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SAFETY ENGINEERING OF ANTHROPOGENIC OBJECTS

COMPARATIVE ANALYSIS OF ASSUMPTIONS FOR NUMERICAL SIMULATION OF THE EFFECTS OF FIRE - SAFETY OF EVACUATION FROM THE BUILDING STRUCTURE

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Abstract

Ensuring a safe evacuation for the users of a building is a major goal when designing structures and systems protecting them against the effects of a fire. The article discusses the safety assessment for evacuation of users from a building exemplified by an analysis using computational fluid mechanics to reproduce the environmental conditions during a fire. It presents a way to evaluate the possibility of a safe evacuation of users from a facility by indicating the criteria for the assessment of conditions on the evacuation routes during emergency evacuation. In order to verify the criteria for assessing the evacuation safety, a three-dimensional model of the object under consideration has been prepared, for which a dedicated calculation solver of Fire Dynamic Simulator fluid mechanics has been used to recreate the fire conditions in the building. Prepared calculation model takes into account both the development of a fire on a given floor of the building and the simulation of the designed fire ventilation system in operation. In the paper the authors compare the assumptions used to create a calculation model and analyze their impact on the assessment of evacuation safety. Comparative analysis of the assumptions used to prepare the fire model allowed to draw conclusions particularly important for the people evaluating the evacuation safety on the basis of the analysis of the operation of fire ventilation systems using the computational fluids mechanics.

Key words: Evacuation safety, fire modelling, CFD simulation

INTRODUCTION

Fire incidents in buildings are one of the most dangerous hazards when it comes to evacuation safety. In order to reduce the aftermath of fire in buildings, systems are designed to improve the fire evacuation safety. These systems include fire ventilation systems, which nowadays are complex installations using the control of individual elements of the system depending on the fire scenario. The essence of the operation of fire ventilation system is to remove smoke and control the spread of fire to enable the evacuation and protection of people in the facility during the fire until the arrival of fire-fighting and rescue services [2-5]. According to the Polish regulations, safe evacuation is assured by fire ventilation systems able to ensure that "...neither smoke nor temperature preventing safe evacuation will occur along the protected passageways and escape routes during the time needed to evacuate people. [1]. Particularly important is the protection of escape routes during a fire on those floors of the building, where the risk of fire and its consequences are high. These floors include, among others, underground levels, especially underground garages. The design of fire ventilation systems in underground garages is a complex, multi-stage issue, which causes ventilation designers many problems. That is because of the complex nature of the physical phenomena that accompany the formation and development of a fire, against the effects of which the fire ventilation system should provide protection. A useful tool for assessing the performance of fire ventilation systems at the design stage is conducting thermal-flow analyses using the computational fluid mechanics CFD to recreate the conditions occurring in a building during a fire.

1. Evacuation safety assessment criteria

The main goal in assessing the performance of smoke extraction systems is to ensure the safe evacuation of users from the fire compartment by maintaining appropriate environmental conditions on the evacuation routes. According to the understanding of national legislation [5]:

"The smoke ventilation system should :

1) *remove smoke with an intensity which ensures that, neither smoke nor temperature preventing safe evacuation will occur along the protected passageways and escape routes during the time needed to evacuate people.*

It is considered appropriate environmental conditions to maintain smoke and temperature at a level that enables safe evacuation. In order to clarify the functional statement above relating to 'smoke or temperature preventing safe evacuation', the following temperature and visibility criteria have been formulated on the basis of tests and experiments [1], [4]

- - the expected smoke temperature must not exceed 60 °C at 1,8 m from the floor
- - The temperature of smoke under the ceiling must not exceed 200 °C.
- - The local visibility range of signs illuminated by reflected light shall not be less than 10 m

To ensure the conditions for safe evacuation, the above criteria should be fulfilled at the evacuation points leading to the emergency exits on a given floor for the time necessary to complete the evacuation.

The time necessary to evacuate users from a given space represents the time required by the occupants to recognize and interpret alarm signals, make decisions and react to an emerging threat, start an evacuation and the time to move to a safe zone. The total time required for evacuation is the sum of the above times [6], [7] (Fig.1).

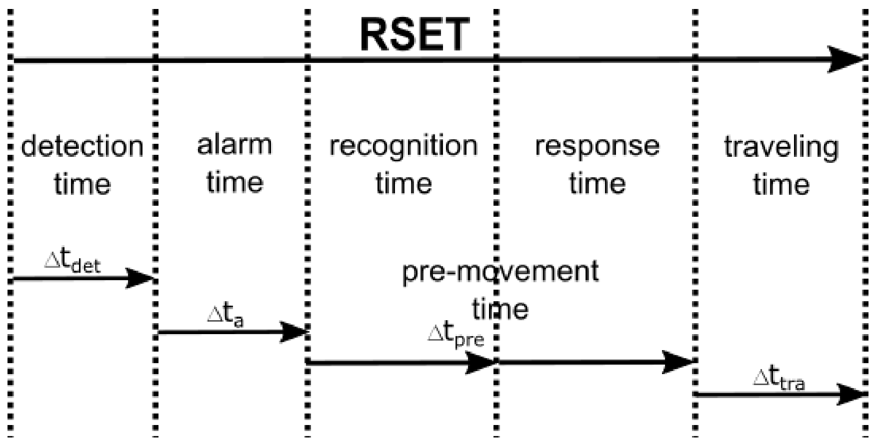

Figure1. Diagram showing the components of the total safe evacuation time, own elaboration based on [6]

2. Subject of analysis

The analyzed object, for which a three-dimensional model has been prepared, is a one-storey underground garage underneath a multi-family residential building with an area of about 2183 m^2 and a ceiling height from the floor of 2.9 m to 3.6 m, with numerous downgrades in the form of girders.

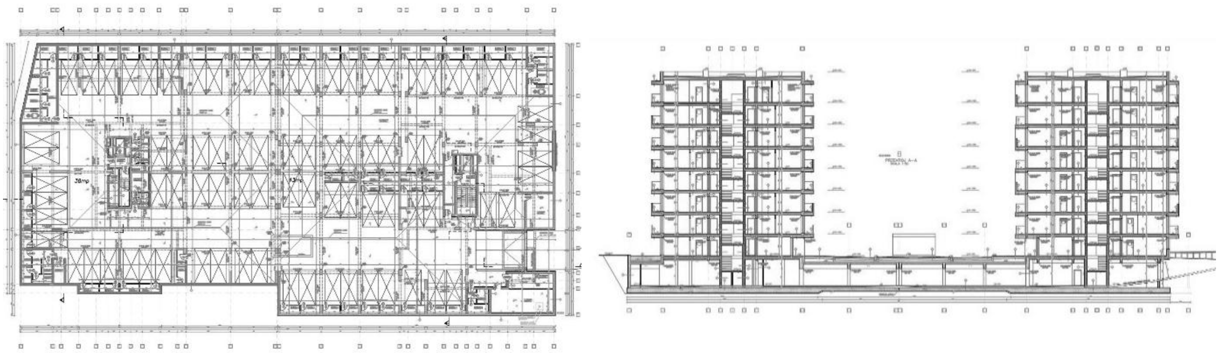

Figure 2. Projection and cross-section of the analyzed object

The garage has been designed with induction fire ventilation system with an exhaust capacity of 160 000 m3/h (PW1 - fig.3.), to which air is supplied through a compensation point (PKN1 - fig.3.) and an open garage door (PKN0 - fig.3.) located on the opposite side of the exhaust. In the garage floor space, 6 jet fans were designed to support the transfer of fire gases towards the exhaust shafts. The majority of the garage area allows people to evacuate in two directions leading to three emergency exits marked on the fig.3. (WE1, WE2, WE3). A schematic diagram of the fire ventilation system designed for the garage under consideration and possible evacuation exits are shown in the figure below.

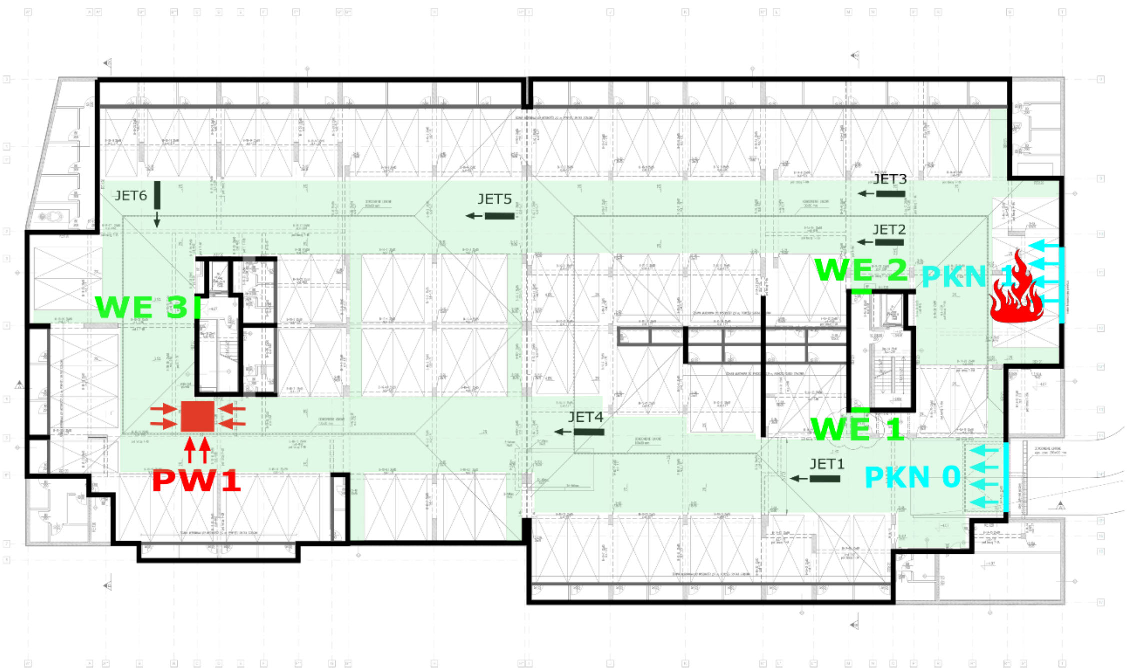

Figure 3. Schematic diagram of the operation of the fire ventilation system in the underground garage under consideration, the markings on the diagram refer to: PW - exhaust point, JET - jet fan, PKN - compensation point, WE - emergency exit, [own elaboration]

3. Model assumptions

The architectural and sanitary designs of the object under consideration were used to prepare a 3D model. The materials used to build the model were adopted on the basis of the design and consist mainly of concrete, steel and aluminum. The initial conditions refer to summer conditions (temperature 20 °C), in which the smoke extraction systems have the hardest working conditions. The turbulence model is the LES model with the sub-segment turbulence model (SGS) of the Deardorff model. The most important part of the assumptions are those relating to the purpose of the article and to the source of the fire. This article presents two different standards for the mapping of the passenger car fire development curve used for the analysis of the efficiency of smoke ventilation in an underground garage not equipped with sprinkler system. Particular attention was directed at the comparison of the impact of the design fire selection in relation to evacuation safety from the fire compartment. In the underground garage under consideration, the total required safe evacuation time is 300 s, in which the fire modelling standards will be compared. The first of the compared standards is the fire modelling based on the British Standard BS 7346-7:2013, which considers the fire of two passenger cars with an area of 25 m, circumference of 20 m and maximum power of 8 MW [11]. The course of the fire development curve over time assuming a development according to the square curve "αt^2". (α= 0.00988 kW/s^2) is shown in Figure 4 and is hereinafter referred to as curve 1. The second standard for modelling a fire in an underground garage uses a fire development curve derived from the Dutch standard NEN 6098:2010, which refers to a fire of 3 passenger cars with a maximum fire power of about 9.4 MW, [12], [1] (hereinafter referred to as curve 2). The course of development of both fire curves in time required for safe evacuation from the garage space is shown in Figure 4.

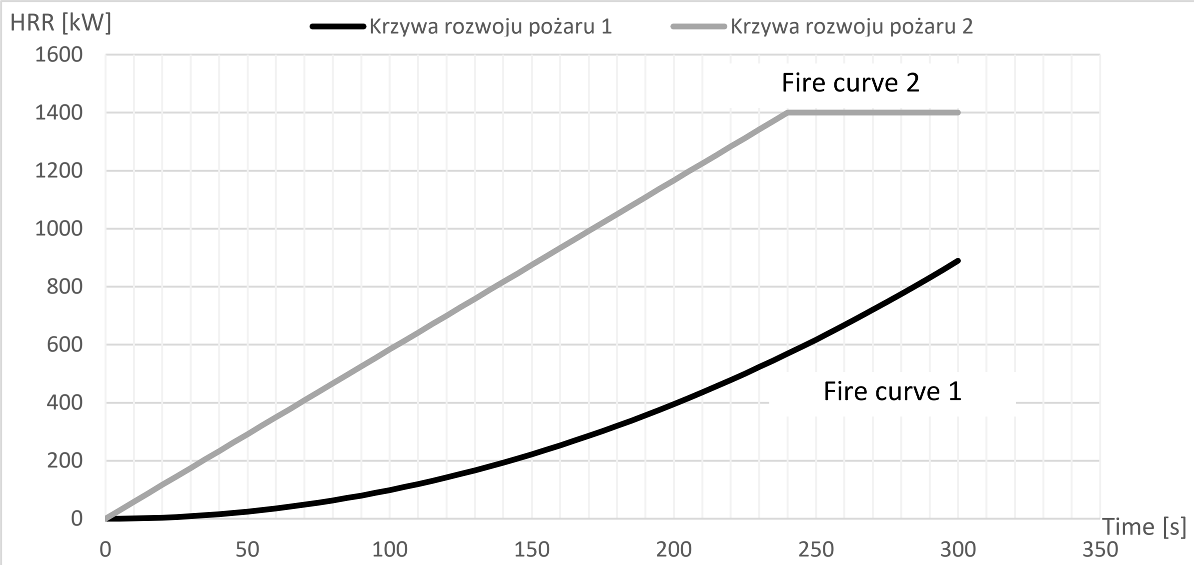

Figure 4. Course of fire development curves based on BS 7346-7:2013 standard, α = 0.00988 kW/s2, (curve 1) and according to NEN 6098:2010 (curve 2) during the evacuation time in the considered underground garage, own elaboration based on [11], [12].

4. Calculation solver

The analysis was carried out using a calculation solver Fire Dynamic Simulator (FDS) which is a computational fluid dynamics (CFD) model dedicated to fire-driven fluid flow. During the calculation FDS numerically solves a form1of the Navier-Stokes equations appropriate for-low-speed (Ma < 0.3), thermally-driven flow [8]. This form of Navier-Stokes equations is refer to flow with an-emphasis on smoke and heat transport from fires [8]. Detailed information of equations and the numerical algorithm are contained in the FDS Technical Reference Guide [9]. Fire Dynamic Simulator is based on Large Eddy

Simulation (LES) with difference sub-grid model of turbulence (Constant Smagorinsky, Dynamic Smagorinsky, Deardorff, Vreman, RNG-Renormalization group eddy viscosity model, WALE-Wall Adapting Local Eddy-viscosity model) [6]. In this study to performed calculation Deardorff SGS model has been used as an default model to analyze the heat transfer from fire [8]. The governing equations in Fire Dynamic Simulator refer to conservation equations of mass, momentum and energy for a Newtonian fluid [8], [9].

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u)\rho + \nabla(\rho u \times u + pI) = \nabla \cdot \tau + \rho g \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h)\rho + \nabla \cdot (\rho h u) = \frac{D\bar{p}}{Dt} + \dot{q}^{"}_{comb} - k\nabla T - \sum_i h_i \rho D_i \nabla Z_i + \dot{q}^{"}_{rad} \tag{3}$$

where:

ρ – density, t – time, u – flow velocity, ∇ –del operator, p –pressure, I –identity matrix, τ –stress tensor, g – force of gravitational acceleration, h –enthalpy energy of the flow, $\bar{p}$ –pressure, $\dot{q}^{"}_{comb}$ –heat release per unit volume through combustion, $k\nabla T - \sum_i h_i \rho D_i \nabla Z_i$ –refere to conductive and diffusive heat fluxes, $\dot{q}^{"}_{rad}$ –transfer of heat from radiation

Fire Dynamic Simulator taken into consideration heat radiation as an equation of radiative transfer (RTE). The equation of radiative transfer expresses the loses (absorption), gains (emission) and redistributes energy (scattering). The form of the equation in FDS is given [9]:

$$-\nabla \cdot \dot{q}^{"}_{rad}(x) = k(x)[U(x) - 4\pi I_b(x)] \quad ; \quad U(x) = \int_{4\pi} I(x,s')\,d\,s' \tag{4}$$

where:

$k(x)$ – absorption coefficient, $I_b(x)$ – source term, $I(x,s)$ – solution of the radiation transport equation (RTE) for a non-scattering grey gas

5. The calculation model

Based on the design and assumptions, the three-dimensional representation of the geometry of the object along with the physical properties of the materials and environmental conditions, using the graphic user interface of the calculation solver FDS, was made. The model of the considered garage is presented below.

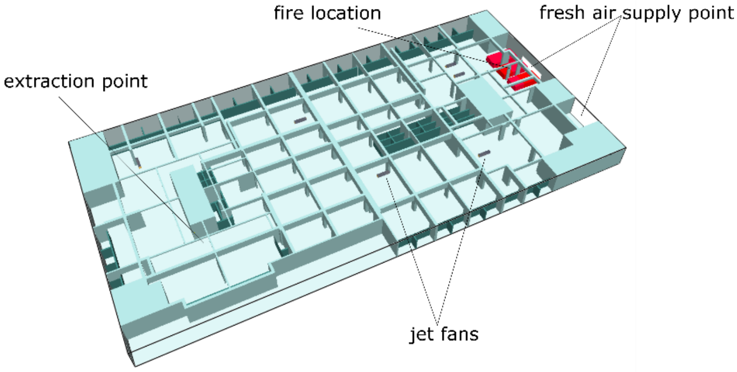

Figure 5. Three-dimensional model of the considered space

In order to implement the calculation methods of fluid mechanics in the calculation solver Fire Dynamic Simulator, the calculation space is discredited by means of a calculation grid on which approximate form of the conservation equations of Energy, mass and momentum are solved. The solver used to model turbulence uses the Large Eddy Simulation method using a structural calculation grid. The dimensions of a single calculation cell have been selected to meet condition $\frac{D^*}{\partial x}$ values ranged from 4 to 16 [13], where D^* is a characteristic fire diameter and ∂x is a mesh cell size. Characteristic fire diameter D* is defined as [8]

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}}$$

Where:

$\dot{Q}$ − heat releas rate of the fire, ρ_∞ −air density, c_p − thermal capacity of air, T_∞ − ambient air temperaturę, g −gravitational acceleration

In the analysis, the numerical model is made up of a structural cubic grid with one sizes of computational cells. The numerical grid is 0.1 m x 0.1 m x 0.1 m. The total number of grid elements amounted to 10 506 240 cells.

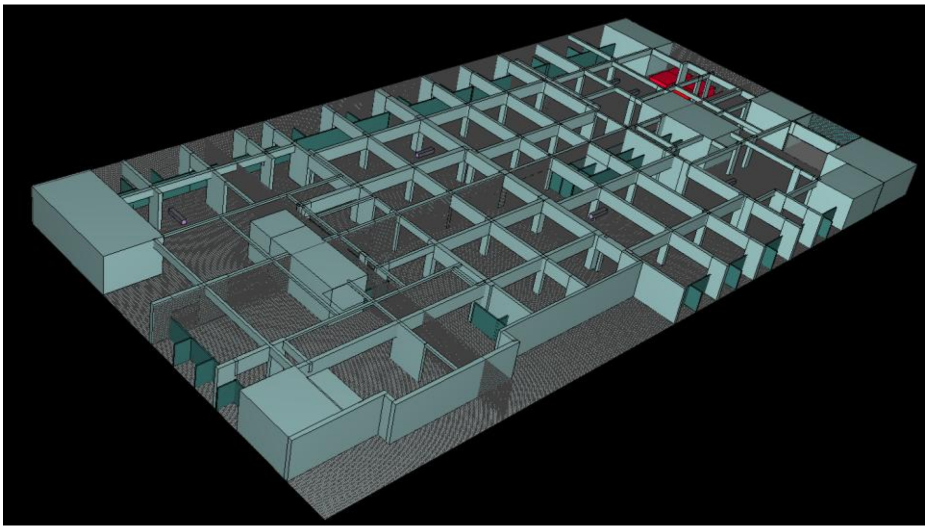

Figure 6. Numerical grid resolution

6. Results

As a result of the analysis, the distributions of parameters to be evaluated were obtained: visibility and temperatures presented in Figures 7-9 for characteristic simulation times: 60 s, 120 s, 180 s, 240 s, 300 s from model fire initiation:

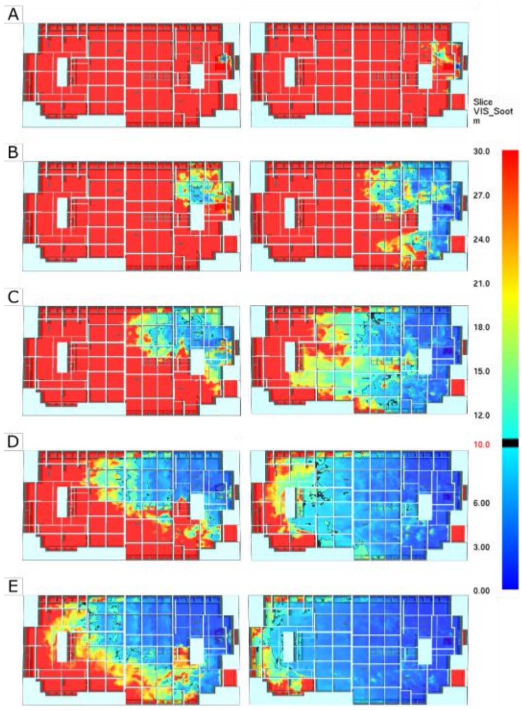

Figure 7. *Results of visibility distribution 1.8 m above the floor for the model fire according to BS 7346-7:2013 standard (curve 1) on the left side and according to NEN 6098:2010 (curve 2) on the right side of the figure respectively for the times from fire initiation: A - 60 s, B - 120 s, C - 180 s, D - 240 s, E - 300 s.*

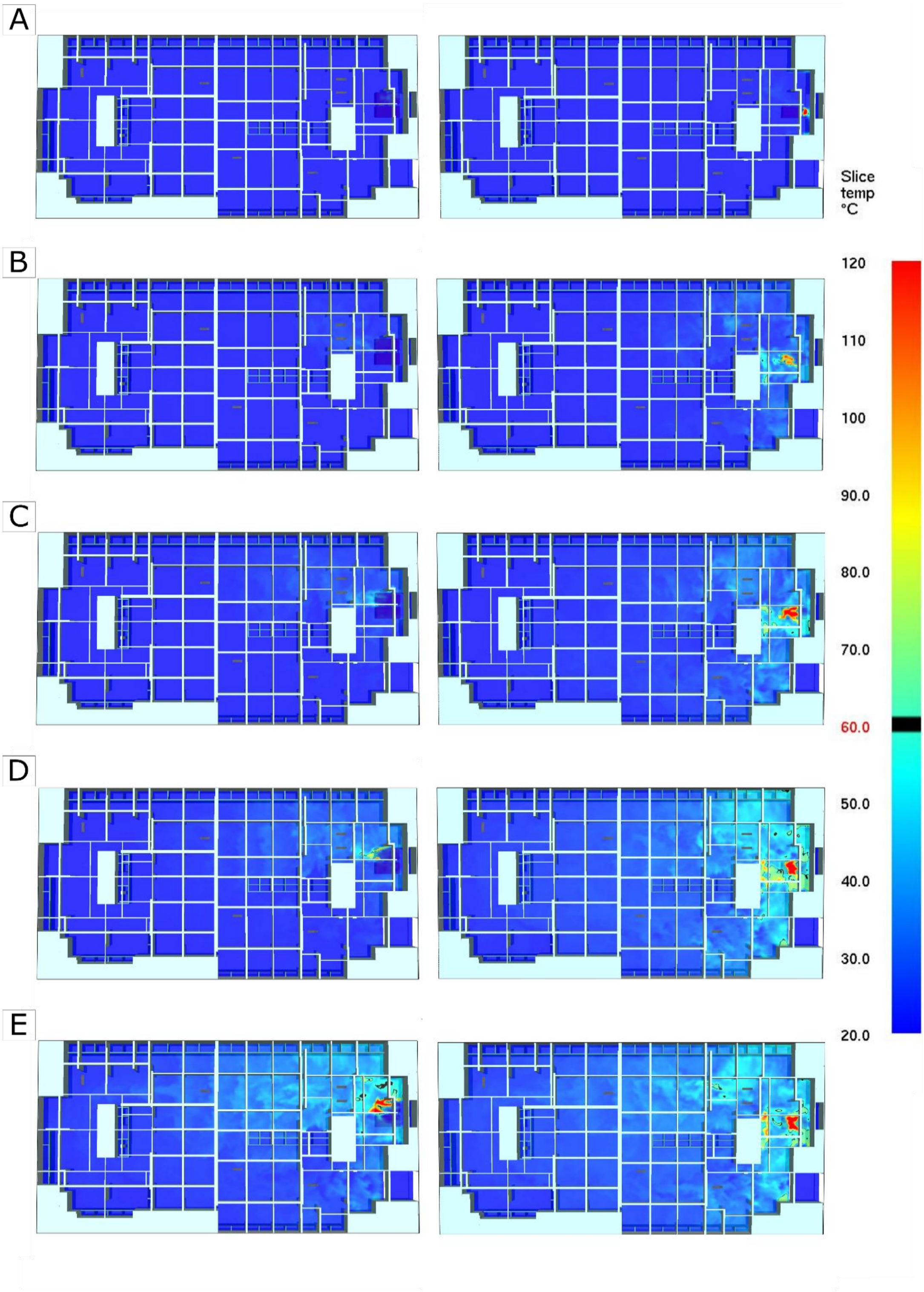

Figure 8. Results of temperature distribution at the height of 1.8 m above the floor for the model fire according to BS 7346-7:2013 standard (curve 1) on the left side and according to NEN 6098:2010 (curve 2) on the right side of the figure respectively for the times from fire initiation: A - 60 s, B - 120 s, C - 180 s, D - 240 s, E - 300 s.

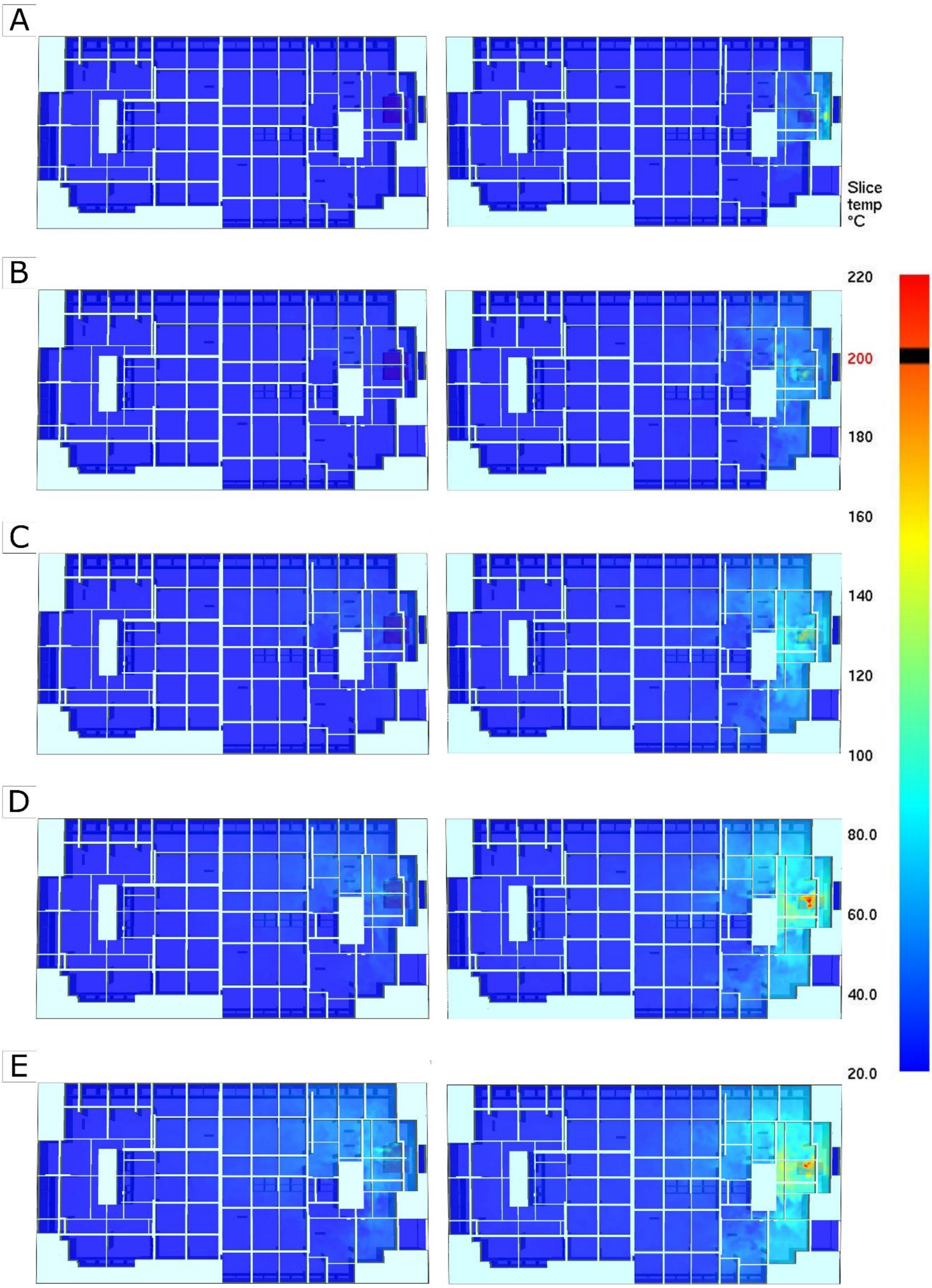

Figure 9. Results of temperature distribution under the ceiling for the model fire according to BS 7346-7:2013, (curve 1) on the left side and according to NEN 6098:2010 (curve 2) on the right side of the figure for times from fire initiation A - 60 s, B - 120 s, C - 180 s, D - 240 s, E - 300 s .

When analyzing the results of the calculations, it should be noted that out of the three parameters considered as criteria for the evaluation of evacuation conditions, the most critical is the visibility related to the signs of reflected light, including building partitions, at a height of 1.8 m above the floor. Comparing the results obtained for the visibility distribution in both cases of fire development (curves 1 and 2) in the initial phase of the fire, i.e. during the time from 0 to 60 s when the fire is detected by the system, there is no smoke in the garage to limit the evacuation possibilities. In the next minute of the fire development, the exhaust fans are activated and the system increases its capacity until the nominal capacity of 160 000 m^3/h is reached. For a fire developing according to curve 1 (Figure 3, B, left side), during the second minute of the fire the EC.2 evacuation exit close to the fire location becomes unattainable. The smoke resulting from a fire under curve 2 (Figure 3, B, right-hand side) will pass through the entire stairwell, thus preventing the occupants from evacuating through the two WE.2 and WE.1 emergency exits. During the next minute of fire development according to curve 1, when the first users of the garage (according to the calculated reaction times according to PD7974-6:2004 [8]) will start to evacuate, a quarter of the garage will be filled with smoke and the WE.1 emergency exit will still be available for evacuating persons, only in the next minute of fire development (4th minute) the users will lose the possibility to evacuate through the WE.1 emergency exit (Figure 3, D, left side). During this time, access to the emergency exit WE.3 located on the opposite side of the garage from the fire initiation point shall remain available. A different situation occurs when a fire develops according to curve 2, for which during the evacuation of the first group of people from the garage space (180 s), in the middle of the garage space, smoke prevents safe evacuation through the lack of sufficient visibility on the escape routes leading to emergency exits WE.1 and WE.2. The smoke engulfing an increasing number of escape routes, resulting in reduced visibility within the area of EC.1 emergency exit just 4 minutes after the fire has been initiated (Figure 3, D, right-hand side). This is comparable to the visibility range of a fire following the curve 1 after five minutes (Figure 3, E, left-hand side). At the same time, the conditions are much worse for a fire developing under curve 2 (Figure 3, E, right-hand side), the smoke is spreading throughout the entire garage, visibility is very limited and access to any of the escape route is denied. The conditions in the garage prevent safe evacuation. In the case of the other evaluation criteria, i.e. temperature at a height of 1.8 m above the floor and temperature under the ceiling, no direct danger to people evacuating from the garage space is observed, only within the fire source itself the conditions for safe evacuation are not met and for the rest of the garage only a deterioration is observed. However, the difference arises when comparing two fire development curves: curve 2, for which the temperature of 60 °C is exceeded at a height of 1.8 m above the floor near the fire itself in the second minute (Fig. 4, B, right side), and for the fire development curve 1, due to the lower fire power (Fig. 2) in the fourth minute respectively (Fig. 4, D, left side). The difference in fire power for the assumed fire development curves also translates into the temperature reached under the ceiling, which in the case of fire development curve 2 in the 4th and 5th minute of the fire exceeds 200 °C only above the source of the fire without deteriorating access to the emergency exits (Fig. 5, D-E, right side). For the fire development curve 1, the temperature under the ceiling is not observed to exceed 200 °C.

CONCLUSIONS

Modelling of the development of passenger car fire in an underground garage is a complex issue, for which curves of the development of passenger car fire derived both from empirical research and theoretical considerations are used. The above article quotes two standards for the course of fire development curves used to reflect the passenger car fire, whose impact on evacuation conditions was compared. The results obtained in the above comparison indicate a significant impact of the selection of the fire development curve on the assessment of evacuation conditions using the fire development curves with a relatively similar maximum power of the modelled fire of about 8 MW for curve 1 (Fig. 1.) modelled on the British standard BS 7346-7:2013 [8] and about 9.4 MW for curve 2 (Fig. 1.) derived directly from the Dutch standard NEN 6098:2010 [9]. Modelling of the development of passenger car fire according to curve 2 is also recommended for use by the national guidelines of the Building Research Institute in the instruction No. 493/2015 [1]. The course of considered fire development curves during the evacuation significantly deviates from each other (fig.1.). In the first minute after the fire detection by the system (60-120 s of fire), the power released from the fire modelled according to the curve 2 is between 492 and 984% higher than the power released during the development of the fire modelled according to the curve 1, which is reflected in the amount of smoke produced according to the ratio of the power released during the course of both curves [9]. As a result of the change of fire power, the temperature above the evacuation passages also changes (Fig.3, A-B; Fig.4. A-B; Fig.5. A-B). In the further course of both curves the differences in the released power decrease with time but still have a noticeable influence on the evaluation of evacuation conditions. When the first person starts evacuation from the garage space (120-180 s of fire), the power released by curve 2 is 328 to 492 % higher than in curve 1 (Fig.3, B-C; Fig.4. B-C; Fig.5. B-C). During the evacuation of the last persons from the garage space (240 - 300 s of fire), the fire power released by curve 2 is 157 to 246 % higher than that of curve 1 (Fig.3, D-E; Fig.4. D-E; Fig.5. D-E). Differences in the power released by model fires lead to variable conditions during the evacuation of users from the underground garage space. If the evacuation conditions are assessed on the basis of visibility at the level of 1.8 m above the floor in the garage under consideration, access for evacuees to the emergency exit WE.1 is approx. 120 s longer for a model fire according to curve 1 than according to curve 2. On the other side of the garage, access to the emergency exit WE.3 is provided until the end of the required safe evacuation time in case of fire development according to curve 1, while for development according to curve 2, users are provided with access to the emergency exit WE3 up to approx. 240 s after fire initiation.

The actual development of a passenger car fire is individual for each case of a fire, so there is no single universal fire development curve that could serve as a model to cover all possible fire cases of cars of different classes, generations, brands and models. On the other hand, standardizing the use of fire development curves leads to comparable results and conclusions from CFD analyses. In extreme cases, CFD analyses using the fire development curves with mild intensity to model a passenger car fire, e.g. the curve presented in this article modelled on the British standard BS 7346-7:2013, may lead to underestimation of the power of the fire and consequently affect the assessment of evacuation conditions in the garage under consideration, which directly translates into the safety of its users.

REFERENCES

[1] W. Węgrzyński, G. Krajewski, Wentylacja pożarowa garaży. Projektowanie, Ocena i Odbiór. Instrukcja ITB nr 493/2015. Instytut Techniki Budowlanej, Warszawa 2015

[2] Rusowicz, A., Grzebielec, A., Dorsz, A.: Zastosowanie metod numerycznych w ocenie bezpieczeństwa ewakuacji - w przykładowym garażu podziemnym. Zeszyty Naukowe Szkoły Głównej Służby Pożarniczej 1, 2017, 61, 23–36.

[3] Baryłka A., Bąk G.: Wpływ pożaru zewnętrznego na wytężenie obudowy schronu wykopowego, Inżynieria Bezpieczeństwa Obiektów Antropogenicznych, 2018, (3-4), 1-8

[4] Procedury organizacyjno-techniczne w sprawie spełnienia wymagań w zakresie bezpieczeństwa pożarowego w inny sposób niż to określono w przepisach techniczno-budowlanych, w przypadkach wskazanych w tych przepisach, oraz stosowania rozwiązań zamiennych, zapewniających niepogorszenie warunków ochrony przeciwpożarowej, w przypadkach wskazanych w przepisach przeciwpożarowych, Biuro Rozpoznawania Zagrożeń, Komenda Główna Państwowej Straży Pożarnej, Warszawa 2008

[5] Obwieszczenia Ministra Infrastruktury i Rozwoju z dnia 8 kwietnia 2019 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Infrastruktury w sprawie warunków technicznych jakim powinny odpowiadać budynki i ich usytuowanie (Dz. U. 2019 poz. 1065)

[6] PD 7974-6:2004 Human factors: Life safety strategies – Occupant evacuation, behaviour and condition

[7] Fire Safety engineering concerning evacuation from buildings, CFPA-E Guideline No 19:2009 F

[8] McGrattan K.B., Hostikka S., McDermot R., Floyd J., Vanella M., Fire Dynamics Simulator User's Guide, NIST Special Publication 1019, Sixth Edition, February 2019.

[9] McGrattan K.B., McDermot R., Hostikka S., Floyd J., Vanella M., Weinschenk C., Overholt K., Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model, NIST Special Publication 1018-1, NIST, February 2019.

[10] Yuen A.C.Y., Yeoh G.H., Yuen R.K.K., Lo S.M., Numerical Study on Small-Scale Fire Whirl using Large Eddy Simulation, Proceedings of the 3rd International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'16) Ottawa, Canada – May 2-3, 2016, Paper No. 165

[11] BS 7346-7:2013 : Components for smoke and heat control systems Part 7 , Code of practice on functional recommedndations and calculation methods for smoke and heat control systems for covered car parks.

[12] NEN 6098:2010 Rookbeheersingssystemen voor mechanisch geventileerde parkeergarages, 2010

[13] U.S. Nuclear Regulatory Commission, Electric Power Research Institute, Veryfication and Validation of Selected Fire Models for Nuclear Power Plant Applications, NUREG-1824, Final Report, May 2007