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Forecast of a fire spreading in a large-area shopping hall

Prognoza rozprzestrzeniania się pożaru w wielkopowierzchniowej hali handlowej

Abstract

The specifics of a forecast fire development in a single fire compartment consisting of a shopping hall characterised by a large area and a relatively low height are analysed in this paper. The fire initiated locally, and after initiation, depending on the ventilation conditions in the zone, more or less intensively spread to the neighbouring areas with or without full development. The propagation of hot exhaust plume was simulated within the environment of the FDS computer code. Three formal models differing in zone size and stacking height have been subjected to analysis. The influence of automatically activated smoke vents has been accounted for.

Keywords: shopping hall, spread of a fire, numerical simulation, fire compartment, ventilation conditions, stacking height

Spis treści

Przeanalizowano specyfikę rozwoju pożaru w pojedynczej strefie pożarowej, którą stanowi hala handlowa charakteryzująca się dużą powierzchnią przy stosunkowo małej wysokości. Modelowany pożar został zainicjowany lokalnie, a następnie, w zależności od warunków wentylacji strefy pożarowej, rozwijał się z mniejszą lub większą intensywnością w strefach sąsiadujących z pierwotnym źródłem ognia, aby w końcu ulec lub też ewentualnie nie ulec pełnemu rozgorzeniu. Przebieg propagacji gorących gazów spalinowych symulowano z użyciem programu FDS. Rozważono trzy scenariusze rozwoju pożaru, różniące się wzajemnie rozmiarem strefy pożarowej i wysokością składowania towarów stanowiących obciążenie ogniowe. Uwzględniono również wpływ, jaki na ten rozwój ma zastosowanie w rozpatrywanej hali automatycznie otwieranych klap dymowych.

Słowa kluczowe: hala handlowa, rozprzestrzenianie się pożaru, symulacja numeryczna, strefa pożarowa, warunki wentylacji, wysokość składowania

1. Introduction

Large-area shopping halls, usually constituting separate fire zones, belong to the peculiar group of enclosed compartments having a relatively low height and a limited number of access openings. Geometries of this type, even when the smoke vents required by law are present and sufficiently numerous, are characterised by difficulties in the efficient ventilation of the considered zone, and this results in a high uncertainty level in forecasting the fire development scenario. Determination, whether in such a case during a fire exposure the developing conditions would allow for the creation of a fully developed fire, or for the whole duration the fire would remain localised with limited intensity and affected area, seems to be the key. A credible reply to the question stated above may be different, depending on the size and geometry of the fire compartment, the fire load accumulated in the compartment, availability of oxygen in exchange with immediate surroundings and the stacking height of the merchandise present [2]. Three mutually corresponding numerical models are analysed in detail here. For each of these models, the fire development is simulated. Each of these models results in a different scenario, i.e. in a different estimate of the warranted safety level.

2. Description of the considered numerical models

A numerical simulation of fire development in a large area shopping hall is performed in each case within the environment of the FDS (*Fire Dynamic Simulator*) computer program, developed by Mc Grattan et al. [7]. It is assumed that the fire load is created by the merchandise stacked on racks. It is also assumed that the merchandise has the parameters of cellulose. For comparative purposes, two alternative scenarios are considered in each case, i.e. when there are automatically activated smoke vents installed, and when there are no such vents. In the first example, a small hall is considered (Fig. 1a), while in the second and third example a substantially larger hall is considered (Fig. 1b) [3]. The difference between the second and third example is in the merchandise stacking height. The simulation performed yields the temperature of gases in the fire plume specified in the selected cross-sections of the hall after various fire exposure periods. The spatial area affected by fire as well as the temporal fire development are compared. The obtained results allow for observation how, at the given height above the floor and at the selected cross-section, the temperature of exhaust gases evolves. Knowledge of this type allows for drawing more rational conclusions pertaining to fire scenario, and thus allows for better selection of necessary active and/or passive fire protection measures.

In all the considered cases convection, radiation and heat transfer through the partitions have been accounted for. The initial heat source was modelled as a localised fire with heat generation intensity of 500 kW/m^2 and total heat output of 25 MW (this value is recommended in [1] as the maximum for the steel structure used to store flammable materials). The duration of this initial fire was assumed as 120 seconds, and its location is indicated on the pictures enclosed below. The fire initiated in this manner developed further progressing or not to adjacent shelf racks located in the hall, but the intensity of this development was conditioned by the geometry of the fire compartment, the fire load gathered in this compartment and available ventilation. The materials stockpiled on the shelf racks has been modelled with the following parameters: the specific heat 1.36 J/(kg×K), heat conductivity 0.25 W/(m×K), volumetric weight 1100 kg/m^2. The flash point has been set at 250°C while the chemical composition has been modelled in a simplified manner, as for cellulose.

3. Scenario A – fire development simulated in a shopping hall of a limited area

It has been assumed that the dimensions of the smaller of two modelled halls are equal to 52.00 m by 36.00 m in plan with a constant height of 4.50 m. The existing and permanently open access gates have been assumed in the numerical model of the hall. These are in particular: one large gate having the dimensions of 3.50 m by 3.00 m, located in the front, shorter wall of the hall and two smaller gates, having the dimensions of 1.00 m by 2.50 m each, located in the side wall (Fig. 1). The sheathing of the hall has been modelled as made of the typical sandwich panels with 15.00 cm thick mineral wool core. The properties of the insulating material, depending on the value of the temperature affecting it have been assumed according to paper [8]. It has been also assumed that before the initiation of the fire the temperature within the hall has been equal to 20°C and was evenly distributed. Moreover, the considered hall was equipped mostly with storage racks of equal stacking height of 3.50 m. On these storage racks are stored materials for sale made of cellulose derivatives (mostly paper materials). These materials yielded the main fire load in the considered fire compartment. In addition 3×5 = 15 smoke vents having the dimensions of 2.00 m by 2.50 m each have been evenly distributed in the roof of the hall (Fig. 1). These vents have been activated individually by sensors set to the activation temperature of 74°C. For comparison, the fire development scenario in the same hall, but without smoke vents in the roof has been analysed as well.

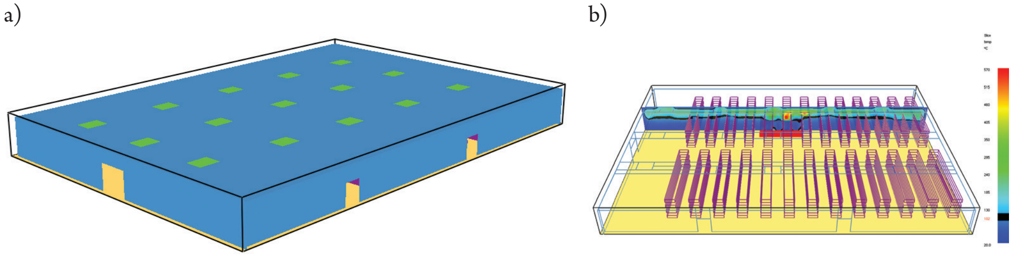

Fig. 1. The scheme of a small area shopping hall considered in scenario A: a) distribution of vertical access gates and horizontal smoke vents affecting the ventilation of the fire zone, b) distribution of the storage racks with combustible materials stacked and location of the vertical cross-section selected by the Authors to analyse the progress of fire [3]

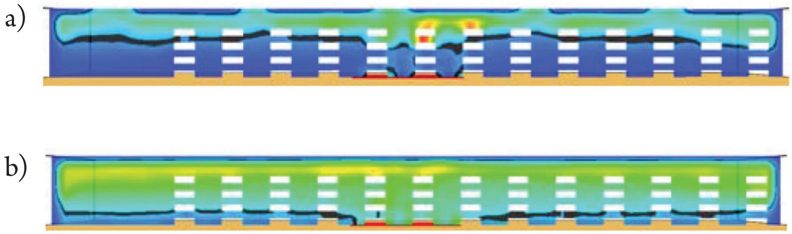

Fig. 2. Exhaust plume gas temperature maps obtained after 10 minutes of a fire exposure in the case of a smaller hall considered in scenario A, including: a) results for the hall equipped with smoke vents, b) results for the hall not equipped with smoke vents [4]

The detailed results obtained for the fire forecast in the smaller of analysed halls are depicted in Fig. 2 and in Fig. 3. Furthermore, in Fig. 1b the location of fire source initiating the development of fire is precisely indicated. This location determines the location of a cross-section in which the temperature of fire plume is mapped in subsequent moments of fire exposure. Let us consider the fire plume temperature distribution obtained after 10 minutes of a fire, under the assumption that the smoke vents operate as indicated above, as the reference one. This reference distribution is depicted in Fig. 2a. The 100°C isotherm is depicted in black in this picture. Thus the temperature of a fire plume contained within this isotherm is higher. Let us note that in this case this isotherm is located relatively high with respect to the floor level, and thus the thickness of the cool air layer above floor should allow for safe evacuation of all occupants. The limited thickness of the hot fire plume near the ceiling is a direct result of operating smoke vents evacuating the hot gases outside the building. This result may be referred to in Fig. 2b, where the analogous distribution of temperature, obtained in the same cross-section of the hall and after the same time of fire exposure, is depicted for the case of a hall not equipped with smoke vents. In this figure it is shown, how much faster would the fire develop in the same geometry of the fire compartment, with the same floor area as well as with the same location of the vertical openings (i.e. permanently open gates described at the beginning of this paper) ventilating the fire zone, in the case of a hall lacking the obligatory additional safety devices. As may be observed in Fig. 2b, the occupant of the fire compartment after 10 minutes of a fire stands no chance for safe evacuation since the temperature of a fire plume along almost the whole height of the considered cross-section, even at the layer just above the floor, reaches or exceeds the level of 100°C.

A comparison of a fire plume temperature distribution in the horizontal cross-section of the hall at the height of 4.00 m above floor level, obtained after 10, 15 and 20 minutes of a fire exposure (Fig. 3) may be interesting for an observer analysing the development of a fire in the smaller of considered halls. One may easily find out that in the 20th minute of the fire forecast for this hall the fire reaches the stage of a fully developed fire in a large area of the considered fire compartment, as most of the combustible materials gathered in the affected zone are on fire and the temperature within the fire plume tends to equilibrate. But this progress to the stage of a fully developed fire is of rather localised character, as it does not affect the whole area of the considered hall.

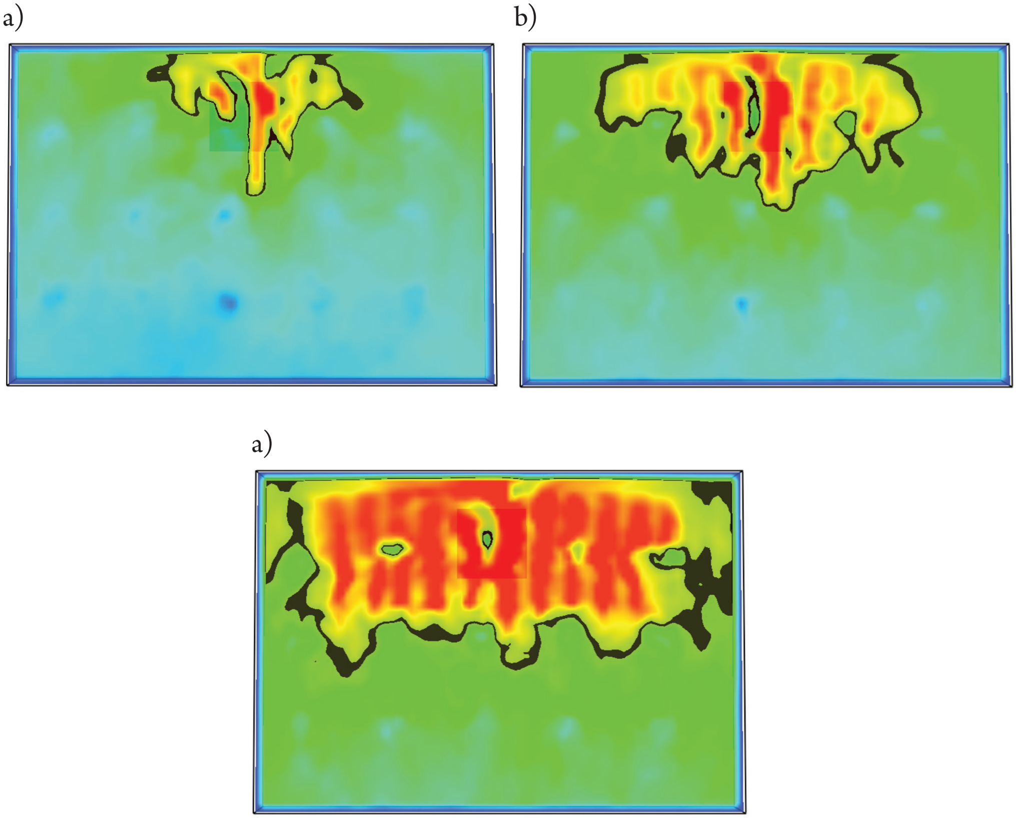

Fig. 3. Fire plume temperature maps obtained for the horizontal cross-section of the smaller hall at the height of 4.00 m above the floor level with smoke vents operating, after: a)10 minutes, b) 15 minutes, c) 20 minutes of a fire exposure, respectively. The isotherm depicted in black on these figures corresponds to the temperature of 350°C. The location of a fire source initiating the fire is indicated by the darkened square [4]

The constatation of fire flaring up in this zone seems to be corroborated by the graph of a fire plume temperature reached in the cross-section depicted in Fig. 1b, 4.00 m above the floor level, somewhat later, i.e. after one hour of a fire exposure. It is depicted in Fig. 4, where the results of simulation for a hall equipped with smoke vents are plotted accompanied by the results obtained for the same hall devoid of these vents.

Undoubtedly, the fire plume temperature obtained in the whole considered cross-section after so long time period is almost evened out. As may be interesting, in the case of the hall equipped with operating smoke vents the temperature at the considered height is much higher than the analogous temperature forecast for the identical structure devoid of smoke vents. In the case of hall lacking the smoke vents the temperature of the fire plume reached level allowing for flare up and continued combustion of the combustible materials gathered in the fire compartment, but the intensity of a fire was strongly affected by the lack of oxygen supporting combustion [6], as this oxygen could reach the fire only through the permanently open access gates relatively distant to the considered cross-section. Thus, in this case, the fire development scenario became typical for the ventilation driven fires and not, as will be in the case of the larger hall, fire driven by the availability of the combustible material.

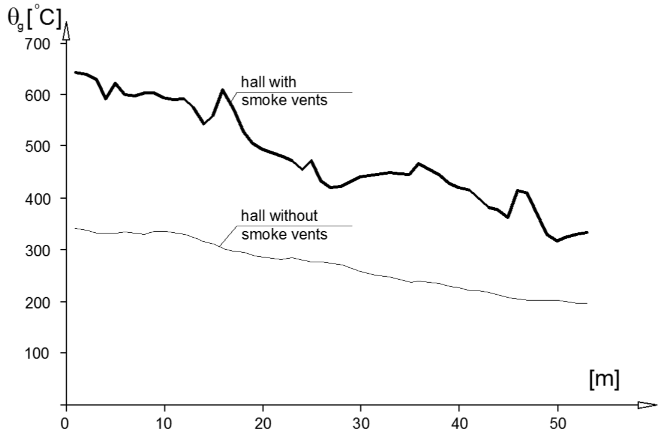

Fig. 4. Graphs of a fire plume temperature obtained after one hour of a fire exposure in the authoritative cross-section of the smaller of analysed halls (depicted in Fig. 1b), at the height of 4.00 m above the floor level [3]

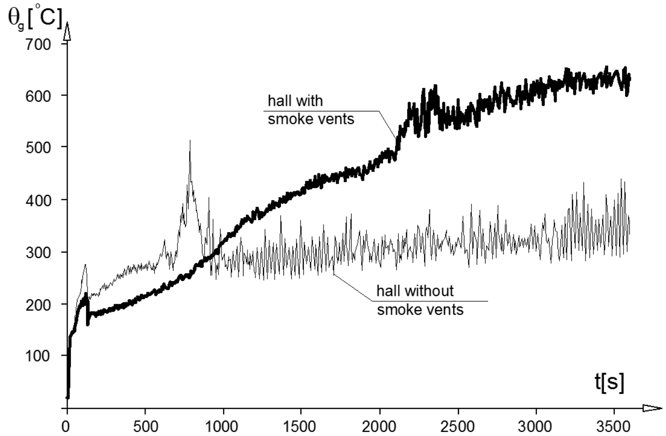

Fig. 5. Evolution of a fire plume temperature during the fire, obtained for the smaller hall at the distance of 3.00 m from the initial fire axis and at the height of 4.00 m above floor level. In the case of the hall with operating smoke vents, a monotonous increase of the averaged measured temperature is observed during the whole analysed fire exposure. For the hall devoid of smoke vents the fire intensity limitation by the lack of available oxygen is visible, and results in the fire development scenario typical for fires driven by ventilating conditions [5]

This conclusion is corroborated by the analysis of Fig. 5, where the temporal changes of a fire plume temperature are depicted as measured at the distance of 3.00 m from the initial axis of a fire representing the fire source, at the height of 4.00 m above floor level. As one may easily observe, in the case of a hall equipped with smoke vents the temperature averaged in the random combustion process increased monotonously during the whole hour of analysed fire exposure. The results obtained for the same hall, but devoid of smoke vents, seem to indicate a completely different fire development scenario. This time the fire plume temperature measured could not reach the sufficiently high level and subsequently increase, similarly to the scenario considered before, because of limited oxygen availability. Due to the temporary damping of a fire this temperature initially rapidly decreased, and subsequently stabilised at the level resulting from a state of equilibrium conditioned by the effective ventilation of a fire zone.

4. Scenario B – fire development simulated in a higher large-area shopping hall with the same stacking height

With respect to the larger of the analysed halls, it was assumed that its plan dimensions are 135.00 m by 60.00 m. The height of the hall is at the same time increased and reaches 7.00 m (Fig. 6). The location and size of access gates are analogous to those assumed for the smaller hall. The only difference lies in the fact that there are three instead of two smaller gates in the longer wall (Fig. 6). The sheathing of walls and roof, the stacking height on the racks and the initial conditions of the simulated fire are identical to those described for scenario A.

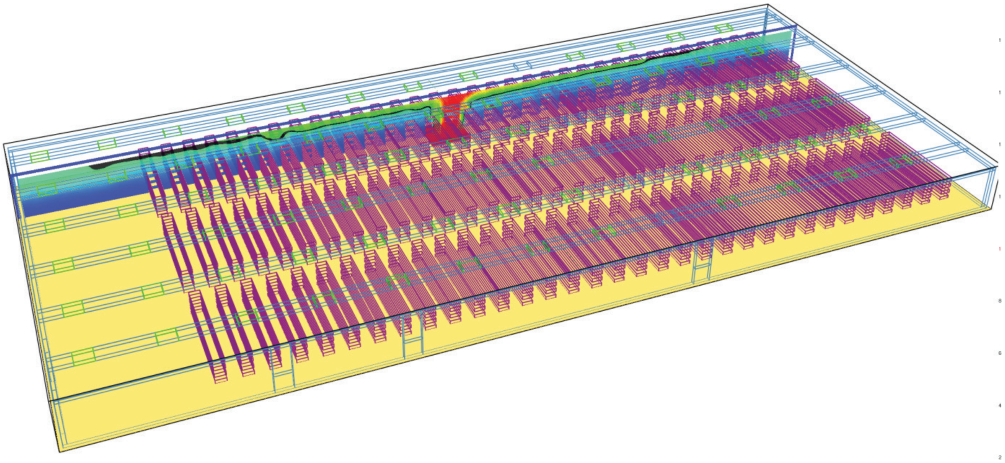

Fig. 6. Scheme of the larger of the analysed shopping halls. The location of storage racks used to hold paper materials constituting the fire load is indicated. The locations of smoke vents are indicated as well. The cross-section oriented parallel the longer wall is also shown here, for which the map of a fire plume temperature has been determined in selected time intervals [3]

The fire development scenario simulated by us earlier for the smaller of the considered halls is not typical for the halls of the same type, but having a larger area. Should the fire zone size be sufficiently large (this is understood as not only the surface area, but also the volume of the hall) the probability of a fire reaching the fully developed stage becomes negligibly small, as for such an event to occur a gathering of combustible materials exhibiting sufficiently high combustion efficiency, and distributed evenly over the whole fire compartment would have to be accompanied by sufficiently favourable ventilating conditions, determined by the existence of numerous and big enough permanently open gate openings in the near vicinity of the fire. Thus the analysis performed in this paper seems to indicate that for large-area shopping halls the properly numerically modelled localised fire would be more appropriate. This statement is in full agreement with observations presented by the authors in [2].

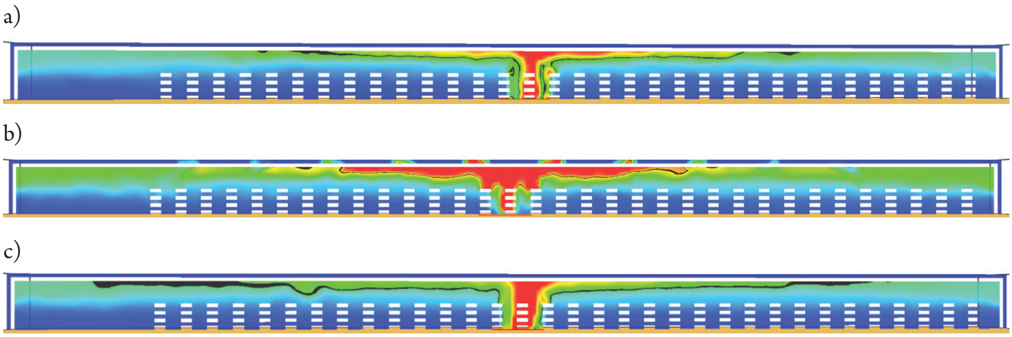

Fig. 7. Exhaust plume gas temperature maps obtained after 60 minutes of a fire exposure in the case of a larger hall considered in fire scenario B, including: a) results for the hall with operating smoke vents, obtained for the cross-section located between vent axes, b) results for the hall with operating smoke vents, obtained for the cross-section located along vent axes, c) results for the hall devoid of any smoke vents [4]

Detailed analysis of a fire plume temperature, similar to those depicted above in Fig. 2, but this time obtained after 60 minutes of a fire exposure and related to the authoritative cross-section specified for the larger of the considered halls, of the scheme depicted in Fig. 6, completely corroborates this opinion. The appropriate maps are depicted in Fig. 7, at the top for the hall with operating smoke vents, i.e. in Fig. 7a for the cross-section localised between the vent axes (the location exactly as depicted in Fig. 6), and in Fig. 7b for the cross-section localised along the vent axes, and at the bottom, in Fig. 7c, for the identical object but devoid of any vents. This time the 100°C fire plume temperature isotherm is depicted in black.

The comparison of maps depicted in Fig. 7 with corresponding maps depicted above in Fig. 2 should be begun with the reminder that the second hall is substantially higher (7.00 m) than the first one (4.50 m). The assumption that the stacking height of combustible materials is kept the same in both halls and equal to 3.50 m, results in a substantial difference in the volume of the open space between the top of storage racks and the ceiling of the hall. Those 3.50 m of empty space below the ceiling kept the fire modelled for the whole 60 minute fire exposure time from developing into the stage of a fully developed fire. The thickness of the fire plume below the ceiling, even after one hour of intensive fire action, proved to be too small to ignite the combustible materials stored on the racks below in the nearest vicinity of the source of a fire. With such a fire development scenario the activation of smoke vents did not substantially affect the temperature of air just above the floor, and thus did not affect the evacuation time available for the occupants. The conclusion of the localised character of the fire attributed to its development after 60 minutes of fire exposure seems to be corroborated by the fire plume temperature values obtained after several periods of duration in the cross-section of the considered hall, but this time 6.00 m above the floor level. These maps are analogous to the maps depicted in Fig. 3 for the smaller of considered halls. The first group of maps depicted below pertains to the hall with operating smoke vents. These maps are presented in Fig. 8. The second group refers to the analogous hall but devoid of any flaps. The maps of this type are depicted in Fig. 9. The comparison of maps depicted in Fig.8d and 9d indicates a slightly larger area affected by the fire in the hall devoid of vents when compared to the hall equipped with vents, which did activate during fire, but this difference seems to become marked only after one hour of fire duration, and in addition seems to be qualitatively and quantitatively inconsequential with respect to the safety warranted to the users of the considered structure.

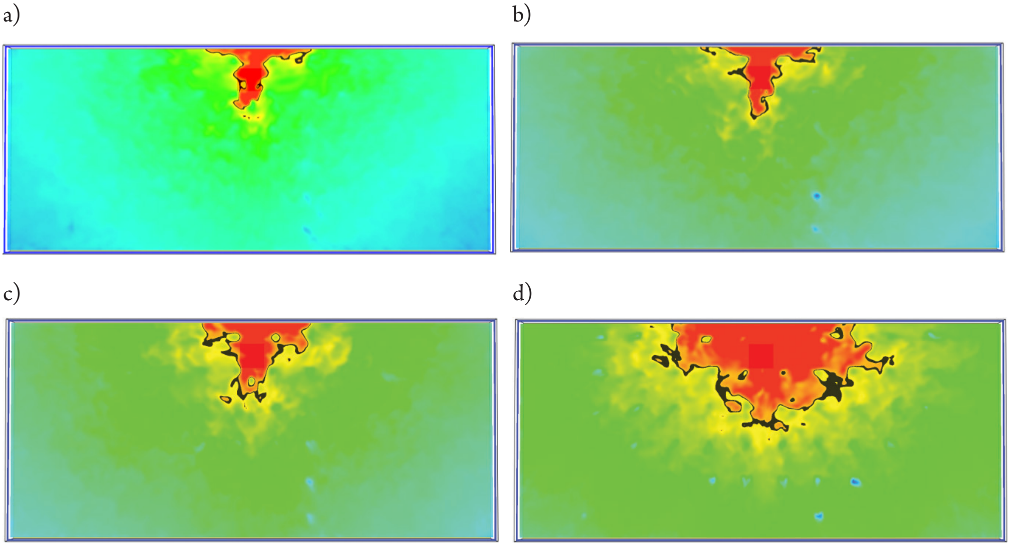

Fig. 8. Fire plume temperature maps obtained in the cross-section of the considered hall (fire scenar-io B), at the height of 6.00 m above the floor level, under the assumption of smoke vents operating correctly, after: a) 10 minutes, b) 20 minutes, c) 30 minutes, d) 60 minutes of fire exposure, respec-tively. The isotherm depicted in black corresponds to the fire plume temperature of 100°C [4]

An additional confirmation of the localised fire action observed in scenario B after 60 minutes of fire exposure is visible after the analysis of a fire plume temperature distribution obtained in the cross-section of the larger hall indicated in Fig. 6, at the height of 6.00 m above floor level. This distribution is depicted in Fig. 10. The graph of temperature forecast for the case of a hall with operating smoke vents is accompanied there with the graph of temperature forecast for the hall devoid of vents. Undoubtedly, in both cases, the maximum of temperature is reached in the direct vicinity of a fire source and diminishes rapidly with increasing distance from that source. The shapes of both graphs are thus substantially different than the shapes of the graphs depicted in Fig. 4, obtained for the smaller of the considered halls. Let us note, however, that that the difference between the results obtained for the larger hall equipped with operating smoke vents, and the same hall devoid of any vents, is mostly negligible.

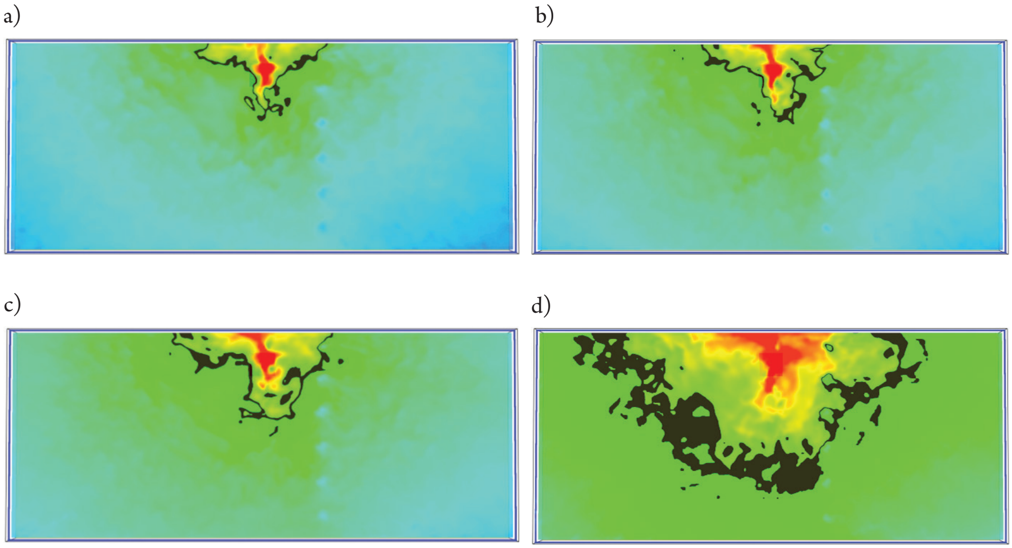

Fig. 9. Fire plume temperature maps obtained in the cross-section of the larger of considered halls at the height of 6.00 m above the floor level, under the assumption that there are no smoke vents, after: a) 10 minutes, b) 20 minutes, c) 30 minutes, d) 60 minutes of fire exposure, respectively. The isotherm depicted in black corresponds to the fire plume temperature of 100°C [4]

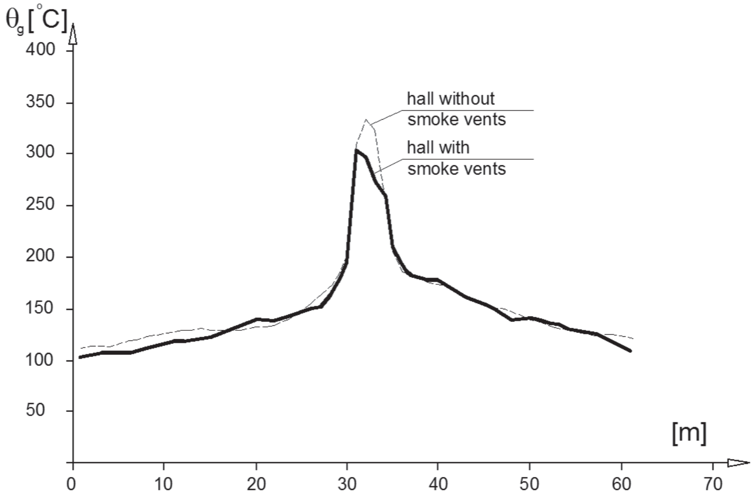

Fig. 10. Distribution of a fire plume temperature in the cross-section of the larger of considered halls at the height of 6.00 m above floor level, obtained for the hall equipped with operating smoke vents and for the other hall devoid of smoke vents, respectively [3]

The next graph depicted in this paper (Fig. 11) allows for a direct comparison of the fire plume temperature evolution at a point located 3.00 m off the initial axis of a fire, at a height of 6.00 m above the floor level. This comparison corresponds to the juxtaposition depicted in Fig. 5, where the analogous results obtained for the smaller hall are depicted. This time, the forecast fire plume temperature increased monotonously regardless of the smoke vents. Thus, there was no question of the possible fire suppression. Such suppression is in any way difficult in such a large volume of the fire zone. The temperature of the fire plume increased in the current case relatively slowly. A quicker increase in the fire plume temperature would have to be a result of a cascading ignition of combustible materials stockpiled on the racks more and more distant from the fire source. Therefore, if in the presented simulation the conditions were lacking for this type of increasing fire development intensity, it must mean that only the energy released in the localised fire, affecting the limited volume of the fire zone, contributed to the increase in the exhaust gas temperature.

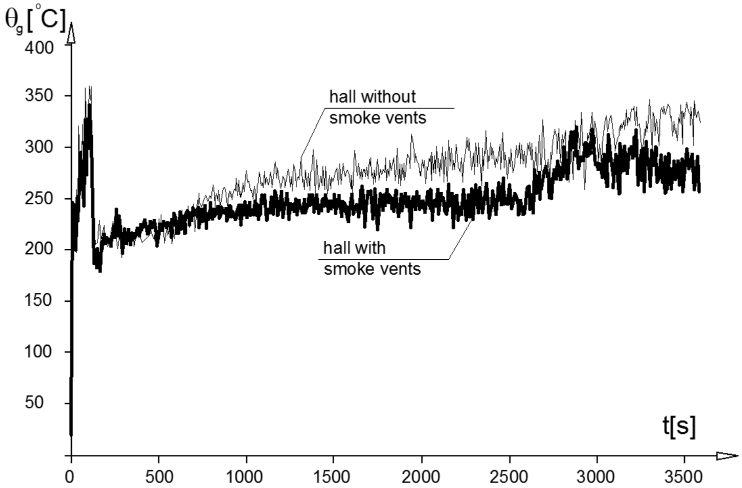

Fig. 11. Changes in the exhaust plume gas temperature inside the considered hall in a location at the distance of 3.00 m from the initial fire axis obtained for the bigger hall, at the height of 6.00 m above floor level – B fire scenario [5]

5. Scenario C – fire development simulated in the large-area shopping hall with an increased stacking height

Scenario C differs from scenario B analysed for the large hall in chapter 4 of the current paper only in that the stacking height of the combustible materials has been changed from 3.50 m to 5.50 m. The spatial distribution of the racks has not been changed in any way. The parameters determining the ignition chances of goods placed on these shelves have not been changed in any way as well. This means that, in this case, the volume of empty space above the racks, where the fire plume may freely propagate, is much more restricted. At the same time, due to the added amount of combustible materials, the fire load in the fire compartment has been substantially increased. Because of that, even at the same power of a fire source initiating the fire as in scenario B, in scenario C, a local ignition of the combustible materials stockpiled in the hall is much more probable and, in turn, the cascading propagation of a fire to the neighbouring storage racks.

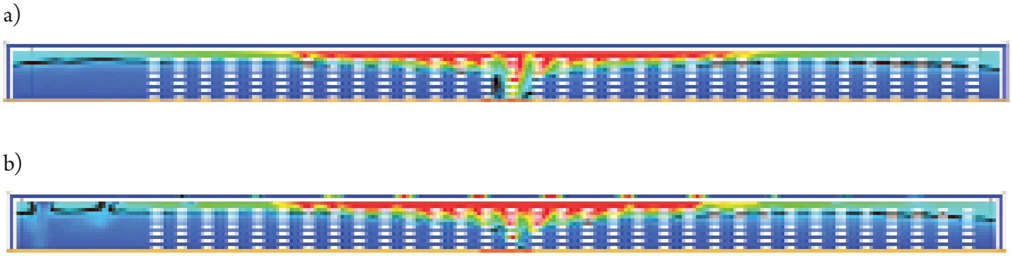

Fig. 12. Exhaust plume gas temperature maps obtained after 60 minutes of fire exposure in the case of a larger hall equipped with smoke vents, considered in C fire scenario, including: a) results obtained for the cross-section located between the smoke vents, b) results obtained for the cross-section located along the smoke vent axis

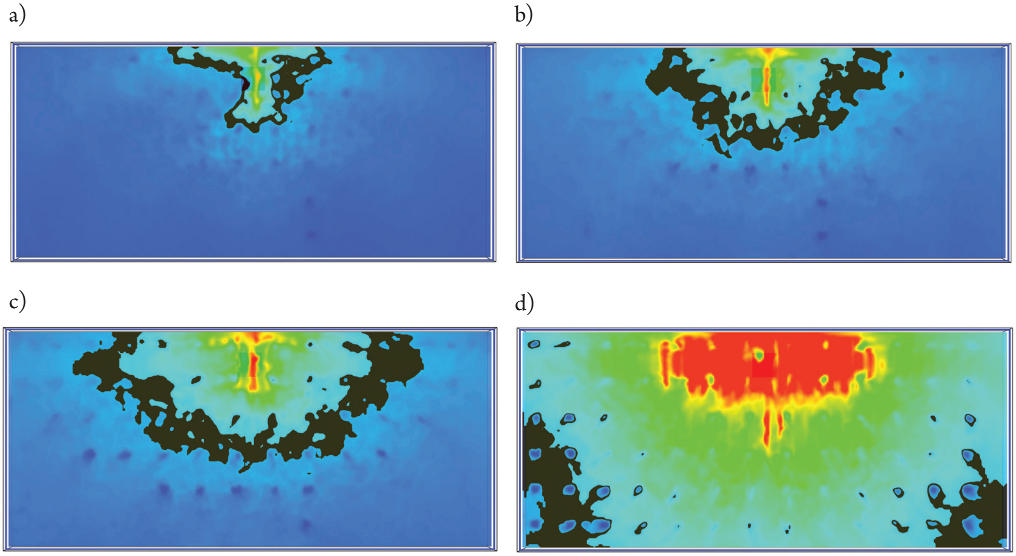

Fig. 13. Fire plume temperature maps obtained for the C fire scenario in the cross-section of the larger hall at the height of 6.00 m above the floor level, under the assumption that the smoke vents are present and operating, after: a) 10 minutes, b) 20 minutes, c) 30 minutes, d) 60 minutes of fire exposure, respectively. The isotherm depicted in black corresponds to the fire plume temperature of 100°C

In Fig. 12, the fire plume temperature maps are depicted for scenario C, after 60 minutes of fire exposure, obtained in the same cross-sections of the considered hall as before. These maps correspond to the analogous maps depicted in Fig. 7. The 100°C isotherm is depicted in black in those pictures as well. The map from Fig. 12a refers to the cross-section located between the smoke vents, while the other one, from Fig. 12b, refers to the cross-section located along the axes of smoke vents. The scenario for a hall devoid of smoke vents has not been considered here.

The maps depicted in Fig. 12 are accompanied by the distributions of fire plume temperatures determined for the C fire scenario, and referred to the horizontal cross-section of the considered hall. These maps are analogous to the maps depicted above in Fig. 9 and referring to the B fire scenario. These maps are gathered together in Fig. 13. One may easily observe that in the C fire scenario, in spite of the retarding action of smoke vents, just after 20 minutes of fire exposure, the fire engulfed a large area of the hall. Thus, its progress was much faster than in the case identified for the B fire scenario. Furthermore, one may see in Fig. 9 that even without any smoke vents, in the B fire scenario, the fire remained at the stage of a localised fire restricted to a relatively small area even after 30 minutes of fire exposure.

Another substantial difference between the fire plume temperature values obtained during the simulation of a fire conforming to the assumptions of scenario C and scenario B in the same cross-section is clearly visible in Fig. 14. A comparison with Fig. 10 shows that here this temperature is much higher than before. Still, however, the simulated fire retained the characteristics of a localised fire, with a clearly observable extreme temperature at the axis of the fire indicating the location of the initial fire source.

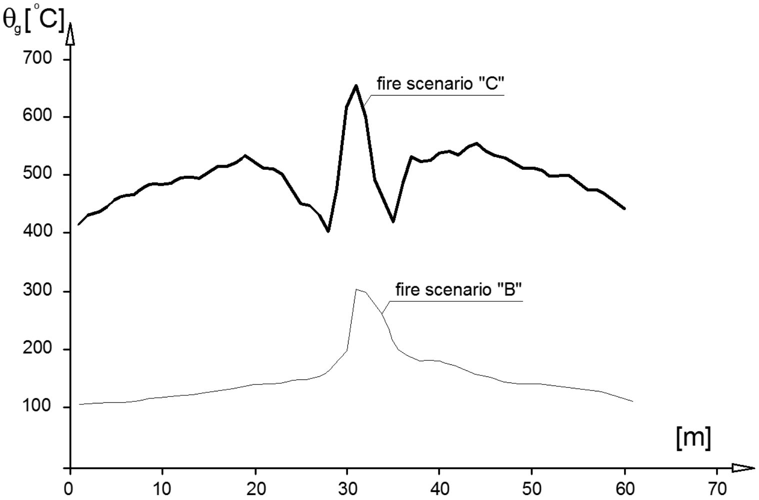

Fig. 14. Fire plume temperature distribution in the cross-section of the larger of considered halls, at the height of 6.00 m above the floor level. The bottom curve has been obtained for scenario B, with operating smoke vents. The top curve refers to the distribution determined for scenario C, also under the assumption of operating smoke vents

The next important difference in the fire development, clearly distinguishing scenario C from scenario B, lies in the different course of the temperature fluctuations of the fire plume, identified at the distance of 3.00 m from the vertical axis indicating the location of the original source of a fire. The curves specific to the compared scenarios are juxtaposed in Fig. 15. This figure corresponds to the analogous one depicted above in Fig. 11. While in the case of scenario B, the activation of smoke vents did not substantially affect the fire development, as its power proved to be insufficient to ignite the combustible materials stockpiled on the racks adjacent to the initial fire source; this was not true in the case of scenario C. In scenario C, the fire developed rapidly, in general, in a monotonous manner, and the operating smoke vents ensured an unlimited supply of the fire supporting oxygen. Hence, there was no question of the possible fire suppression due to the insufficient availability of oxygen.

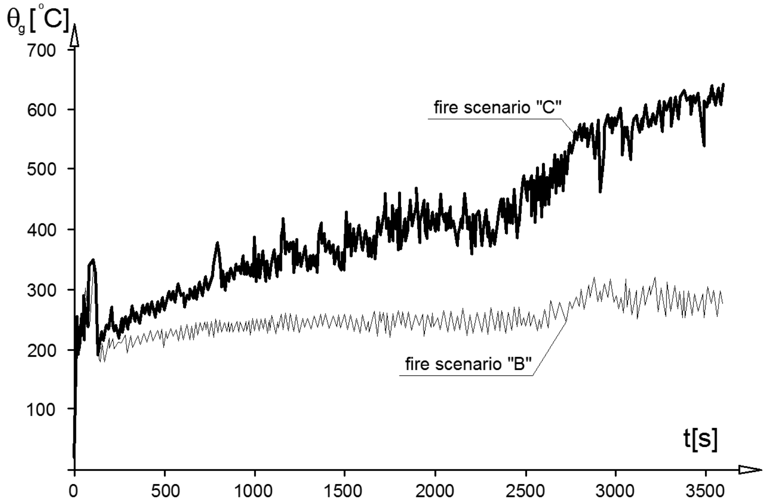

Fig. 15. Changes in the exhaust plume gas temperature inside the considered hall in a location at the distance of 3.00 m from the initial fire axis obtained for the bigger hall at the height of 6.00 m above floor level – comparison of results obtained after simulation of fires developing under assumptions of scenarios B and C

6. Concluding remarks

The conducted analyses unequivocally indicate that in the case of large-area shopping halls, the fully developed fire commonly assumed as the authoritative for evaluation and verification of fire safety level warranted to the users may not be so. In many practically important situations, a localised fire with limited intensity and affected zone may be better justified. Parameters of the model are usually determined by the hall's geometry, known a'priori, but also the hall's real ventilation capabilities in the case of fire initiation, as well as quality and quantity of the accumulated merchandise representing potential fuel and constituting the fire load. In the authors' opinion, the numerical simulation of fire development, performed within the framework of the FDS computer code, presents an efficient computational tool allowing for a reliable prediction of the most unfavourable, but at the same time probable scenario, which may be realised in the given design situation.

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