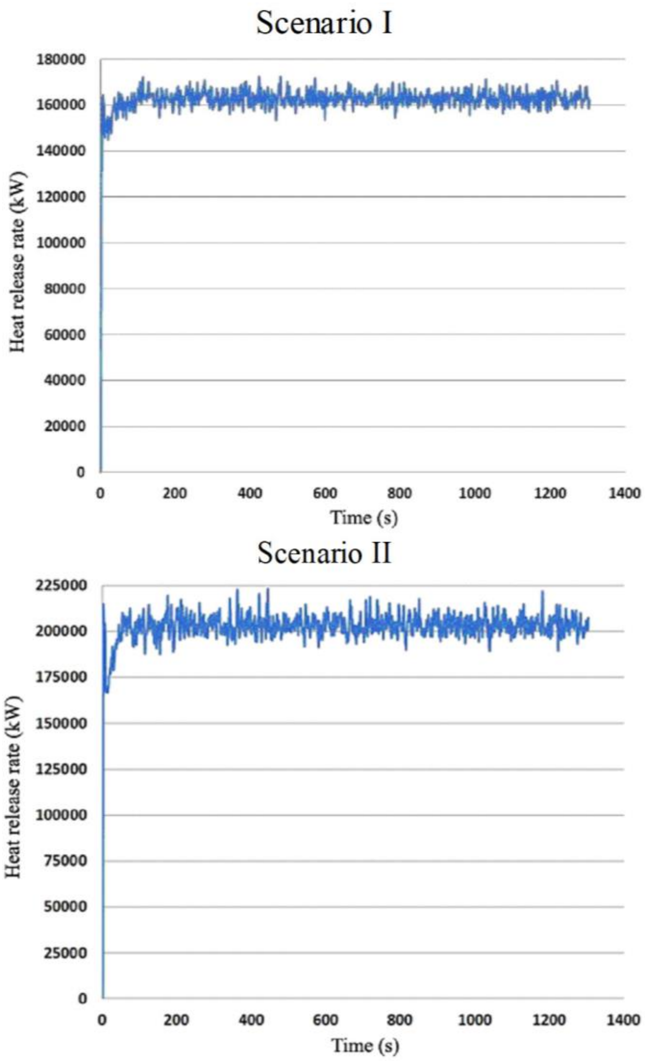

Figure 3. Heat release rate during fire.

Heat fluxes on residential buildings façades

Numerical results of the intensity of incident heat fluxes on the façade surfaces of certain floors of residential buildings A and B exposed to fire are shown in Figs. 4 and 5.

It is obvious that the highest values of heat fluxes on the façades of residential buildings occur immediately after breaking window openings of the office building, when the flame and products of fire suddenly penetrate outside. After that, due to the constant inflow of fresh air into the office building, the combustion process becomes stationary with a constant quantity of heat and smoke. As a consequence of such a combustion regime, in the further fire development in both scenarios, the values of thermal fluxes on glass façades of neighbouring buildings are approximately constant.

Also, it can be noticed that the intensities of heat fluxes are the highest at the level of façades of the second and fourth floors. The reason for this is the configuration of the fire flame. Namely, in the lower part of the first floor of the office building, there is a region of continuous flame where the combustion of flammable material takes place constantly. The radiation of the continuous flame is intense and affects the high values of heat fluxes on the surface of the glass façades of the second floor of both residential buildings.

At the same time, above the continuous combustion zone, due to intensive mixing of volatile components of the materials affected by the fire and the outside air that penetrates into the combustion zone, a fluctuating flame occurs. The inflow of outside air is conditioned by the difference between the pressures inside the space affected by fire and the pressure of atmospheric air. This pressure difference determines the quantity of air that cools the flammable gas mixture in this region. As a consequence, due to the lower flame temperature, lower heat fluxes appear at the level of the façades of the third floor of residential buildings. During the process described above, the mixing of gaseous volatile components of the office building interior and outside air inside the area affected by fire is of low intensity. The flame which flows under the ceiling penetrates into the outer environment, clinging to the façade of the building third floor in the fire. Therefore, the intensities of heat fluxes on glass façades of the fourth floor of residential buildings are higher than heat fluxes on the level of the third floor.

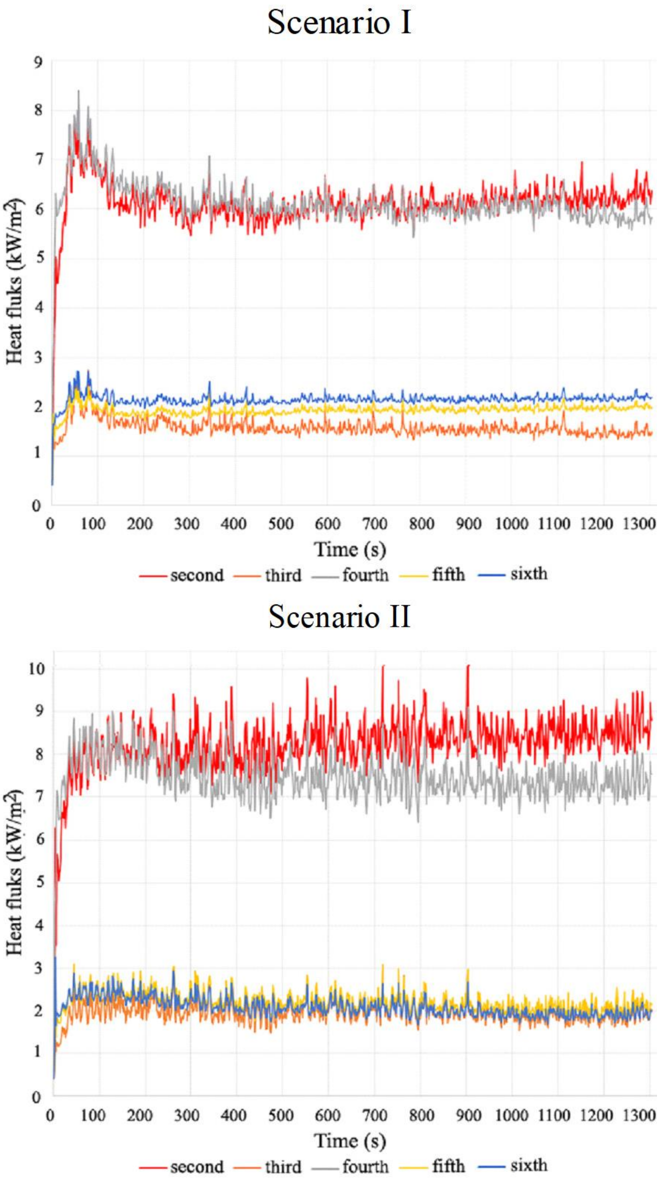

Figure 4. Heat fluxes on different floor façades of building A.

Shape of curves in Fig. 5 imposes a conclusion that in scenario II at certain moments of the fire, the intensities of the incident heat flux on the façades of the second and fourth floors of building B are higher than the critical heat flux value of 12.6 kW/m^2 adopted in many building codes /14-16/. However, a certain time interval is necessary in order for the window glasses to heat up above the permitted values on the mentioned floors under the influence of heat. In this case, only heat flux peaks occur that do not affect the intense heating of the glass façades. Comparative results of average values of heat flux intensities on the façades of the respective buildings floors for different scenarios are given in Table 3.

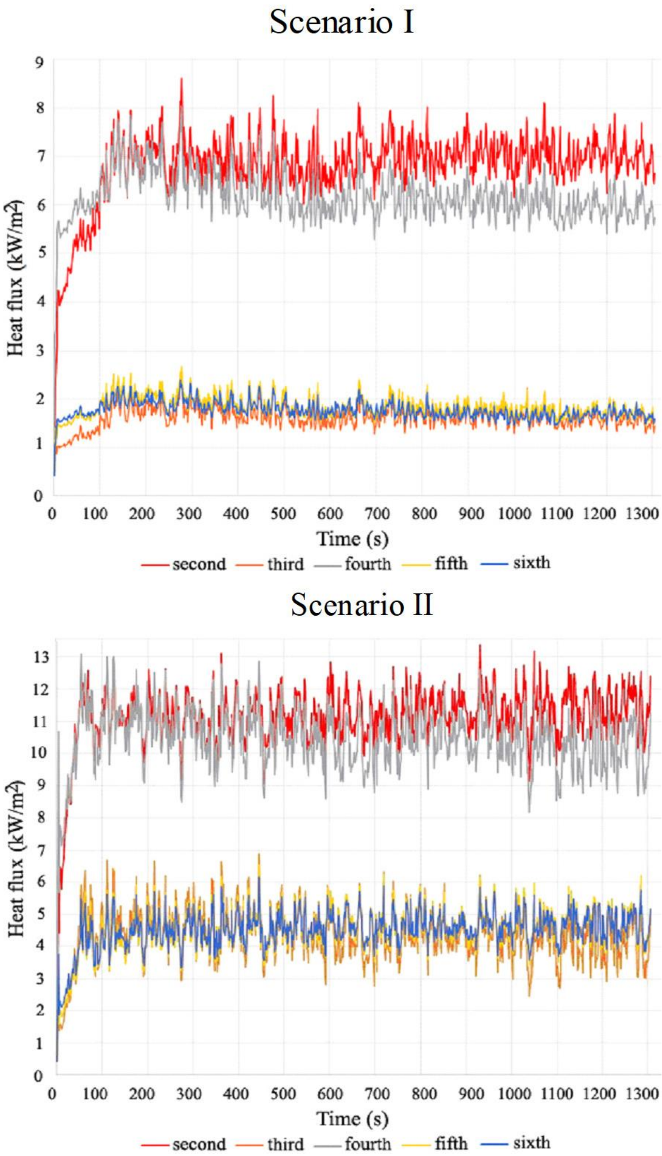

Figure 5. Heat fluxes on different floor façades of building B.

Table 3. Comparative results of heat flux intensities.

Floor	Scenario I (kW/m^2)		Scenario II (kW/m^2)		Increase in flux in scenario II (%)	
	Building		Building		Building	
	B	A	B	A	B	A
Second	7.3	6.2	11.5	8.5	57.53	37.10
Third	1.8	1.7	5.1	2.3	83.33	35.29
Fourth	7.0	6.3	11.4	8.0	62.86	26.98
Fifth	2.0	2.2	4.7	2.4	235.00	9.09
Sixth	1.8	2.0	4.5	2.2	250.00	10.00

By data analysis from Table 3, it can be noticed that the intensities of heat fluxes reach higher values on the façade of building B related to intensities of fluxes on the façade of building A. The reason for this is the smaller distance of building B from the fire-affected office building. Also, in terms of percentage, higher values of heat flux in scenario II occur on the façades of both buildings due to the higher heat of the fire.

Façade temperatures of residential buildings

The temperatures on the façade of buildings exposed to fire radiation are directly dependent on thermal fluxes on the façade surface. The average values of temperatures on façades of some floors of residential buildings are given in Figs. 6 and 7.

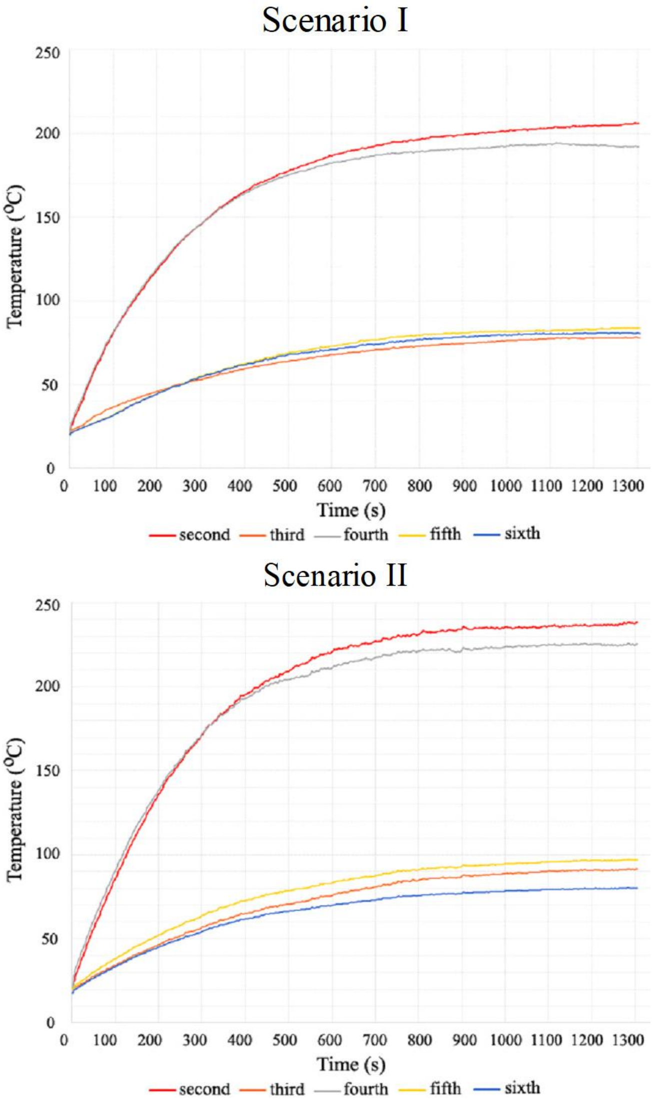

Figure 6. Temperature on floor façades of building A.

Observing the simulation results of temperature on glass façades of residential buildings, it can be concluded that temperatures increase with the duration of fire. Namely, immediately after the bursting of office building window openings, the temperatures on building façades have the lowest values, after which they gradually increase. Due to the fact that temperature values on façades of the irradiated building are directly dependent on the values of incidental heat fluxes, the highest temperature values occur on glass façades of the second and fourth floors of buildings A and B.

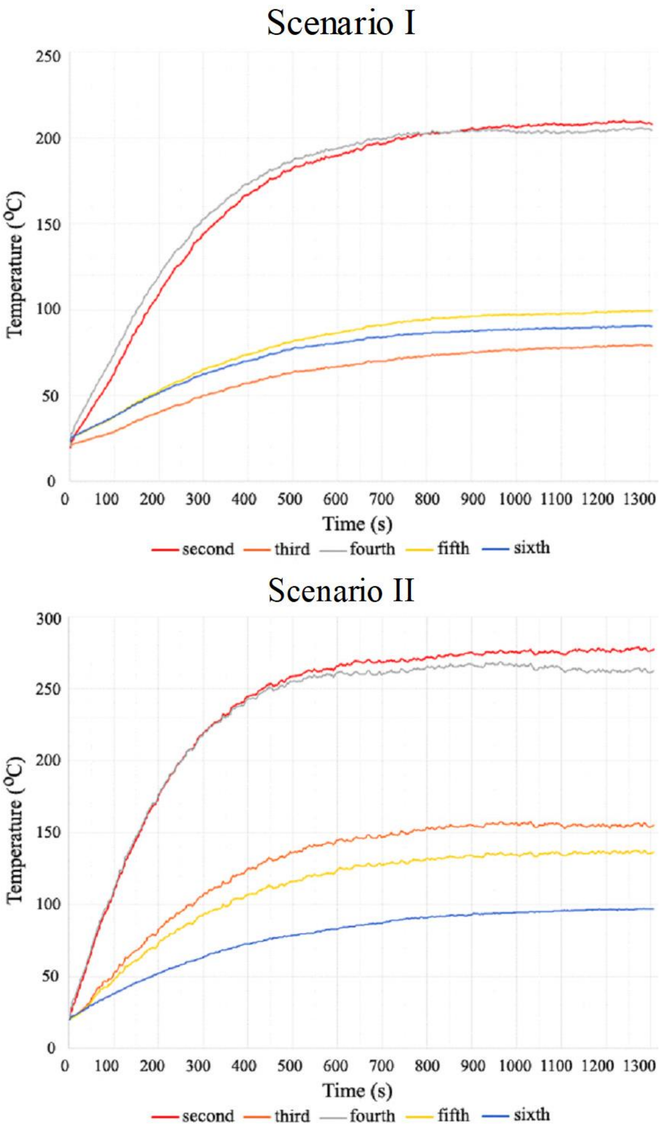

Figure 7. Temperature on floor facades of building B.

CONCLUSIONS

In this study, FDS software is used to simulate the fire of a high-rise office building with the aim to investigate fire impact on the structures of neighbouring residential buildings. Based on the analysis of results of numerical simulations, the main conclusions can be summarized as follows:
– The quantity of material affected by fire affects the heat release rate on which the intensity of thermal radiation of the flame also depends.
– The distance between a building in a fire and a building exposed to its thermal influence determines the intensities of thermal fluxes on its façade.
– Thermal flux intensities on façades of irradiated buildings are caused by the configuration of the fire flame in the office building.
– Temperatures on façades of residential buildings are directly dependent on incidental heat fluxes on the surface of their façades.

ACKNOWLEDGEMENTS

This research is supported by the Ministry of Science and Technological Development of the Republic of Serbia (contract no. 451-03-9/2021-14/200148).

REFERENCES

1. Ahn, C.S., Bang, B.H., Kim, M.W., et al. (2019), *Theoretical, numerical, and experimental investigation of smoke dynamics in high-rise buildings*, Int. J. Heat Mass Transf. 135: 604-613. doi: 10.1016/j.ijheatmasstransfer.2018.12.093
2. Gawad, A.F.A., Ghulman, H.A. (2015), *Prediction of smoke propagation in a big multi-story building using Fire Dynamics Simulator (FDS)*, Am. J Energy Eng., Sp. Issue: Fire, Energy Therm. Real-Life Challenges 3(4-1): 23-41. doi: 10.11648/j.aje e.s.2015030401.12
3. He, Q., Ezekoye, O.A., Tubbs, B., Baldassarra, C. (2016), *CFD simulation of smoke spread through elevator shafts during fires in high rise buildings*, IMECE2015-50484, V08AT10A045 p. 10. doi: 10.1115/IMECE2015-50484
4. Asimakopoulou, E.K., Chotzoglou, K.E., Kolaitis, D., et al. (2019), *Numerical investigation of externally venting flame characteristics in a corridor-façade configuration*, Fire Safety J, 110: 102912. doi: 10.1016/j.firesaf.2019.102912
5. Duny, M., Dhima, D., Garo, J.P., Wang, H.Y. (2019), *Numerical and theoretical evaluations of a full-scale compartment fire with an externally venting flame*, Fire Technol. 55: 2087-2113. doi: 10.1007/s10694-019-00845-5
6. Cheng, H., Hadjisophocleous, G.V. (2012), *Experimental study and modeling of radiation from compartment fires to adjacent buildings*, Fire Safety J, 53: 43-62. doi: 10.1016/j.firesaf.2012.06.005
7. Pesic, D., Zigar, D., Raos, M., Anghel, I. (2017), *Simulation of fire spread between residential buildings regarding safe separation distance*, Tehnički Vjesnik, 24(4): 1137-1145. doi: 10.17 559/TV-20150923233514
8. McGrattan, K., McDermott, R., Weinschenk, C., Forney, G. (2013), *Fire Dynamics Simulator, Technical Reference Guide*, Special Publication (NIST SP) - 1018, Gaithersburg, 2013. doi: 10.6028/NIST.sp.1018
9. TRVB 100/10 A (2010) Brandschutzeinrichtungen - rechnerischer Nachweis. Österreichischen Bundesfeuerwehrverband, Wien.
10. TRVB 126/87 A (1987) Brandschutztechnische Kennzahlen verschiedener Nutzungen, Lagerungen, Lagergüter. Österreichischen Bundesfeuerwehrverband, Wien.
11. SRPS U.J1.030 (1976) Firefighting – Fire Load. Pure national standard. Institute for Standardization of Serbia, Belgrade.
12. EN 1991-1-2 (2002) Eurocode 1 - Actions on Structures - Part 1-2: General Actions - Actions on Structures Exposed to Fire. European Committee for Standardization, Brussels.
13. NFPA 80A (2001) Recommended Practice for Protection of Buildings from Exterior Fire Exposure. National Fire Protection Association.
14. Approved Document, Part B: Fire safety. The Building Regulations 2000 (2006) Department for Communities and Local Government, London.
15. Building Code of Australia (1996) Australian Building Codes Board, Melbourne.
16. National Building Code of Canada (2010) National Research Council of Canada, Ottawa.