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Numerical Simulation of the Airport Evacuation Process under Fire Conditions

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ABSTRACT

The aim of this study was to determine the rate of formation of selected fire threats in the terminal of a local passenger airport and to estimate the time for safe and effective evacuation of occupants of the terminal covered by fire. To achieve this goal, the PyroSim and Pathfinder software was used. The essence of the studies was to determine the time of effective and safe evacuation at two variants of the ignition source and differentiated configuration of the computational mesh and dimensions of elements (a total of four calculation scenarios). Obtained results from computer simulations using Pathfinder indicate that the determined evacuation time for the assumed assumptions and fire scenarios was 46 s for an evacuation of 50 people and 82 s for an evacuation of 600 people. From the point of view of safety of the terminal under analysis, especially safe evacuation under fire threat conditions, the critical parameters that were mainly focused on were the temperature distribution (in quantitative terms) in the immediate vicinity of the fire source and the maximum smoke level (in qualitative terms). Simulations with PyroSim proved that in the adopted calculation scenarios (variants), the value of temperature and the degree of smoke will not reach a level threatening the safe and effective evacuation. In other words, comparisons of the simulation results give reason to conclude that in the building in question, users can safely evacuate outside the building before the critical fire parameters are exceeded.

Keywords: airport evacuation, simulation of evacuation, simulation of fire development.

INTRODUCTION

Emergency situations at airports are becoming increasingly common as air transport develops. Therefore, it is extremely important to prepare for the effective evacuation of people from the threatened area in order to minimize the negative effects of various adverse events. In recent years, tools for computer simulation of the evacuation process and simulation of the spread of various types of threats, with particular emphasis on the development of fires, are increasingly used for this purpose.

Airports vary in size and in the specific features of their architecture and equipment. Some of them are small facilities serving the local air traffic, while others are huge complexes providing international communication. All of them have one thing in common – they are exposed to emergency situations threatening the health and lives of many people. In just a few years, there have been dozens of cases when a passenger terminal filled with people had to be evacuated due to a threat to their safety [1]. In aviation industry, safety issues are one of the most important areas of interest, which is constantly being researched and improved. The use of the latest technological solutions in the field of simulation of evacuation processes significantly helps in planning the course of emergency situations taking into account practical, economic and safety aspects. Computer tools also help to evaluate architectural solutions, equipment and evacuation procedures from the perspective of safe and effective evacuation.

Individual human behaviours during the evacuation process may change depending on the

surrounding conditions. This means that human behaviour does not only depend on the personal characteristics of the individual, but also on the environment in which the individual is located, i.e. the architectural characteristics of the building and the type of emergency situation (fire, earthquake, etc.) [2].

The features of architecture and infrastructure of the evacuated building (size, elements of buildings, size and shape of rooms, location of exits and graphic information) as well as human interactions forced by them have a direct influence on the course of evacuation [3]. Also the degree of filling the building with people is an important factor of influence. When studying the evacuation process, it should be taken into account that the number and distribution of people in each room of the building affect the estimated evacuation time and procedures of evacuation [4].

In an emergency situation, the ease with which the correct escape route can be found has a huge impact on survivability under threats. The choice of the evacuation route is determined by the level of spatial orientation of the evacuee, architectural diversity, presence and visibility of evacuation signs, etc. [5]. Unfortunately, people usually choose evacuation routes leading to known exits that are used in the daily operation of the airport terminal, and rarely choose exits intended only for evacuation (not used for human traffic in normal use). Studies have shown that emergency exits are used during evacuation when they are open and the distance to the main exit (in daily use) is twice the distance to the nearest emergency exit [5].

Of course, the characteristics of the existing threat always affect the behaviour of passengers and personnel of airport terminal and sometimes affect the physical characteristics of the facility itself. For example, an explosion and earthquake can destroy the infrastructure or part of a building and block escape routes and exits. The impact of fire on evacuating people is more complex due to the high temperature and the spread of smoke. The effect of high temperature on human organism depends on the duration of exposure, current humidity, characteristics of clothing of individual people [6]. Smoke is also a very strong informational stimulus that something bad is happening and one should leave the endangered area as soon as possible. The presence of smoke slows down or prevents the evacuation of people only after some time of its influence on their organisms, whereas

in the first phase of its appearance it stimulates their reaction making it more intense [3]. Some people are inclined to move in smoke, correcting the escape route or retreating only, when they lose visibility, have difficulty breathing or are overwhelmed by a sense of fear. In the absence of visibility, people often move along the walls of the building. In some cases, burning of specific materials may release poisonous gases leading to unconsciousness and death [7].

The protection of human occupants during a fire is one of the primary design objectives of any fire safety system of a building. The first studies on this topic were carried out theoretically and with the use of limited-scale experiments [8, 9]. When fire occurs in a large airport terminal hall, in the first phase the flames and smoke spread more vertically than horizontally to the adjacent spaces of the building. Since the movement of smoke forced by the development of a fire depends on many different factors, it is difficult to illustrate the development of this threat by small-scale tests. Hence, full-scale tests of smoke propagation have been started for buildings with large internal volume [10–16].

According to statistics compiled by the "American Fire Protection Association", the cause of death during a building fire is poisoning and suffocation with an overall ratio of 80% due to smoke and toxic products of combustion, 13% from high temperature and 7% from other causes [17]. Hence, when analysing the evacuation conditions from the airport terminal, it is necessary to consider the evacuation conditions of people, taking into account the impact of the above-mentioned fire effects. Studies on evacuation from different types of buildings can be found in the literature, e.g.: Sun et al [18] conducted a numerical simulation of fire spread in conjunction with the evacuation of people from a school building. Song et al [19] studied the problems of fire extinguishing and human safety in an airport terminal. In terms of quantitative research, Chen [20] conducted an analysis of the dynamics of fire development and numerical simulation of passenger evacuation from a subway station, giving the determinants of safe evacuation of passengers. In turn, Liu et al [21] simulated the evacuation of people from a highrise building during a fire. The very interesting study from the point of view of the authors of this paper was published by Li and Zhang, [22] in which the study of fire propagation and

evacuation of people from a burning student dormitory building was carried out with usage of FDS and Pathfinder software applications. In this study, an interesting combination of the results of fire development and the resulting combustion products with the simulation of human evacuation was used, through which the influence of the impact of fire products on the conditions and effectiveness of human evacuation was taken into account.

In this paper, it was also decided to use two types of simulation software, i.e. Pathfinder to study the evacuation of people from the terminal of local passenger airport and PyroSim to study the dynamics of fire development in this facility. In addition, the results of numerical analysis were presented for four fire scenarios (computational variants), which took into account the differentiated manner of the flame spread and the associated dynamics of fire development. This was possible through the theoretical determination of HRR curves and THR values for the analysed computational domain and a specific computational variant.

NUMERICAL MODELS

The subject of numerical analysis was a model of three-storey passenger terminal of the airport in Modlin near Warsaw with the usable area of 12,066.3 m² and cubic capacity of 75,900 m³, presented in Figure 1.

The presented model consists of 305 rooms and zones arranged on two floors. The dimensions

of the model are 174.2×47.2 m. The model does not include level -1, which is inaccessible to passengers using the terminal. The model of the facility was created with using modellers of Pyro-Sim and Pathfinder software. This geometry was used as a basis for numerical analyses for fire and evacuation models adopted.

Analysis of fire effects, realized on the basis of the basic CFD equations [23] assumed the investigation of thermal effects - in the form of temperature changes in the immediate vicinity of the fire source - and the degree of smoke. For this purpose, computer simulations of 4 computational variants classified into two model groups A and B were performed. Within the group A, 2 research variants were performed, related to the flame propagation on the front surface of the fire simulator with dimensions of $1 \times 1 \times 0.5$ m located in one of the corners of the terminal (Figure 2a and 2b), in accordance with guidelines adopted in ISO 9705 [24]. Two subsequent variants in group B assumed the flame propagation along a vertical wall with dimensions of 8.6×4.2 m, which such wall constituted one of the internal building bulkheads of the terminal catering partition (Figure 2c and 2d).

The special feature of model A1 was the implementation of the scenario in which at the beginning of the simulation, the fire is covered by the entire combustible surface. The main feature distinguishing variants A2, B1 and B2 was the software consideration of fire propagation along the combustible surface from the point of fire initiation. In the case of models A2 and B1, the spread of the



Fig. 1. Three-dimensional model of the passenger terminal of the airport in Modlin



Fig. 2. Fire source location (a) and temperature reading point distribution (b) for group A models and fire source location (c) and temperature reading point distribution (d) for group B models

flame to adjacent layers of the already developing fire occurred in the moment of reaching the ignition temperature of gaseous products of thermal decomposition equal to 300 °C. In model B2 the adopted flame propagation velocity for pine wood was $3.3 \text{ mm} \cdot \text{s}^{-1}$ [25].

Regardless of the course and location of the fire source, the dynamics of its development was modelled by giving the initial value of HRR parameter (Heat Release Rate) for laminated wood-based panel equal to 500 kW·m⁻² [26]. Assumed simulation duration was 120 s.

On the basis of the obtained geometrical model, computational meshes for numerical analyses were defined. In each of the analysed model variants were used rectangular finite elements of non-structural meshes. Due to the large linear dimensions of the analysed terminal in comparison with typical dimensions of meshes used in simulations of fires in public buildings, in the first stage it was necessary to perform a series of pilot simulation studies carried out for the target values of HRR and simulation time, and arbitrarily adopted dimensions of meshes. Obtained results became the basis for the evaluation of the maximum volume covered by the smoke. Analysis of the obtained results enabled identification of those parts of the geometric model which did not require division into finite elements. In addition, on the basis of analysis carried out, it was possible to identify areas where it was reasonable to locally increase the degree of compartmentation of the computational domain with finite elements - especially in the immediate vicinity of fire sources. Local densification was to increase the accuracy of reading the values especially temperature in selected points of the domain. Ensuring the continuity of the values of monitored parameters - mainly the values of temperature and the degree of smoke - on the border of meshes, was performed by the mutual overlapping of nodes of neighbouring meshes. As a result of the analysis of pilot tests, it was possible to determine the number and parameters of calculation meshes used in the case of four basic simulation variants A1, A2, B1 and B2. A screenshot presenting the computational domain with a division into finite elements is presented in Figure 3 (in this figure, Roman numerals denote consecutive meshes within particular model variants), while the related parameters of computational meshes are presented in Table 1.



Fig. 3. Screenshots showing the computational meshes for the analysed model variants A1 (a), A2 (b), B1 (c) and B2 (d)

Preparing a 3D model for evacuation simulation in Pathfinder software came down to importing the CAD model of the terminal presented in Figure 1.

Each time, within the scope of conducted simulations, a variable-based and control-based mathematical model of the movement of people during evacuation was performed. The main concept of this type of model is the assumption, that for each evacuating person, in each step of the simulation, momentary directions of movement are chosen so that their individual evacuation time is as short as possible. Two simulation variants were tested, assuming the evacuation of 50 people (variant E1) and 600 people (variant E2). A screenshot presenting the distribution of evacuated people in the above variants is presented in Figure 4.

Table 1. The parameters of computational meshes in the model variants A1, A2, B1 and B2

Coloulation variant	Mach number	Dimensions of the mesh	Quantity of elements	
		W x L x H [m] *		
A1	I	11.6 × 10.8 × 11.2	2,880,836	
	II	164 × 48.8 × 11.2		
	III	11.6 × 29.6 × 11.2		
	IV	11.6 × 8.4 × 11.2		
A2	I	11.6 × 3.6 × 4.4		
	II	11.6 × 29.6 × 4.4	2,906,559	
	III	11.6 × 15.6 × 4.4		
B1	I	11.6 × 8.4 × 11.2	2,146,396	
	II	11.6 × 10.8 × 11.2		
	III	11.6 × 29.6 × 11.2		
	IV	78 × 48.8 × 11.2		
В2	I	11.6 × 8.4 × 11.2		
	Ш	11.6 × 10.8 × 11.2	11,968,348	
	III	11.6 × 29.6 × 11.2		
	IV	78 × 48.8 × 11.2		

* W-width, L-length, H-height





Fig. 4. Screenshot showing the example of the arrangement of evacuated people at level zero in the variant E1 - 50 people (a) and E2 - 600 people (b) with the marked forbidden exits: I - evacuation exit prohibited for travellers

Taking into account the usable area of the terminal and the number of evacuated people, the average density of evacuated people in the facility for variant E1 (50 people) is 0.005 people/m², while for variant E2 (600 people) it is 0.06 people/m². The common part of both variants is basic division of evacuated people into two groups: employees and travellers. These groups are further differentiated by age and/or gender due to differences in average travel velocities and locations during evacuation command. The division between employees and travellers is due to the use of different

Variant -	Evacuation speed [27]	Characteristic cross-sectional dimension [27]	Height	Number of persons				
	m·s⁻¹	cm	m	-				
Travellers								
Child	0.9	31.72	0.9	E1: 0				
				E2: 11				
Woman	1.15	36.74	1.7	E1: 0				
				E2: 229				
Man	1.35	41.61	1.8	E1: 0				
				E2: 229				
Senior > 60	0 0	29.76	1.7	E1: 0				
	0.0	30.70		E2: 15				
Employees								
Woman	1.15	36.74	1.7	E1: 25				
				E2: 42				
Man	1.35	41.61	1.8	E1: 25				
				E2: 66				
Evacuation	0	41.61	1.8	E1: 0				
coordinator	2			E2: 8				

Table 2. Personal profiles of variants E1 and E2

evacuation paths and access to selected areas only for employees located in the terminal. Another restriction consisted in blocking the possibility of evacuation of a given group of people through a selected emergency exit marked separately in Figure 4. The list of basic parameters which characterize both groups, with special attention paid to personal profiles of people included in these groups, is presented in Table 2. The distinguished personal profile from the list presented in Table 2 is the employee – evacuation coordinator due to an additional evacuation limitation. It consists in starting the evacuation by this profile only when each of the other profiles is outside the simulation domain of the analysed terminal.

RESULTS AND DISCUSSION

Undoubtedly, one of the most important factors affecting the effectiveness of safe evacuation is the degree of smoke and temperature in the area covered by fire, especially in its first phase. This is due to the fact that the smoke and / or increase in temperature are factors that trigger human defence mechanisms that consist in initiation of the process of evacuation from the place covered by fire. Creation of other fire threats, i.e. creation of harmful to human health gaseous products of combustion: CO2, CO, NO2, etc. take on the importance of critical parameters for longer evacuation times covering the successive phases of fire development. The above is the justification for the selection of a set of critical parameters: the degree of smoke and temperature changes, and assumes their sufficiency within the framework of conducted analyses for a time not exceeding 120 seconds. Thus, most of the attention was devoted to the analysis of smoke propagation and to the observation of areas where the temperature exceeds the accepted temperature of 60 °C according to PD - 7974-6: 2019 [28].

The results of numerical analyses of fire simulation in the Pyrosim software application

As mentioned above, from the point of view of safe operation of the terminal under analysis, and in particular safe evacuation under fire threat



Fig. 5. Temperature changes over time for the model variants A1 (a), A2 (b), B1 (c) and B2 (d) analysed

conditions, the critical indexes on which the main attention was focused were the temperature distribution (in quantitative terms) in the immediate vicinity of the fire source and the maximum smoke level (in qualitative terms). Additionally, for each fire scenario the temperature of 60 °C was adopted as a criterion of effective and safe evacuation, and for this temperature the distribution of isothermal surfaces was analysed. Within the framework of the present study, the distribution of other fire effects has not been analysed - such analyses will be the subject of separate considerations.

Temperature changes in time in selected points of the domain in close proximity to flammable surfaces - see Figure 2c and 2d - are presented in Figure 5, while the distribution of 60 °C isothermal surfaces is shown in Figure 6. The recorded maximum temperature values indicate the dominant character of the component of convective heat exchange in comparison with the radiation component. Since maximum temperatures occur for those points which were located above the fire source. This is directly confirmed by the distribution of the monitored iso-surfaces. Analysis of their courses for 120th second of simulation shows that in case of variants A1 and A2 the influence of temperature on ability of effective and safe evacuation is limited to about X = 12 m from the central point of burning surface. At the same time this value for group B models is X = 7 m.

Moreover, using the information on iso-surface displacement in time, the maximum velocities of vertical movement of the 60 °C front were estimated; they are respectively:

- ca. 1.5 m·s⁻¹ in case of model A1 and A2,
- ca. 2.1 $m \cdot s^{-1}$ in case of model B1 and B2.

The obtained results confirm the information contained in the literature that high temperature is not the main threat to the evacuation process in the case of large-scale facilities such as the airport.

Figure 7 presents the results of computations presenting the smoke area of the computational domain in 120th second of simulation for 2 simulation variants: A1 and B1. The selection of the presented results is justified by the fact that in above-mentioned two computational variants after 120th second of simulation the area covered by fire has taken the maximum of flammable surfaces defined in domain. This in turn translates into the generation of a maximum amount of smoke.

Moreover, the estimation of the velocity of the vertical movement of smoke was performed. As a result, these velocities were found to be:

- ca. 1.4 $\text{m}\cdot\text{s}^{-1}$ in case of model A1,
- ca. 2.0 $\text{m}\cdot\text{s}^{-1}$ in case of model A2,



Fig. 6. Course of isothermal surfaces 60 °C for analysed model variants A1 (a), A2 (b), B1 (c) and B2 (d) for 120th second of simulation



Fig. 7. Screenshots showing smoke in the computational domain at 120th second of simulation for variants A1 (a), (b) and B1 (c), (d)

- ca. 2.0 m·s⁻¹ in case of model B1,
- ca. 1.3 $\text{m}\cdot\text{s}^{-1}$ in case of model B2.

Taking the geometric centre of the fire area as a starting point, the results of analyses of both models were compared. On this basis, it was found that the more unfavourable situation, from the point of view of safe evacuation, occurs in the case of model A1. This is due to the existence of a local increase in the degree of smoke associated with the construction in the form of canopy over the horizontal combustible plane, which blocks the flow of vertical smoke stream over the fire area (Figure 7b). It should be noted that a similar structure is present above the combustible surface in model B1, but in this case the area of the canopy is approx. 10 times smaller than the canopy area in model A1. As a result, for the 120th second of simulation in model A1, the zone with the highest degree of smoke density is located below the height of 2.7 m and includes the passenger area of the terminal. The effect of blocking the vertical smoke stream is also reflected in the formation of smoke in the ceiling zone. In model A1, a qualitatively noticeable increase in smoke density occurs above a height of H = 5.90 m ($H_{\odot} = 56\%$ of the maximum

terminal height). For comparison, the limit of the ceiling smoke zone for model B1 (Figure 7c) is located at a height of H = 7.7 m, i.e. $H_{\frac{6}{2}} = 73$ % of the maximum height.

The analyses also included an assessment of the maximum smoke extent in the horizontal plane (Figures 7a and 7c). In model A1 for 120 seconds of simulation, the smoke range reached $L_{\frac{9}{2}} = 23\%$ of the total terminal length, i.e. approx. 40.6 m, while for model B1 $L_{\frac{9}{2}} = 29\%$, i.e. approx. 51.2 m. However, it should be emphasized that the maximum range is related to the displacement of smoke layers located in the ceiling zone. In this case, the parameter $L_{\frac{9}{2}}$ takes the features of a critical parameter, from the point of view of safe evacuation, for times many times longer than those analysed in this study.

In order to complete the information concerning the course of fire, the course of HRR (Heat Release Rate) value was determined as a function of time, which is presented in Figure 8, as well as the calculation of total heat release THR (Total Heat Release) released during 120 seconds of simulation (Table 3) for each of analysed variants.

The obtained research results are particularly important for a specific group of



Fig. 8. Time course of changes in HRR values for the analysed model variants A1 (a), A2 (b), B1 (c) and B2 (d)

objects, which are airports. These are largescale facilities with a large ceiling space. Large space buildings tend to accumulate great amount of smoke and the smoke layer successively descends. Smoke production rate is determined by the scale of the fire source and heat release rate (HRR), which also has influence on the smoke layer rate of descend. So, in order to ensure sufficient time for occupants to evacuate from the fire scene before the smoke layer descends, one should: install smoke exhaust equipment, reduce the amount of flammable goods, decoration and furniture in the terminal space.

The results of evacuation simulation in Pathfinder software application

The most important result of the evacuation simulation was to obtain the course of changes

in the number of people staying on the terminal area as a function of the evacuation time. The results of the simulation are shown in Figure 9. The analysis of the results allows for the conclusion that the maximum evacuation time for evacuation variant E1 (50 people) does not exceed 46 seconds, while for variant E2 (600 people) it does not exceed 82 seconds.

The determined evacuation times are supplemented with screenshots presenting the evacuation paths shown in Figure 10. Their analysis allows to indicate the areas of local densities of people during evacuation. Thus it is possible to indicate the areas of the terminal where there is a potential risk of congestion, which reduces the efficiency of safe and effective evacuation.

For the areas indicated in Figure 10c and 10d local densities reach 1 person/ m^2 and 4 persons/ m^2 respectively.

Table 3. Total heat released THR during 120 s of fire simulation

Parameter	A1	A2	B1	B2
	10 ^{5.} kW			
THR	2.93	0.18	4.29	0.07







Fig. 10. Screenshot of escape routes for simulations E1 (a) and E2 (b) and selected areas of local congestion, indicated by arrows for variants E1 (c) and E2 (d)

It should be noted that the evacuation process simulation results for variant E1 have been positively verified on the basis of annual practical evacuation tests conducted on a group of 50 people in the analysed airport terminal.

CONCLUSIONS

As part of these analyses, four fire variants and two evacuation variants were simulated. In the case of fire analysis, the computation of the proposed variants was to check the impact of the

location of the fire focus on the conditions of creation of the selected fire threat. In addition, the impact of the number of evacuated people on the basic parameters of the evacuation, such as evacuation time, the determination of the evacuation paths and areas threatened by congestion during the evacuation, were also checked. As a result, we obtained information on fire and evacuation parameters for a large-size technical facility, which such parameters enable to draw conclusions on the possibility of conducting safe evacuation in a fire threat situation. Equally important result of the conducted analysis was the development of methodology and presentation of the concept of preparation of numerical models - especially computational mesh - of large-size facilities of critical infrastructure, thus contributing to the expansion of knowledge on the widely understood branch of simulation of safety threats caused by fire.

Qualitative analyses showed that the shape of the terminal and its considerable geometric dimensions contribute to a situation in which the maximum accumulation of smoke concerns the area under the ceiling and locally the volumes located below the built-in eaves. The scale of local but, as analyses have shown, also sub-ceiling accumulation of smoke results from the size of the horizontal surface of the canopy which blocks the movement of the vertical stream of smoke.

Quantitative analysis enabled us to determine the range of impact of elevated temperature. The data, obtained primarily from the temperature values read at selected points of the computational domain and from the distribution of the 60°C iso-surface, show that the greatest danger associated with the impact of thermal radiation concerns the passengers located in the radius of 7.3 m from the eruption for group A scenarios and 11 m for group B variants.

By comparing the results of qualitative and quantitative analyses, it was confirmed that the critical parameters for fire will not be exceeded in the passenger terminal during the designated evacuation times.

In addition to the practical aspect of the fire analyses carried out, HRR curves and THR values were determined, which allow for the fire dynamics to be reproduced for the analysed computational domain and a specific computational variant.

Fire analyses were complemented by evacuation simulations. In addition to numerical determination of most probable evacuation paths and areas of congestion, time required to evacuate all passengers from terminal area was determined. Results of computations enables us to conclude that evacuation time for passengers in variant E1 (50 people) does not exceed 46 seconds, while for variant E2 (600 people) it is no longer than 82 seconds.

The findings made on the basis of the results of fire simulations carried out, in conjunction with the results of fire simulations, indicate that for the analysed facility – Warszawa-Modlin airport terminal – there are conditions for safe evacuation in the event of fire threat. It should be noted that the evacuation process simulation results for variant E1 have been positively verified on the basis of annual practical evacuation tests conducted on a group of 50 people in the analysed airport terminal.

The results of the analysis proved that the use of modern software tools for simulating fire (PyroSim) and evacuation (Pathfinder) enables to conduct studies on various types of technical facilities. The developed modelling methodology can be implemented to simulate subsequent fire and evacuation scenarios. In this way, the software can contribute to improving the safety of existing facilities, but also provide a convenient engineering tool to support the design of new technical facilities.

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