



ABSTRACT OF PhD THESIS

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PERFORMANT SOLUTIONS FOR EMERGENCY VENTILATION IN THE METRO SYSTEMS

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1. Introduction

Metro networks are currently the best solution for internal urban transport. However, due to the growing number of passengers using this mode of transport, passenger safety issues are becoming more and more pressing. [1]

After the invention of electric locomotives, subway networks developed rapidly in most crowded cities, first in Europe and then worldwide, reaching at the beginning of 2018, according to data provided by the International Public Transport Union UITP - "L'Union Internationale des Transports Publics" [2], to have metro systems in 182 cities from 56 countries. The accelerated development of metro networks in recent years is best highlighted by the following data: since year 2000, 75 new metro networks have become operational, which means a 70% increase over previous years, most of which are built in large urban agglomerations in Asia.

Of the total number of subway stations built between 2008 and 2018, 87% are equipped with *platform screen doors* that prevent people from falling onto subway lines when the train is not in the station. Also, 77% of all automatic stations are equipped with such equipment, the global trend being to adopt this technology in most stations to be built [3].

A statistic on the nature of accidents on subway networks was compiled by Yan et al. [4], which found that 68% of accidents were fires and 12% explosions. Other types of possible subway accidents (train derailment, poison gas, power outage, flood or earthquake) have a very low probability of occurrence.

The deadliest fire in a subway tunnel is considered to have taken place on October 28, 1995 in Baku, Azerbaijan, killing 289 passengers and injuring 265 others (most of them intoxicated with smoke) [5]. Another disaster at a subway station occurred on February 18, 2003, at Daegu Central Station, South Korea [6]. In this case, the fire was started by a 57-year-old man who spilled 4 liters of gasoline in wagon no. 1 of a train approaching the station entrance. The total number of casualties was 142 people killed on the train, 50 asphyxiated on the 2nd and 3rd floors of the station while trying to escape, and 148 injured, including 10 firefighters.

Another subway incident with huge potential for casualties is the sarin attack that took place on the morning of March 20, 1995 in Tokyo [8], where 5 followers of an extremist religious cult broke with the tip of their umbrellas 5 bags containing 30% concentration sarin dust. Following the release of the sarin agent, 12 people (those closest to the perforated bags) died, but more than 5,500 passengers were affected, most of them with neurological sequelae for the rest of their lives [9].

Alan Beard and Richard Carvel investigated in the *Handbook of tunnel fire safety* [10] 75 incidents involving accidents followed by fires in railway or subway tunnels and concluded that most fires in underground tunnels (more than two-thirds of total number) were initiated as a result of an electrical or mechanical failure, only in a few isolated cases one can speak of human error. A dozen of them were intentionally caused by arsonists or followers of terrorist organizations who intended to generate as many victims as possible. The importance of fire prevention in underground metro construction is also underlined by the fact that the number of victims of accidents in this environment is much higher than the number of victims of accidents in car tunnels, although they are much more common. For example, the number of accident victims in Baku and Daegu far exceeds the total number of accident victims in car tunnels.

In this context, it should be noted that in the case of subway networks, the most serious problems related to passenger safety remain those related to the evacuation of smoke from fires (regardless of their nature) or toxic compounds (chemical or biological).

Investigations are also being made into how these emergency ventilation systems can be coupled with other systems that will lead to increased safety in the operation of subway networks. Such a system, which reduces the number of accidents and improves the evacuation conditions in case of fire, consists in installing automatic protection doors, known in the literature as PSD - platform screen doors or PED - platform edge doors, depending on the type of construction (the PED system is similar to the PSD system, only it does not reach the height of the ceiling). These systems create a physical barrier between the platform of the metro station and the train lines, thus reducing the risk of injuries through direct contact of passengers with the train, as well as the penetration of various objects on the train lines. In addition, by developing strategies / operating scenarios for these systems, coupled with ventilation (scenarios that take into account the positioning of the fire source), it is possible to control the spread of smoke and its correct evacuation, to limit the number of people affected and at the same time facilitate the intervention of rescue teams.

Therefore, the objective of the doctoral thesis is to develop numerical models that can verify the operation of ventilation systems in emergency situations in the most difficult scenarios and configurations, as well as to make predictions about the impact of the use of PSD systems in such situations.

2. The current state of knowledge in the field of doctoral thesis

2.1. Emergency situations in metro tunnels

To determine the effective solutions for tunnel ventilation in emergencies, the researchers are focused on determining the values of specific parameters for the development of fire in tunnels, such as critical ventilation velocity, backlayering distance, flame length, maximum smoke layer temperature and toxic gas concentration.

The critical velocity is the longitudinal ventilation velocity required to prevent the smoke layer from moving against the ventilation direction, and the backlayering distance is the length travelled by the smoke layer in the counter current of the longitudinal ventilation. In other words, in order to reduce the backlayering distance to zero, the longitudinal ventilation velocity in the tunnel had to be at least equal to the critical velocity.

2.1.1. Configurations with straight tunnels

Straight subway tunnels are the most studied configuration in this field, most studies (experimental and numerical) and theoretical analysis on fire parameters specific to tunnels are based on this configuration [11].

A large number of articles present comparisons between the results obtained experimentally and those from numerical simulations, as is the case of studies published by Hu et al. [12] (showing a deviation of only 4°C for the predicted temperature at a distance of more than 80 meters from the fire source), Altan and Sumen [13] (which determined the critical ventilation velocity for a tunnel with an obstacle), Weng et al. [14] (studied the critical velocity and backlayering length of smoke in a tunnel through a 1/10 scale experiment and CFD simulations using Fire Dynamics Simulator for 9 different tunnel configurations), Kazemipour et al. [15] (studied the effect of fans installed at the entrance of road tunnels, the results showing discrepancies between 5% and 15% between simulation and experiment), Guo and Zhang [16] (conducted a comparative study between the results of empirical formulas, experiments and numerical simulations performed in FDS and Fluent to determine the critical value of longitudinal velocity in a tunnel, the results being very close), as well as Xi and Hu [17] (studied the effect of airflow on the development of a train on fire moving through the tunnel, resulting in a variation of only 4% of the numerical results compared to the experimental results).

Other articles present only numerically obtained results, such as the research conducted by Teodosiu et al. [18] (who studied the efficiency of the ventilation system formed by a general ventilation plant in each station and an inter-station ventilation plant), Tang et al. [19] (conducted a comparative numerical study between two identical geometry tunnels, one at normal altitude and pressure and the other at a higher altitude), Harish et al [20] (studying the effect of natural ventilation on tunnel smoke propagation and the dependence of the smoke layer temperature on the size of the natural ventilation ducts), Zhang et al. [21] (studied numerically the critical ventilation velocity and the backlayering length of the smoke), F. Wang and M. Wang (studied the impact of the location of the fire source in the tunnel section, by analytical methods of calculation and numerical simulation, concluding that in the case of fire close to the side wall of the tunnel, the distance travelled by the smoke in the opposite direction to the ventilation is much smaller), González et al. (analyse the effect of natural ventilation shafts on the attenuation of the piston effect induced by the movement of the train through the subway tunnel), as well as Huang et al. [22] (using dynamic discretization network CFD simulations to study

the effect of the subway train piston on the movement of air through organized natural ventilation ducts).

2.1.2. Configurations with inclined tunnels

These configurations are found where the terrain or other factors (rivers, buildings, etc.) do not allow the construction of a straight tunnel, which is why it needs to be tilted at a certain angle to the horizontal. The distribution of smoke and hot gases in such tunnels is completely different from the horizontal tunnels due to the fact that specific "buoyancy effect" and "stack / chimney effect" phenomena occur [23]. Therefore, special attention should be paid to the way in which emergency ventilation solutions are designed for such configurations, the most commonly used methods for analysing and verifying how smoke evacuation is ensured are numerical studies.

Regarding experimental studies, there is some research, for example Chow et al. [24] conducted experiments at a scale of 1:50 on a 2 m long tunnel with an adjustable angle of up to 300 m and observed that the shape of the smoke layer is influenced by the angle of inclination.

Yi et al. [25] also used a scale model (1:60) to experimentally study longitudinal ventilation in a tunnel inclined at various angles to the horizontal ($\pm 3\%$, $\pm 1.8\%$, $\pm 1\%$). Based on the results obtained, the study authors proposed correlations between the degree of inclination of the tunnel and the critical ventilation velocity.

However, most studies involving fires and smoke in tilted tunnels are based on CFD simulations. Ji et al. [26] performed a series of numerical simulations using FDS software for car tunnels with slopes ranging from 5% to 15% from horizontal, in order to develop empirical correlations linking the degree of inclination of the tunnel to the heat release rate of the fire and the maximum temperature in the smoke layer.

Guo et al. [27] used the FDS software to simulate fires in tilted tunnels with slopes of 0.75%, 0.89% and 2.8% respectively to determine which type of configuration is safer in case of fire (single tunnel for both directions or one tunnel for each direction). FDS simulations were also used by Wan et al. [28] to study the backlayering length in inclined tunnels with slopes between 5% and 25%, the results showing that there is a critical degree of inclination for which the stack or chimney effect is substantially reduced and the smoke evacuation efficiency is improved. In a study based solely on numerical simulation, Zhang et al. [29] observed that the maximum smoke layer temperature and backlayering length decrease as the tunnel inclination increases from 1% to 8%.

Also based on CFD simulations, but this time using Fluent 18.1 software, Zhou et al. [30] studied the impact of the inclination of the tunnel ($\pm 3\%$) on the smoke distribution of a burning train traveling through the tunnel. The results of the study show that as the slope of the tunnel increases, the temperature of the upstream smoke decreases. Cano-Moreno et al. [31] performed numerical simulations on the evolution of fire and evacuation of people and concluded that increasing the slope of the tunnel from 1% to 2% greatly increases the potential number of victims in the case of pedestrian evacuation of passengers through the tunnel.

There are also studies on inclined tunnels that are based on both numerical simulations and experimental studies. For example, Chow et al. [32] used both study methods to demonstrate that the critical air ventilation velocity required to prevent backlayering is higher in inclined tunnels than in

horizontal tunnels. Small-scale experiments and numerical simulations targeted a tunnel inclined at angles of 0° , 3° , 6° and 9° from the horizontal.

Fires in sloping tunnels with slopes between 0° and 30° were also studied by Chow et al. [33], using CFD (Fluent) simulations, and the numerical results were compared with the results obtained from small-scale experiments, the two data sets being very close. Also, Zhao et al. [23] performed 28 small-scale experiments (1:20) and full-scale numerical simulations for 31 scenarios of fire in an inclined tunnel at 5° , 7.5° and 10° , to analyse the impact of certain factors (tunnel slope, heat release rate, location of the fire source) on the direction of smoke flow. Another example of a comparative experimental (small scale 1:10) - numerical study is the one conducted by Han et al. [34], which showed that as the slope of the tunnel increases, the inclination of the smoke layer intensifies.

2.1.3. Configurations with curved tunnels

A special category of tunnels are those that, in order to follow a route imposed by geological or technical constraints, have a certain curvature in the horizontal plane. There are also specific problems in the event of a fire in such configurations: the movement of hot smoke is influenced by the asymmetry of the tunnel walls, as is the movement of the longitudinally ventilated air [35].

Based on a research project funded by the National Research Council of Canada, which includes both experimental and numerical studies, Kashef and Saber [36] evaluated the effectiveness of emergency ventilation strategies in straight and curved regions of the Ville- Marie Tunnel from Montreal, recommending several technical solutions adapted to that tunnel.

Zhang et al. [37] studied by numerical simulations the dependence between the degree of curvature of a tunnel and the critical velocity of the longitudinally ventilated air, concluding that the backlayering distance increases with the radius of curvature of the tunnel, being maximum when the radius tends to infinity (straight tunnel).

These results are also confirmed by Wang et al. [35]: in case of fire, the critical speed is 7% higher for a curved tunnel than for a straight one.

2.1.4. Configurations with inclined and curved tunnels

It should be noted that the phenomena related to longitudinal ventilation and the spread of smoke resulting from fire are much more complex in the case of inclined and curved tunnels. In addition, being less common, these configurations have been less studied, which is why the literature contains few examples of smoke evacuation from a curved and tilted subway tunnel.

Caliendo et al. [38] conducted a numerical study in which they investigated several fire scenarios in tunnels with a radius of curvature between 185 and 400 m and a 2% longitudinal slope. The study aimed to evaluate the efficiency of the ventilation system in emergency situations and showed that the most difficult scenario is one in which the fire is located in the middle of the length of the tunnel and in the middle of the width of its section.

Zhong et al. [39] performed measurements in a curved and inclined tunnel and showed asymmetric temperature distributions, variations in the vertical position of the maximum temperature, as well as variations in the backlayering length.

2.2. Emergency situations in metro stations

2.2.1. Subway stations without platform screen doors/platform edge doors

In order to determine the efficient ventilation solutions of the metro stations in emergency situations, the evolution of fire parameters in the station (flame length and maximum smoke temperature) and the distribution of smoke and toxic gases are followed. In general, the studies look at how certain operating configurations of the station's ventilation systems can ensure the minimum conditions necessary for the safe evacuation of people.

For example, Wu et al. [40] uses CFD numerical simulation in FDS and studies a 2-level subway station configuration, the conclusion of the study being that smoke evacuation can be achieved even in the absence of mechanical ventilation.

Luo et al. [41] studied the interaction of the mechanical ventilation system with natural ventilation on a 3-level subway station configuration, both experimentally (using a 1:50 scale station model) and numerically, the results of the simulation being almost identical to that of the scaled experiment.

In another article based on numerical simulations, Gao et al. [42] used a two-level subway station configuration with an atrium vestibule, which also has an opening for natural ventilation and observed a 57% decrease in CO in the atrium if hybrid ventilation is used instead of mechanical ventilation only.

Special attention was paid by Zhang et al. [43] on how to check fire safety scenarios involving the evacuation of large numbers of people from a subway station with an underground level (waiting platform) and a vestibule. In order to validate the numerical results, an *in-situ* experiment was performed, the conclusion being that the fire parameters observed in the simulation have values very close to those measured during the experiment.

In the case of burning subway trains that manage to reach the station, there is the problem of ventilating the smoke as quickly as possible using the ventilation systems from that station. Hu et al. [44] conducted a series of simulations to determine the most efficient way to interact with ventilation systems in a subway station in China.

To determine the optimal rate of smoke evacuation from a subway station, Zhang et al. [45] performed simulations using FDS to test the efficiency of the ventilation system at several operating speeds (3 to 10 m/s), concluding that the optimum ventilation velocity is 8 m/s.

The article published by Wu et al. [46] studies the temperature distribution in a metro station in which 3 positions of the fire source are considered, each with 5 different values of the heat release rate.

Another study based on experiment and simulation was conducted by Lee et al. [47] in a Tokyo subway station, the experimental results for the maximum temperature in the smoke layer differed by 10-C from the numerical results.

2.2.2. Subway stations equipped with platform screen doors/platform edge doors

Internationally, studies in the field of subway station ventilation are focused on several directions of research, thus having at present numerous data on air quality (including pollutant concentrations) in subway stations, thermal comfort in stations (including air velocities and the impact of the piston effect generated by the arrival of a train in the station), sound comfort etc.

On the other hand, studies on the implementation and impact of PSD and PED systems in subway station are becoming more numerous. Research has shown that the use of automatic security doors in subway networks has many benefits.

Among the advantages of installing these security doors are the decrease in the number of suicides in subway stations (Chung et al. [48], Ueda et al. [49]), the decrease in the level of noise in subway stations (Soeta and Shimokura [50]), maintaining thermal comfort parameters in stations with lower energy consumption (Hu and Lee [51]) and maintaining a cleaner climate on the passenger platforms.

There are a small number of studies investigating the operation of PSD doors in conjunction with the operation of ventilation systems in subway stations so that smoke is evacuated efficiently in the event of a fire, including the study published by Li and Zhu [52] (who studied the hypothesis of a fire that broke out on the platform and concluded that opening the automatic protection doors on both sides of the platform increases the time to maintain safe evacuation conditions for people by 100 seconds), Chen et al. [53] (who studied the effect of PED and PSD doors on the evacuation of smoke from a Taipei subway station and proposed a way to improve the ventilation strategy by opening only 8 doors near the fire), Meng et al. [54] (comparative study between the advantages of PSD and PED doors in case of fire), Hu et al. [44] (investigated the most effective way to cooperate with smoke extraction facilities at the level of the tunnel and the platform of a subway station, in case of a train fire stopped in the station), Wang et al. [55] (which presented the best smoke evacuation solutions for the analysed configuration), Roh et al. [56] (who concluded that PSD doors increase the time available for passenger evacuation), Wu et al. [57] (proposed a natural ventilation model for a subway station with two underground levels and PSD door systems), respectively Jung et al. [58] (the effect of PSD doors on smoke and pollutant evacuation in the event of a fire in a subway station with three underground levels).

Careful study of the bibliography available in the literature highlights the fact that it is not possible to generalize the solutions considered effective in terms of increasing the safety of passengers on subway networks, from one configuration to another. In order to implement appropriate systems, as well as their correct use (e.g., coupling ventilation - PSD / PED doors) depending on the situation, it is necessary to carry out in-depth studies, specific to the analysed configuration.

The number of articles on emergency ventilation in subway stations with PSD doors is small, mainly due to the fact that researchers have focused on other issues related to the comfort of people in the station, the degree of air pollution, sound insulation of PSD doors etc. For this reason, it was considered important and opportune to study this type of scenario in the doctoral thesis for a subway station in Bucharest.

2.3. Synthesis and conclusions

Most of the articles presented in this chapter use CFD numerical simulation as the main research method to analyse the evolution of fire-specific parameters in tunnels and subway stations.

In terms of smoke evacuation from subway tunnels, most studies refer to classic straight tunnels, which are also the most common in reality. The parameters followed are the critical ventilation velocity, the smoke backlayering distance, the maximum temperature in the smoke layer and the concentrations of pollutants (CO and CO₂). Depending on how the tunnel ventilation system manages to reduce the backlayering distance to zero, the maximum tunnel temperature and the toxic gas concentration, the efficiency of the ventilation system for that scenario is assessed.

Horizontally inclined or curved tunnels require special care when it comes to evacuating smoke from the fire, as the asymmetry of the tunnel walls (in the case of curved tunnels) influences the movement of hot smoke and decreases the efficiency of longitudinal ventilation (increasing critical velocity), while the slope of the tunnel influences the distribution of smoke and hot gases by the fact that specific thermal phenomena occur ("buoyancy effect" and "stack / chimney effect").

Obviously, curved and inclined tunnels are the most unfavourable case for efficient ventilation in emergency situations due to the complex phenomena that characterize the flow of smoke and hot gases in such constructions. This is also the reason why in this paper the efficiency of the proposed ventilation system was studied for a configuration consisting of two subway stations and the curved connecting tunnels between them, from which a tunnel is also inclined.

Regarding the subway stations, it was found that, in addition to the advantages related to the comfort of passengers on the platform, the automatic protection doors influence the evacuation of smoke in emergency situations generated by fires. These aspects are studied more and more often, but the conclusions of the studies depend on many factors such as the power of the fire, the place of fire, the operation of ventilation systems in the station and tunnels, the geometry of the station, the existence of fire extinguishers, etc. However, a general conclusion from the study of the available literature is that properly used PSD / PED systems contribute to smoke evacuation and increase the time available for emergency evacuation of passengers.

Therefore, in this thesis, a numerical study was carried out to verify the efficiency of smoke evacuation in the case of a burning train reaching the platform, in a station equipped with PSD doors.

3. Construction of the CFD numerical model for the emergency situation of a train stopped in a curved and inclined tunnel

The CFD numerical model was developed entirely using the Ansys Fluent 15.0 academically licensed software package and the computing unit from the Department of Thermohydraulic Systems and Atmosphere Protection, with the following technical characteristics: 24xDVD optical drive, 5TB hard drive, motherboard Asus Dual LGA DDR3, processor Intel Xeon 3.1 GHz 8 core, video processor GeForce GTX 2 GB, 64GB DDR3 RAM memory and LCD monitor 27”.

3.1. Configuration of the studied metro system

The main objective of this study is to verify the operation of the proposed ventilation system for a configuration consisting of two subway stations connected by two tunnels, in case of the most unfavourable scenario regarding the occurrence of an emergency situation.

The geometry that was the basis of the study represents the construction project of a subway station and the related tunnels that will complete the M6 subway line from on the route 1Mai - Otopeni Airport.

The geometry of the computing domain was built using the pre-processor in the Ansys Fluent software package, based on the construction plans for the 1 Mai station and the two connection tunnels. It is mentioned that the geometry was represented on a real scale, taking into account accurately all the constructive details that influence the air flow in the calculation field (resistance pillars, interior stairs, technical spaces, platform, exit corridors to the surface etc.).

The metro stations are built on two underground levels (vestibule and platform level), the connection between them being ensured by three internal stairs and an elevator. The interior dimensions, at the level of the platform, are about 200 m long, 16 m wide and 4 m high. Subway stations are island-type, with the platform built in the middle and a subway line on each side of it.

The peculiarity of the studied geometry lies in the fact that the two tunnels are curved (the radius of curvature is 250 m), one of them (tunnel 1) is also inclined, in order to pass under two other tunnels previously built (M4 subway line) . The slope of this tunnel is 3.1%, and the local minimum coincides with the point of curvature, the length of the tunnel being approximately 835 m (Fig. 1).

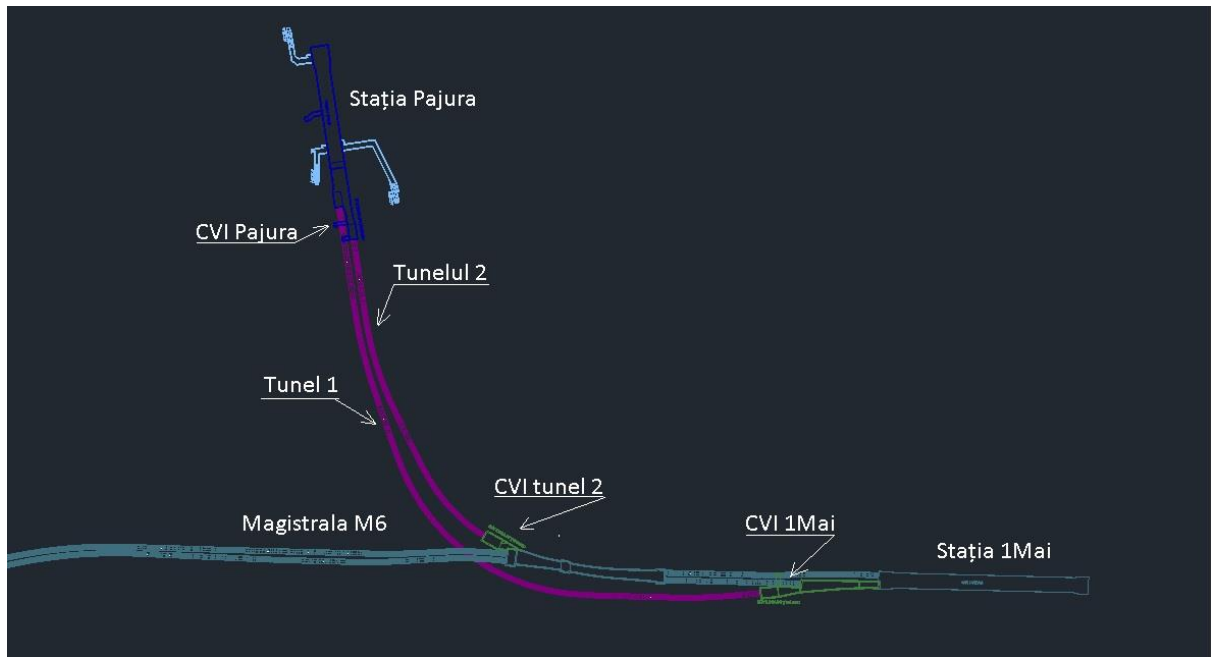


Fig. 1 Overview of the studied metro network

3.2. Emergency scenario

In order to carry out a relevant study on the efficiency of the emergency ventilation system for the studied subway configuration, it was considered, according to the data in the literature [38] [39], that the most disadvantageous scenario would be for a train to on fire to stop in tunnel 1, at the lowest point and in the area of maximum curvature.

The emergency scenario underlying this study complies with the provisions of the *Norms for fire prevention and extinguishing, endowment with technical means for fire prevention and extinguishing and rescue of persons, specific to the Bucharest Metro Transport Company METROREX S.A., approved by Ministerial Order Transports, Constructions and Tourism no. 1287 of 10.08.2006* [59], which specifies the actions to be performed by Metrorex personnel in case the trains have malfunctions that lead to fires.

Regarding the nature of the fire outbreak, it was started from the idea that a mechanical or electrical failure located under the chassis of the train, close to the middle of its length, led to the generation of a fire. This hypothesis is supported by several bibliographic references, such as the statistics made by Alan Beard [60], who concluded that out of 75 subway fires, about two thirds have a mechanical / electrical cause or Chen's study [53] in which he presents 14 subway fires caused by hot brakes on train sets or faulty electrical equipment. Other statistics by Zhou et al. [61] or Olenick and Carpenter [62] point out that about 50% of subway train fires are started under the train chassis, in the area of the braking systems, where other electrical, mechanical and hydraulic components are also found.

Regarding the maximum power of the fire outbreak, the specialized literature indicates values starting from 3 MW [63] to 43 MW [64], but considering that in Bucharest old subway trains are still used, within these simulations a maximum value of 30 MW was chosen for the fire outbreak.

The evolution of the fire had a t^2 -type intensification model (Fig. 2), so that the maximum HRR and pollutant emissions increased in the first 10 minutes of the simulation, as in the case of a real fire [65]. This approach for the evolution of fire power over time is often found in fire safety studies, as well as in other tunnel fire simulations [27] [63] [66].

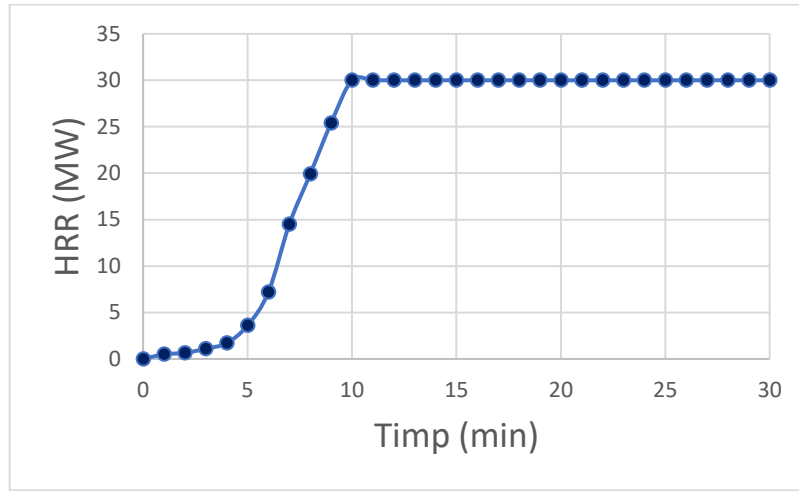


Fig. 2 Evolution of heat release rate during the simulation

In order to obtain the fire development curve and the corresponding CO and CO₂ emissions as close as possible to the actual values of a fire with a maximum heat release rate of 30 MW, the specialized program *Fire Dynamics Simulator* (FDS) was used, the maximum concentrations of pollutants obtained being presented in Fig. 3.

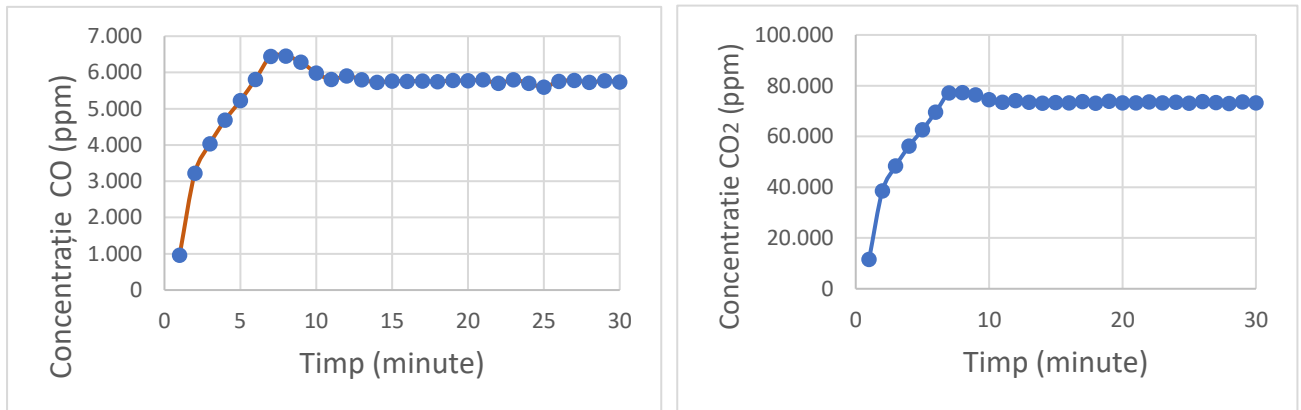


Fig. 3 Pollutants emissions extracted from FDS simulation

It should be noted that this working hypothesis is a simplification of the combustion process, as a real fire involves several combustible materials that generate a large amount of combustion products, with a complex chemical composition and varying amounts of compounds.

3.3. Ventilation system

The ventilation system of the studied metro network is an atypical one, as it consists of an mid-tunnel ventilation plant (CVI) located in the middle of tunnel 2, two end-of-station ventilation systems (CVI) located at the ends of the two metro stations and the general ventilation plants (CVG) of the two metro stations. An important aspect is that all these five ventilation plants mentioned above have the same air flow and can operate for both extraction and air introduction, having two operating modes: normal and emergency. Each of the five ventilation plants provides a flow of 200,000 m³/h in normal mode, respectively 400,000 m³/h in emergency mode.

Normally, another mid-tunnel ventilation plant should have been installed in the middle of tunnel 1, but due to the fact that the M4 metro line passes over tunnel 1, it cannot be built. Therefore, in order to comply with the fire safety norms, the solution based on the construction of the two end-of-station ventilation plants located at the end of the tunnels, near the Pajura and 1 Mai stations, was proposed.

Thus, the ventilation of tunnel 2 (both in normal and emergency operation) is provided by the CVI located in the middle of the tunnel, while the ventilation of tunnel 1 (which is curved and inclined) is provided only by the two CVIs located at the end of the tunnel to ensure its longitudinal ventilation

As for the general ventilation system of a subway station, it consists of 80 circular devices, with a diameter of 30 cm, placed parallel to the long side of the platform, above the train tracks, 40 on each side. (Fig. 4)

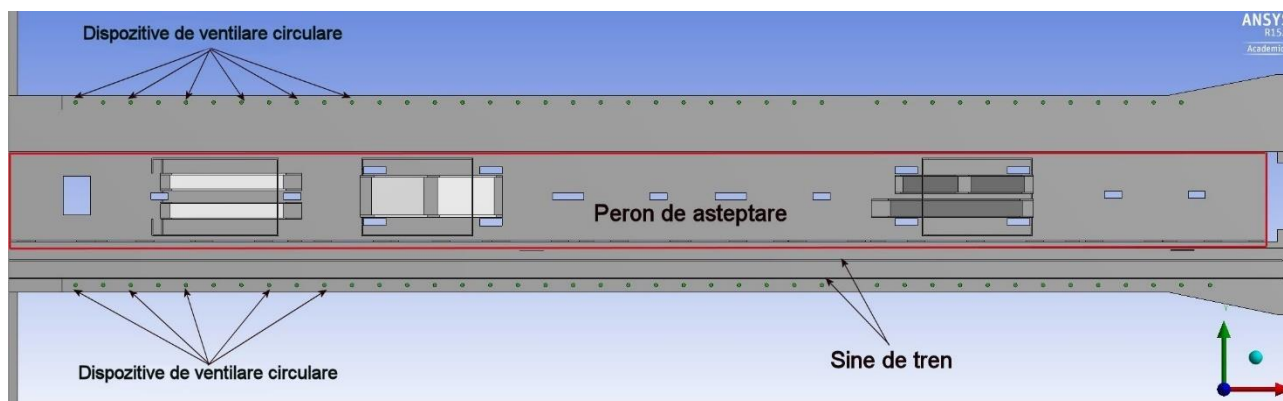


Fig. 4 Ventilation devices within the metro station

3.3.1. Normal operation mode

During the summer, the air is introduced through the general ventilation plant (CVG) of each metro station and through the end-of-tunnel ventilation plant Pajura, being evacuated through the end-of-tunnel ventilation plant 1Mai and mid-tunnel ventilation plant from tunnel 2 (Fig. 5). The normal operating flow for both all the ventilation plants is 200,000 m³/hour. The outside air is cooled in the station ventilation plant before it is introduced into the subway stations, and if the temperature of the ventilated air exceeds 25⁰ C the ventilation is interrupted, so as not to generate thermal discomfort in the subway stations.

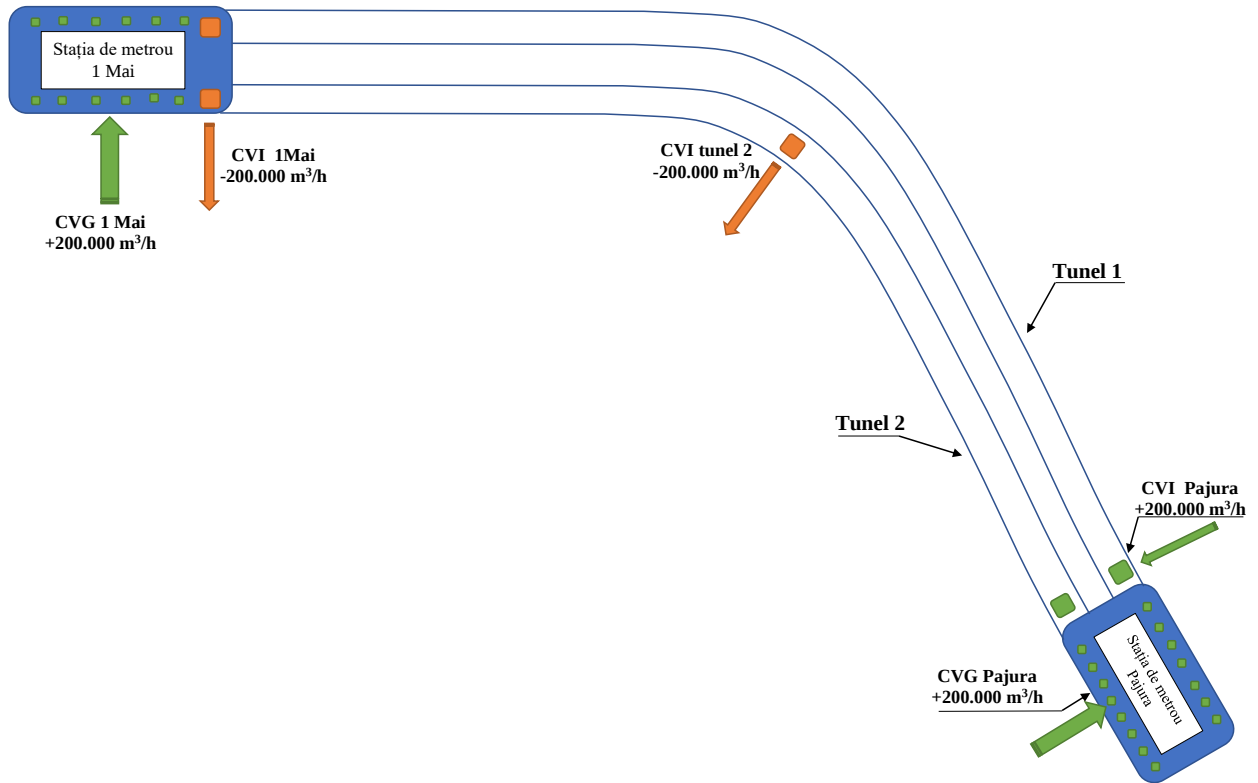


Fig. 5 Normal operation mode of the ventilation system

3.3.2. Emergency operation mode

Regarding the operation of the ventilation system in emergency mode, in case a train is stuck in tunnel 1, at the lowest point, the air is introduced through the general ventilation plant of Pajura station ($200,000 \text{ m}^3/\text{hour}$) and the end-of-tunnel ventilation plant Pajura ($400,000 \text{ m}^3/\text{hour}$) and is discharged through the end-of-tunnel ventilation plant 1Mai ($400,000 \text{ m}^3/\text{hour}$), while the general ventilation plant of 1Mai station and mid-tunnel ventilation plant from tunnel 2 are closed. In this way, the classic longitudinal ventilation is ensured: fresh air flows on the passenger evacuation route (the part of the tunnel between the fire and Pajura station) and the evacuation of smoke and toxic gases is realised towards 1 Mai station.

It is very important to note that the end-of-tunnel ventilation plant Pajura air intake / exhaust device, corresponding to tunnel 2, is closed by means of a damper, in this way all the air flow introduced by end-of-tunnel ventilation plant Pajura is conveyed in tunnel 1. Likewise, end-of-tunnel ventilation plant 1Mai extracts air only from tunnel 1, the ventilation device in tunnel 2 being closed, as can be seen in Fig. 6.

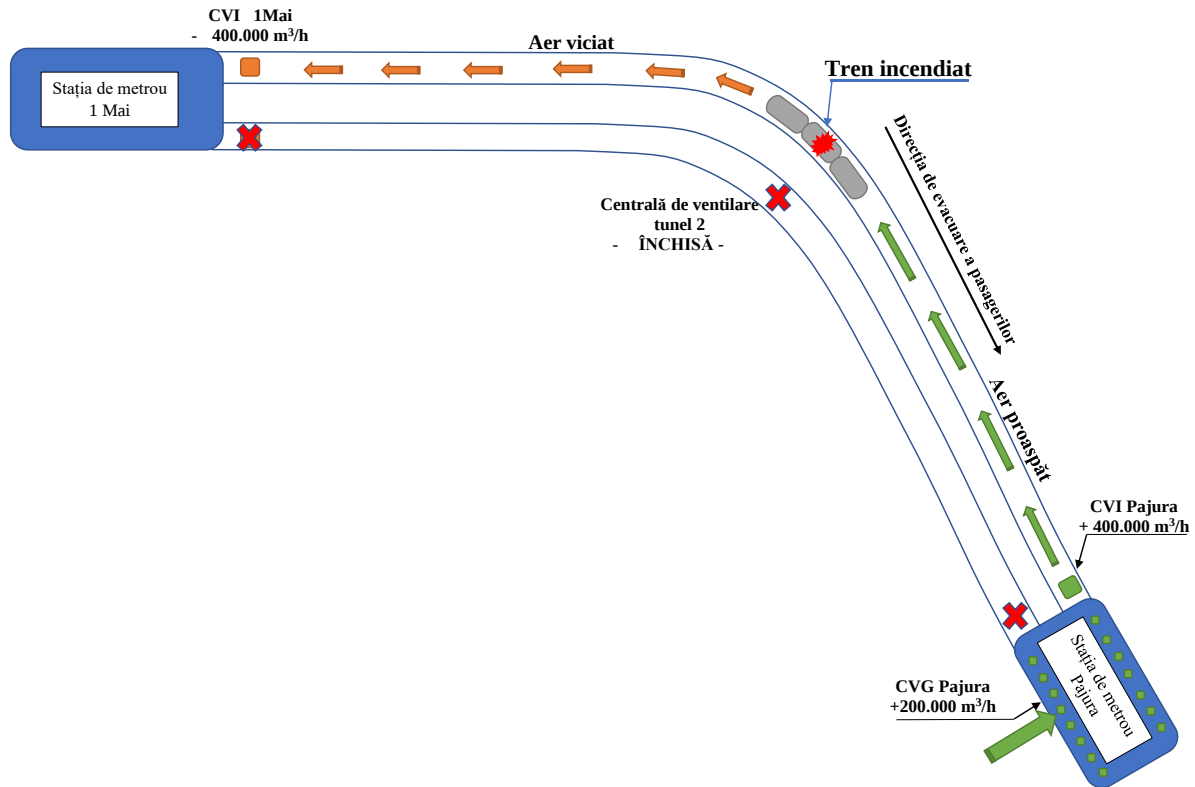


Fig. 6 Emergency operation mode of the ventilation system

3.4. Construction of the numerical model

3.4.1. Geometry

According to the design of the Pajura metro station and the connecting tunnels with 1 Mai station, the geometry for the entire studied metro configuration was realised in Design Modeler.

The 1Mai metro station was built on the same model as the Pajura station, the difference being the connection part of the station with the two tunnels, which is more complex in this case, as the 1Mai station is the connection point with two other metro lines, M4 and M6.

3.4.2. Mesh

Given the size and complexity of the studied geometry, it was imperative that the mesh be unstructured, consisting of finite volumes of tetrahedral shape.

In the study, the mesh was created using the specialized program of the Ansys Fluent 15.0 package (Ansys Meshing), which allows the user to control the way the mesh performs both globally and locally.

The global control functions allow a general control of the discretization elements, so that there are not big differences between the elements of the same calculation field that would later lead to errors in obtaining the numerical solution or even to the divergence of the solution. They ensure the quality control of an element by relating it to the size, orientation and position of neighbouring elements, the mesh network starts to be built from the boundary of the computational domain and going step by step inside it. [67]

In order not to refine the mesh of the whole field and thus obtain high costs, perhaps even prohibitive, in terms of computing time and computer resources required to perform numerical simulations, the mesh was completed in some areas with high gradients of variables by inserting local sizing functions in the following areas:

- The area near the walls of end-of-tunnel ventilation plant 1Mai, Pajura and mid-tunnel ventilation plant from tunnel 2 (Fig. 7);
- The area near the air intake devices through Pajura station ventilation plant, respectively 1Mai station ventilation plant;
- The area near the seat of fire;
- The area near the train tracks.

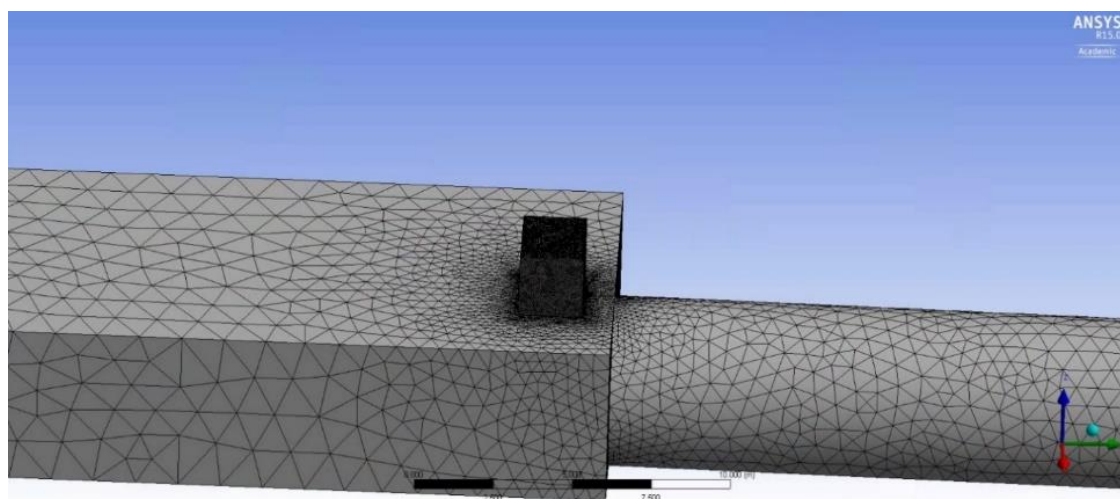


Fig. 7 Local mesh of the wall of a ventilation plant

Following the application of the global and local control functions of the mesh, **23.285.891** elements were obtained.

3.4.2.1. Quality control of the spatial discretization elements

The quality of the mesh is verified by the skewness criterion. This criterion is applied to triangular elements (tetrahedral faces) and shows how close a face or cell is to the ideal shape.

The closer the value of the asymmetry factor is to 1, the more deformed the cells are and the poorer the quality of the network. On the other hand, as the value of the factor approaches 0, the generated cells are close to the ideal shape and create a quality mesh. The results of this verification for the realized discretization network are presented in Table 1.

Tabel 1 Numărul elementelor de discretizare și calitatea lor

Number of elements	Percentage from the total volume		Skewness value	Qualitative evaluation of the mesh
$3,23 \cdot 10^6$	15,1 %	75,1 %	0,0489	Very good quality
$6,86 \cdot 10^6$	31,4 %		0,147	
$6,46 \cdot 10^6$	28,6 %		0,244	
$4,14 \cdot 10^6$	16,5 %	23 %	0,342	Good quality
$1,86 \cdot 10^6$	6,5 %		0,44	
$5,56 \cdot 10^5$	1,63 %	1,91 %	0,537	Satisfactory quality

$1,33 \cdot 10^5$	0,26 %		0,635	
$3,88 \cdot 10^4$	0,027 %		0,733	
$1,42 \cdot 10^4$	0,0013 %		0,831	Weak quality
$1,82 \cdot 10^3$	0,000016 %		0,928	Very weak quality

It is observed that the mesh network consists of 75.1% of elements with an asymmetry factor of less than 0.25, so with elements of very good quality. 98.1% of the obtained elements have an asymmetry factor of less than 0.5, which means that the vast majority of discretization elements have a good quality and the network can be used later to perform numerical simulation.

3.4.2.2. Verification of results independency from the mesh

Checking the independence of the results from the discretization level involves identifying the optimal number of elements of a discretization network for which the numerical solutions obtained can no longer be improved by a finer discretization. Given that we did not have the opportunity to use experimentally obtained data to validate the numerical results, the verification of the independence of the discretization network was performed by reporting the parametric results obtained using meshes with the largest possible number of elements, taking into account the available hardware infrastructure and the computation time required, especially for transient simulations.

Thus, 3 mesh networks were created with a number of 14 million, 23 million and 30 million elements obtained by using the global and local control functions described above. The local control of the discretionary network targeted the same areas in all 3 cases, being the areas in the field where air flow is of particular importance. For each of the 3 discretization networks, a steady-state simulation was performed and the evolution of two parameters (air speed and temperature) at a point in the calculation range, considered representative (point located at the intersection of tunnel 1 with Pajura metro station, one meter below the ceiling) was registered.

The results obtained with each of the 3 discretization networks were compared using the air velocity fields in a cross section through the Pajura metro station, as well as by the evolution of the 2 air parameters at the mentioned point in the last 1,000 iterations.

Fig. 8 shows the air velocity fields in a cross section made in the middle of Pajura station, a section that includes two ventilation devices located on either side of the platform, above the train tracks. As can be seen, there are no major differences between the air jets formed by the ventilation devices, and minor differences can be noticed in the way the air velocities are distributed in the platform area.

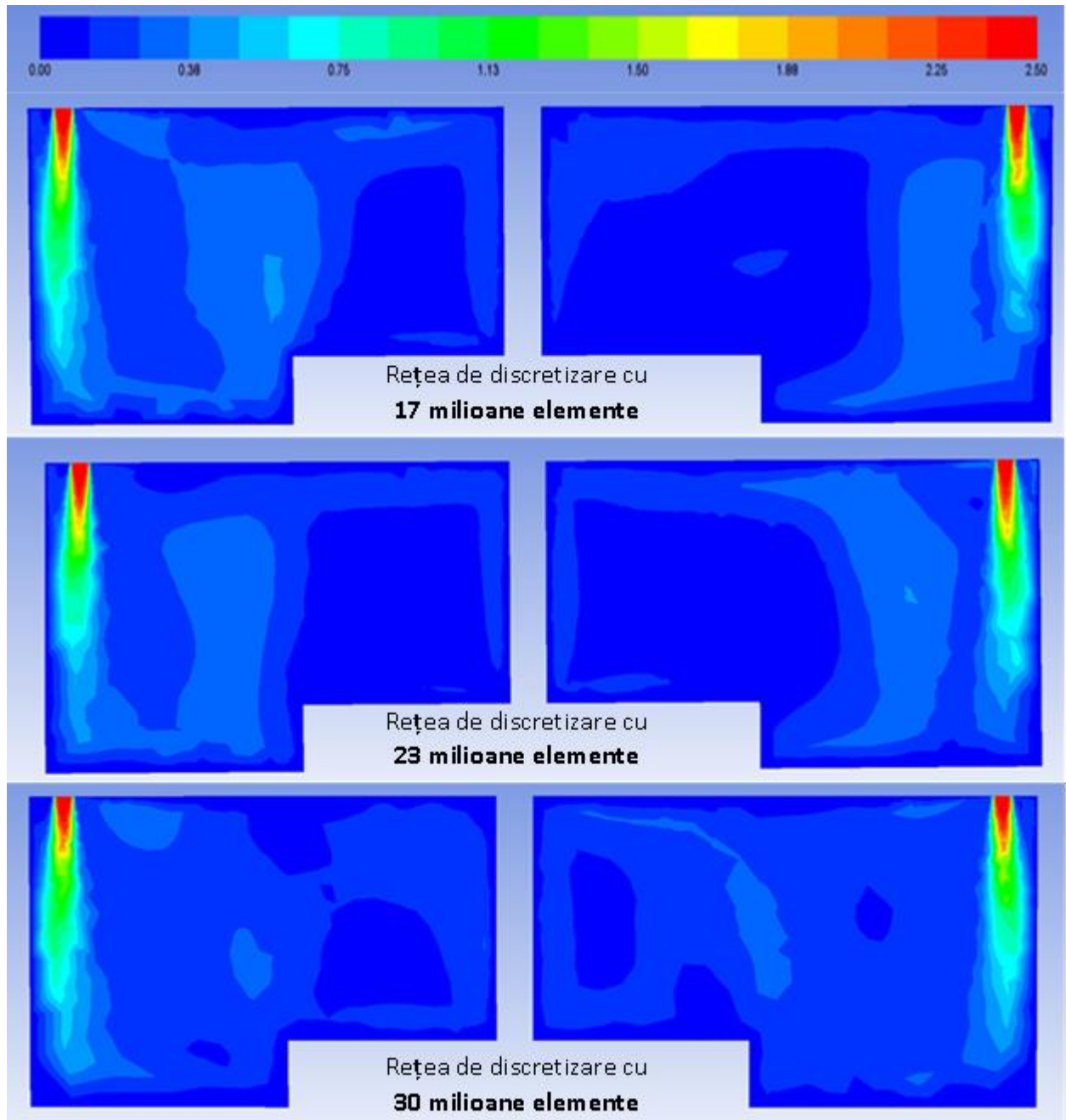


Fig. 8 Air velocity fields (m/s) in a transversal section for the 3 meshes

Fig. 9 and Fig. 10 show the air speed, respectively the air temperature at the test point, and it can be seen that the air speed in the case of the discretization network consisting of 17 million elements fluctuates after 11,000 iterations, which does not characterize the air flow in the case of the other two meshes. In addition, the air speed values obtained in the two meshes with 23 million and 30 million elements respectively are close, the difference between them being only 3.5%. Also, the air temperature in the case of the discretization network with 17 million elements is lower than the temperatures obtained in the simulations performed using the other two discretization networks, whose temperature values are very close (1% difference). Therefore, we can consider that by increasing the number of elements of the discretization network from 23 to 30 million elements, no major improvements are made in terms of air flow through the computational field, which is why the network was used to conduct the study. In addition, the time required to complete the 11,000 iterations using the 30 million element mesh was 182 hours (approximately 8 days), which would

have led to a prohibitive computation time in transient mode. By comparison, the time required to complete the 11,000 iterations using the 23 million element mesh was 125 hours (5 days), resulting in significant time savings.

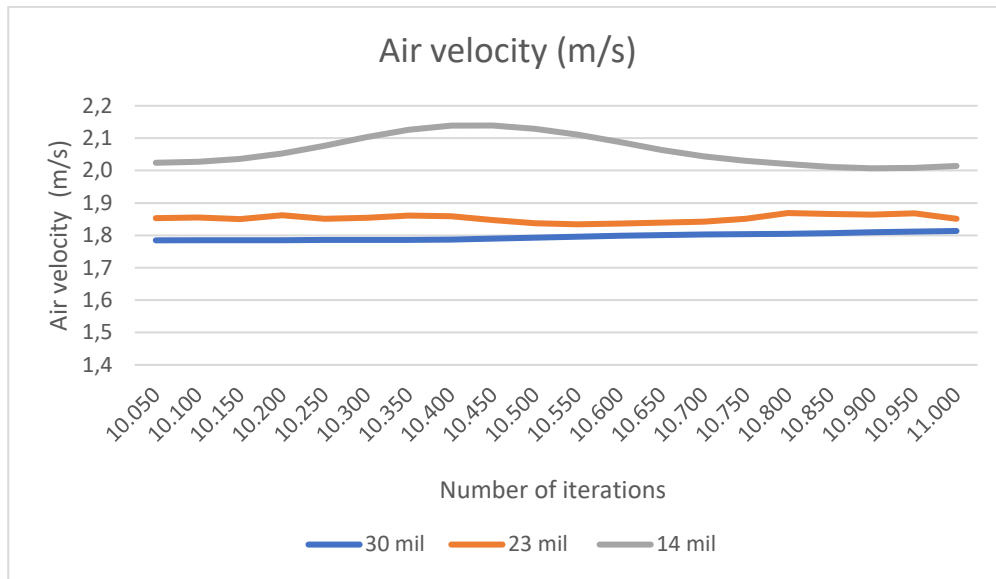


Fig. 9 Air velocities registered in the control point in all 3 simulations (m/s)

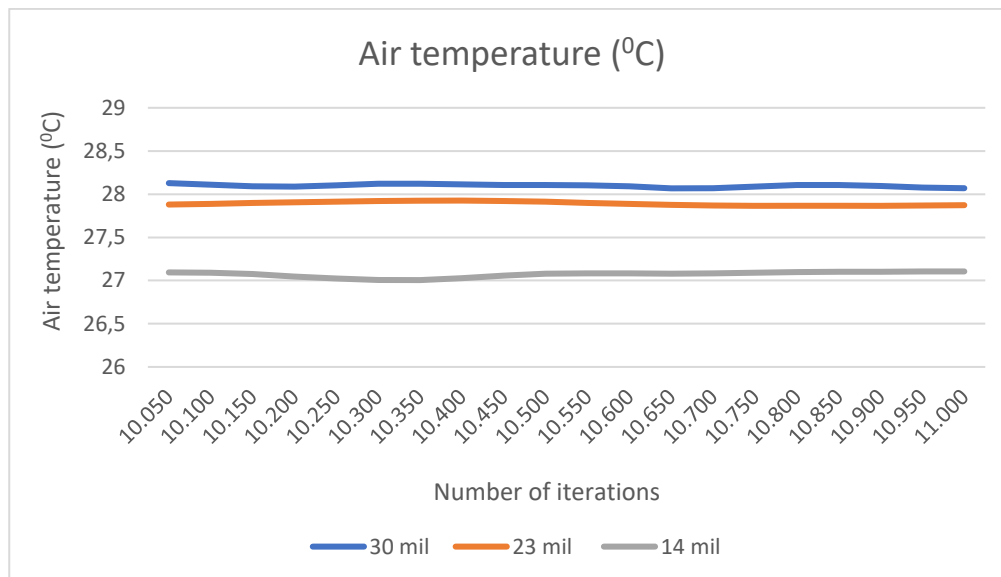


Fig. 10 Air temperatures registered in the control point in all 3 simulations (°C)

3.4.3. Modelling of turbulent flow and near solid borders flow

In order to choose the air flow model, we took into account that inside the subway stations and tunnels we encounter predominantly turbulent flows, accompanied by heat transfer and mass transfer.

Based on these considerations, the RANS turbulence model with two equations $k - \epsilon$ was used. This is a robust, economical and fairly accurate model for a wide range of turbulent flows, which is why it is mainly used in industrial flow simulations and heat transfer.

Given that this study does not aim to capture in detail the flow of air near the walls and taking into account the large size of the geometry, the model of the standard wall function was chosen as a flow pattern near the walls. Choosing a more complex model that better captures the influences of the walls on the air flow through the subway station would have required a finer discretization near the

walls, which would have led to a greater number of calculation elements and implicitly at a time unjustifiably high calculation.

In order to obtain optimal results using the standard wall functions, it is recommended to discretize the calculation range so that the dimensionless distance y^+ (or y^*) has values less than 5 or within the range 30-300. When using advanced wall features, it is not recommended to exceed 5 for y^+ (or y^*). It is important to note that none of the wall functions generate good results if y^+ (or y^*) has values between 5 and 30 [68].

In this study, y^+ has the values shown in Table 2, which belong to the range 30-300, as recommended in the Ansys Fluent 15.0 manual [67].

	Walls of tunnel 1	Walls of tunnel 2	Walls of the train	Walls of the train tracks	Walls of 1Mai station	Walls of Pajura station
Average value of y^+	296,16	208,10	283,17	75,37	110,16	122

Table 2 y^+ values obtained in this study

3.4.4. Modelling radiative heat transfer

From the five radiation models that can be used in Ansys Fluent 15.0, the discrete ordinate (DO) radiation model was chosen for this study because it is more versatile than the other models and can be used for the entire range of optical thicknesses. The calculation cost is modest for normal angular discretization and memory is reduced as long as fine angular discretization is not performed. [69].

3.4.5. Modelling pollutants dispersion

In order to simulate the fire that occurs in case of the emergency situation described in Chapter 3.2, the simulation included the most important effects of a fire: the resulting high temperature and the high concentrations of CO and CO₂ present in the smoke. Although smoke has a much more complex composition and contains a large number of pollutants, in different concentrations depending on the nature of the fuel material, carbon monoxide and carbon dioxide are indispensable compounds in the structure of smoke, being the pollutants monitored in all experiments presented in the literature [70] [71] [72].

Therefore, in the study, a mixture of air, CO and CO₂ in different concentrations was defined, depending on the place of introduction into the calculation domain and the time of its introduction.

The concentration of the components of the mixture at the initialization of the calculation was set differently, in order to have values as close as possible to those measured in the metro stations. Thus, a concentration of 403.7 ppm for CO₂ [73] and 0.627 ppm for CO [74] was set for the outside air that is introduced into the calculation area through the ventilation plants. For the initialization of pollutant concentrations in stations and tunnels, as well as for the air that is introduced into the calculation area through the tunnels leaving the two subway stations, the concentrations obtained from the measurements performed in several subway stations in Taiwan have been set [75]: for CO₂ a concentration of 692.5 ppm, and for CO a value of 2.447 ppm.

3.4.6. Boundary conditions

The boundary conditions have been set to simulate the actual operation of the ventilation system in summer conditions. Thus, air velocities were imposed on the input devices in the metro stations and at the tunnel ventilation plants corresponding to the flow rates provided by the respective ventilation units. Also, the openings at the limit of the calculation range (the three surface exits and four connecting tunnels of the Pajura and 1 Mai stations with the neighbouring stations in the metro network) are considered to be at atmospheric pressure, so as to maintain the mass balance of air flows.

The boundary conditions used (centralized in Table 3) were determined based on data from the experimental study [76] conducted at the Piata Unirii metro station.

Table 3 Boundary conditions used in the study

Parameters	Value	Observations
Wall temperature in the stations	20 ⁰ C	[76]
Subway wall temperature	17 ⁰ C	
Tunnels wall temperature	12 ⁰ C	
Air temperature in the stations at initialization	20 ⁰ C	
CO ₂ air concentration in stations at initialization	692,5 ppm	[75]
CO air concentration in stations at initialization	2,447 ppm	
Temperature of air that is introduced in the station	25 ⁰ C	Summer scenario
Temperature of air that is introduced in the tunnel	30 ⁰ C	Summer scenario
CO ₂ fresh air concentration	403,7 ppm	[73]
CO fresh air concentration	0,627 ppm	[74]
Surface air temperature (<i>backflow</i>)	30 ⁰ C	Summer scenario
Velocity of air introduced in the stations	+ 2,42 m/s	Corresponding to a mass flow of 200.000 m ³ /h
Velocity of air introduced/extracted in the tunnels	+/- 9,1 m/s	Corresponding to a mass flow of 200.000 m ³ /h

For the simulations performed in the study, a pressure solver was used, which uses for the discretization of the differential equations the finite volume method, the most recommended for simulating fluid flow in complex geometries. It used an algorithm for independent solving of moment and pressure conservation functions - SIMPLE, which is recommended to use in case of complex geometries, which have meshes with a high skewness factor (maximum skewness factor in our study was 0.92).

In terms of spatial discretization, second-order upwind schemes have been used for pressure, momentum, turbulent kinetic energy, energy dissipation rate, CO and CO₂ concentrations and energy, as these are recommended in case that the mesh cells are not aligned with the flow. They contribute to more accurate results, even if they prolong the time needed to achieve convergence.

The time step used to calculate the solution was fixed at 1 second, and the maximum number of iterations to solve each time step was 20 iterations.

The main elements related to the numerical solution within the developed CFD model are presented in Table 4.

Table 4 Numerical solutions settings

Solver	Pressure based (velocity formulation: absolute)
Velocity-pressure coupling	SIMPLE algorithm
Spatial discretisation (gradient)	• <i>Least squares cell based</i>; • Pressure: second order; • Velocity, turbulence, CO, CO₂, energy: second order upwind; • Discrete ordinates (radiation): first order upwind; • Under-relaxation factors: ○ pressure: 0,2; ○ body forces: 0,3; ○ density: 0,3; ○ velocity: 0,3; ○ turbulent viscosity: 0,3; ○ CO/CO₂: 0,3; ○ energy: 0,4; ○ discrete ordinates (radiation): 0,7
Solving the discretised equations system	Gauss-Siedel with multigrid algebraic methods (convergence acceleration)
Transient simulations	First order implicit (number of iterations / time step: 20) Tiem step: 1 second.

3.5. Simulation procedure

An important objective in carrying out the simulation was to represent the reality as much as possible, ie to apply as few simplifying hypotheses as possible. In this respect, the simulation performed respects the operation of the ventilation system of the subway network both under normal conditions and in emergency situations. Special attention was paid to switching from one operating mode to another, with the simulations being performed first in steady state to describe the standard mode of operation of the ventilation system, then based on the results of this steady state simulation (now considered initialization values) the transient simulations were launched, with the introduction of the heat and pollutant source (fire source) and with the switching of the ventilation system to the emergency operation mode. This working method allows the capture of the interaction of the fire source with the movement of air through the computational range (from the first time step of the transient simulation), established during the stationary simulation. The transient simulation lasts 30 minutes.

3.5.1. Steady state simulation

The first simulation was performed in stationary mode, without fire outbreak, while the ventilation plants of the subway stations and the end-of-tunnel Pajura ventilation plant introducing air and the end-of-tunnel 1Mai ventilation plant and mid-tunnel 2 ventilation plant extracting air, according to Fig. 40 of chapter 4.3.1. The aim of this simulation is to generate a stable air flow regime in the computational range, these data will be the initialization data of the simulation in transient regime.

In order to verify the stability of the model, 12 control points were established in the calculation field, in which the values for 4 parameters were monitored: air velocity, air temperature and CO and CO₂ concentrations in the air. Given that the values of the mentioned parameters do not show significant changes in the last 1,000 iterations, it is considered that the solution has stabilized and these results are used as initialization data for the transient simulation.

3.5.2. Transient simulation

In order to switch the simulation to transient mode, the boundary conditions have been changed to correspond to the transition of the ventilation system from normal operation to emergency mode. In this sense, the air is introduced through the ventilation plant of Pajura subway station ($200,000 \text{ m}^3 / \text{h}$) and the end-of-tunnel Pajura ventilation plant ($400,000 \text{ m}^3 / \text{h}$) and is extracted through end-of-tunnel 1Mai ventilation plant ($400,000 \text{ m}^3 / \text{h}$), while the ventilation in 1Mai subway station and mid-tunnel 2 ventilation plant is closed.

The fire was also introduced as a source of heat and pollutants (CO and CO₂). In the developed numerical model, the seat of fire was represented as an oval surface with a length of 3 m and a width of 0.25 m arranged between the wheels of the train, at half its length. The respective surface is both a heat and pollutant source and is shown in Fig. 11.

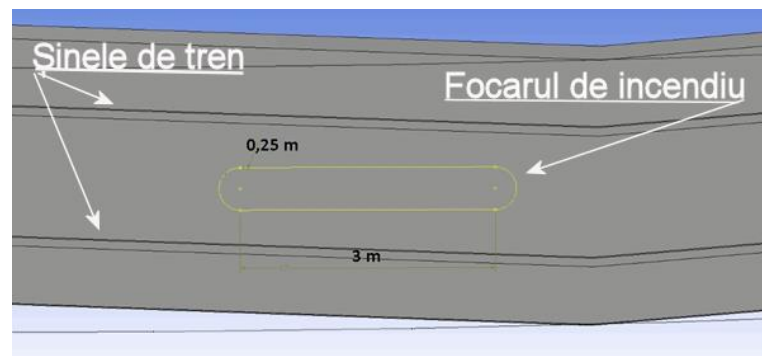


Fig. 11 Seat of fire representation

Under these conditions, more than 47,000 iterations were run for each of the two simulations, in a CPU computation time of approximately 810 hours (27 CPU hours for each simulated minute), to simulate the air flow through tunnels and stations for 30 minutes.

The stability check of the calculation model is performed by analysing the balance of mass air flows in the calculation domain at different minutes in the simulation. This balance represents the difference between the flow rates of air entering the range and the flow rates of air leaving the range. In Table 5 it can be seen that the mass air flow balances show satisfactory values, the maximum error (non-closure) being 0.11%.

Table 5 Mass air flow balances

	Min 1	Min 2	Min 4	Min 7	Min 11	Min 15	Min 20	Min 30
Mass air flow balance [kg/s]	-0,274	0,182	0,0323	0,204	0,174	0,117	0,078	0,040
Percentage value	0,11%	0,077%	0,014%	0,086%	0,073%	0,049%	0,033%	0,017%

3.6. Results from the transient simulation

The results of the transient simulation are presented minute by minute for the first 5 minutes after the fire broke out as these are the most important minutes for the emergency evacuation of passengers. The simulation results after 10, 15 and 30 minutes, respectively, are also presented to highlight the effect of emergency tunnel ventilation on hot air and pollutant evacuation and to have an overview of the tunnel emergency ventilation throughout the simulation.

The results are presented in the form of longitudinal sections that capture the air flow, air temperature and concentrations of CO and CO₂ in 4 important areas on the route of passenger evacuation:

- the middle area of the train where the fire source was located;
- the end of the train in the direction of 1Mai station;
- the end of the train in the direction of Pajura station;
- end-of-tunnel Pajura ventilation plant.

The need to draw up 4 longitudinal sections on the escape route results from the fact that tunnel 1 is horizontally curved and the entire distance between the two metro stations cannot be captured in a single longitudinal section, not even the entire length of the train located in the tunnel.

Fig. 12 shows the longitudinal section drawn by the fire and it can be seen that it includes at the ends the space between the walls of the tunnel and the body of the train.

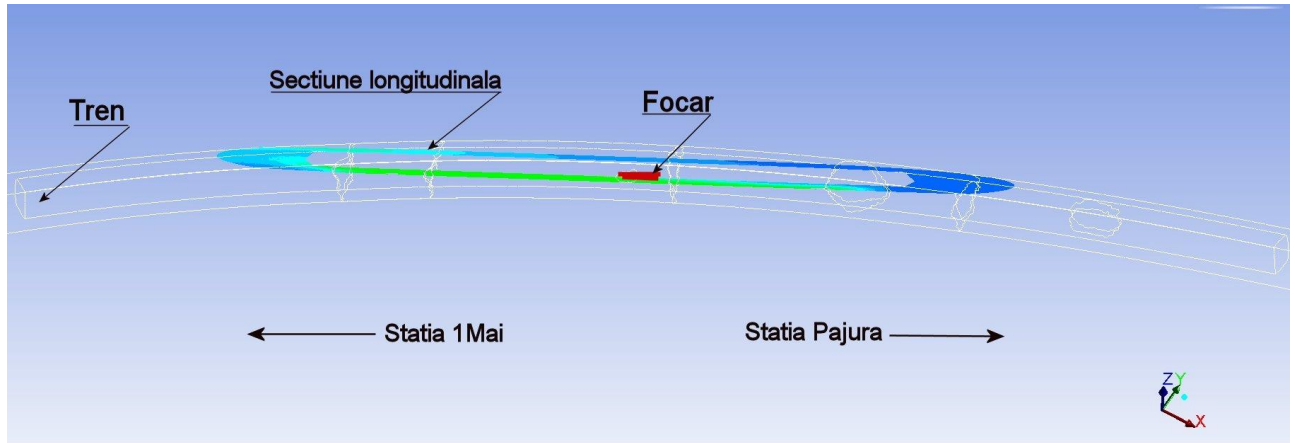


Fig. 12 Tunnel 1 longitudinal sections through the seat of fire

In Fig. 13 it can be seen that there are no major changes over time in the air flow around the train, which means that the operation of the emergency ventilation system is well stabilized. Also, the maximum airflow velocity does not exceed 3.5 m/s, a value that is below the air velocity limit on the evacuation routes imposed by NFPA 130 [77]. In addition, air velocity values between 3-5 m/s were also determined in the full-scale experiment of the METRO project [78].

Fig. 14 shows the air temperature fields and it is visible how the hot air under the train (near the fire source) is directed in time towards the 1Mai station, in the opposite direction from the evacuation of the passengers. It is important to note that due to the very large temperature differences of the areas captured in the section (the area near the fire source and the more remote areas towards Pajura station), a smaller scale was chosen for the graphic representation, which would highlight the air flow direction to the left side. The maximum air temperature in the region, in the first minutes of the simulation, has values between 1200⁰-1800⁰ C, in accordance with the temperature levels determined experimentally by Ingason and Lonnermark [64] for fire outbreaks with similar HRR values to those from this study. Moreover, there is no risk of burns affecting the respiratory tract of passengers evacuating to Pajura metro station because the air temperature in this area does not register values higher than 35⁰C, a value below the limit of 60⁰ C imposed by the NFPA 130 standard [77].

Regarding the CO, respectively CO₂ concentrations, we can observe in Fig. 15 and Fig. 16 that in the first 4 minutes of the simulation there are concentrations higher than the average values under the train a few meters to Pajura station, but starting with minute 4 the polluted air is directed towards 1Mai station, not reaching values that endanger the lives of passengers on the evacuation route. The same observation as in the case of temperature is valid here, in the sense that in order to be able to

graphically represent the average concentrations of CO and CO₂ in the air, the maximum values near the fire source are not captured, reaching values of 4,162 ppm for CO and 42,960 ppm for CO₂.

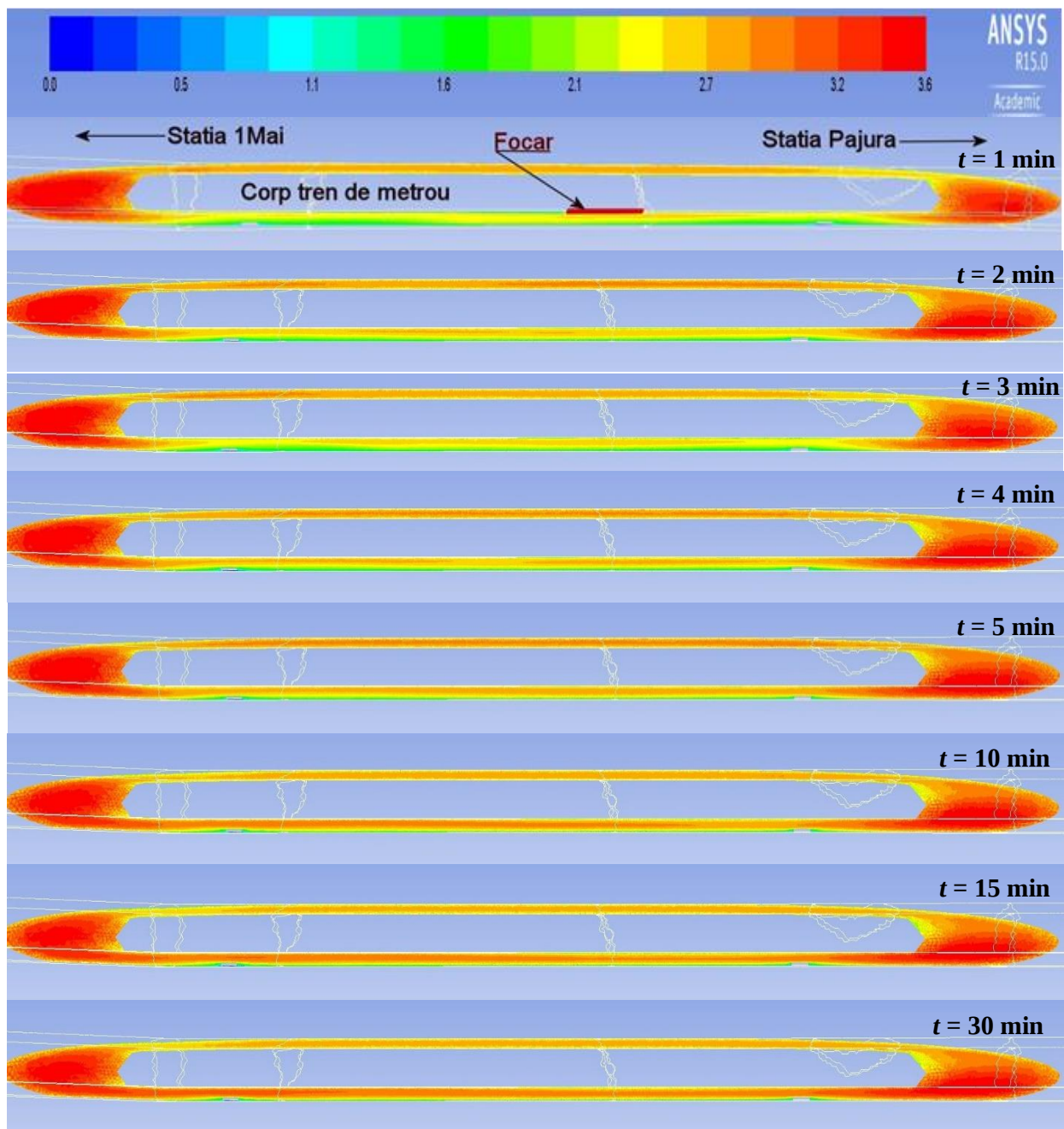


Fig. 13 Section through the seat of fire area – air velocity (m/s)

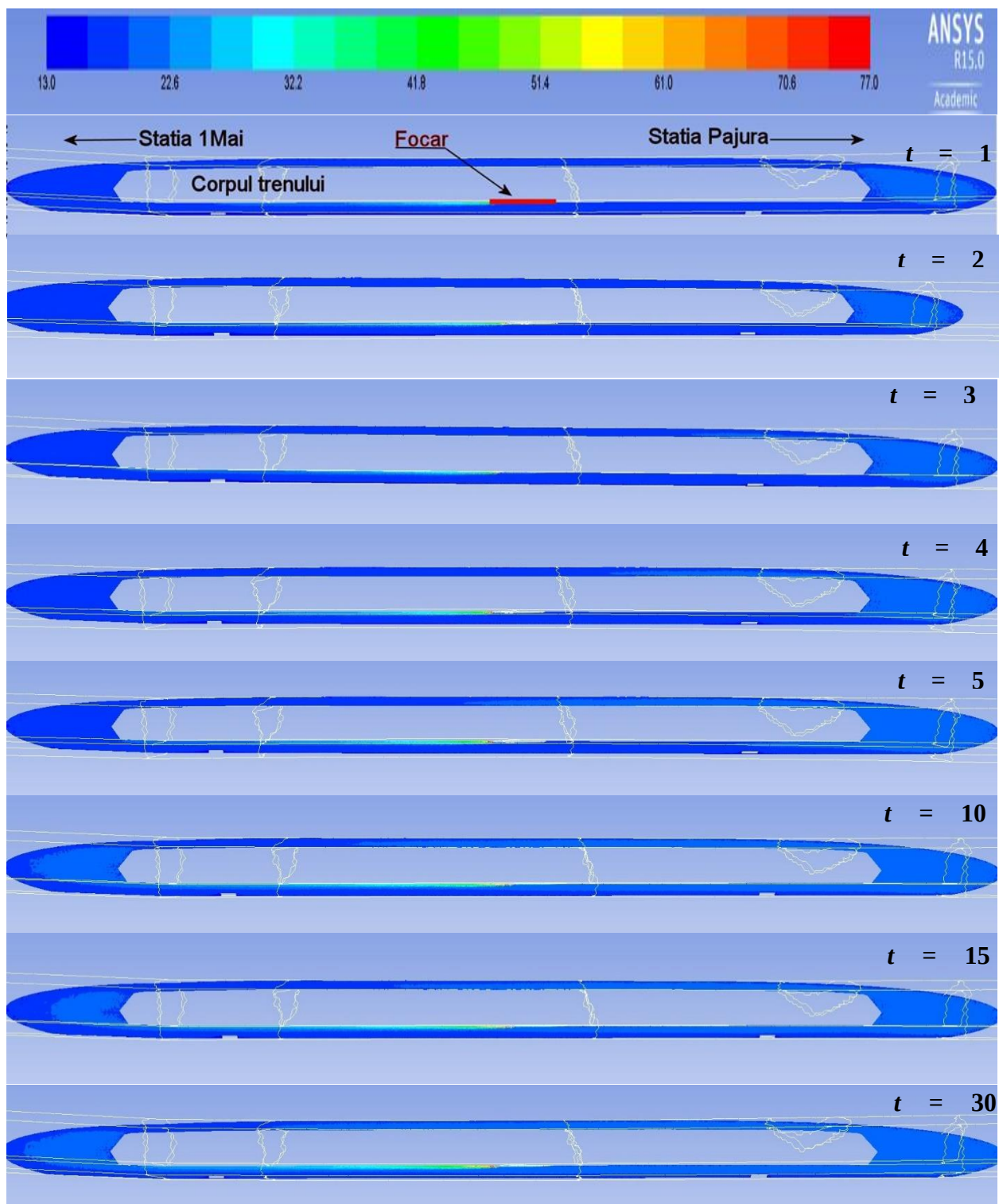


Fig. 14 Section through the seat of fire area – air temperature (°C)

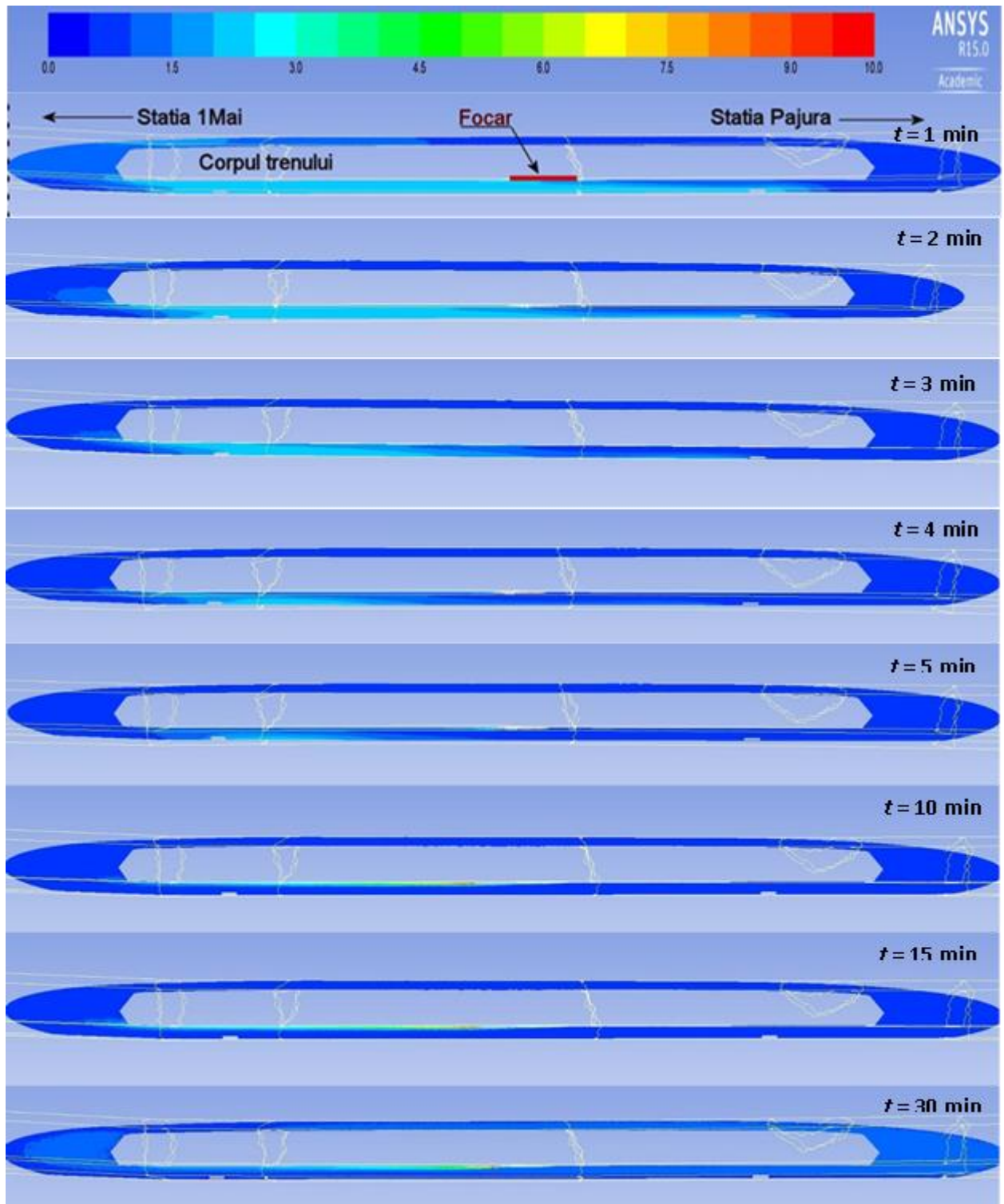


Fig. 15 Section through the seat of fire area –CO concentration (ppm)

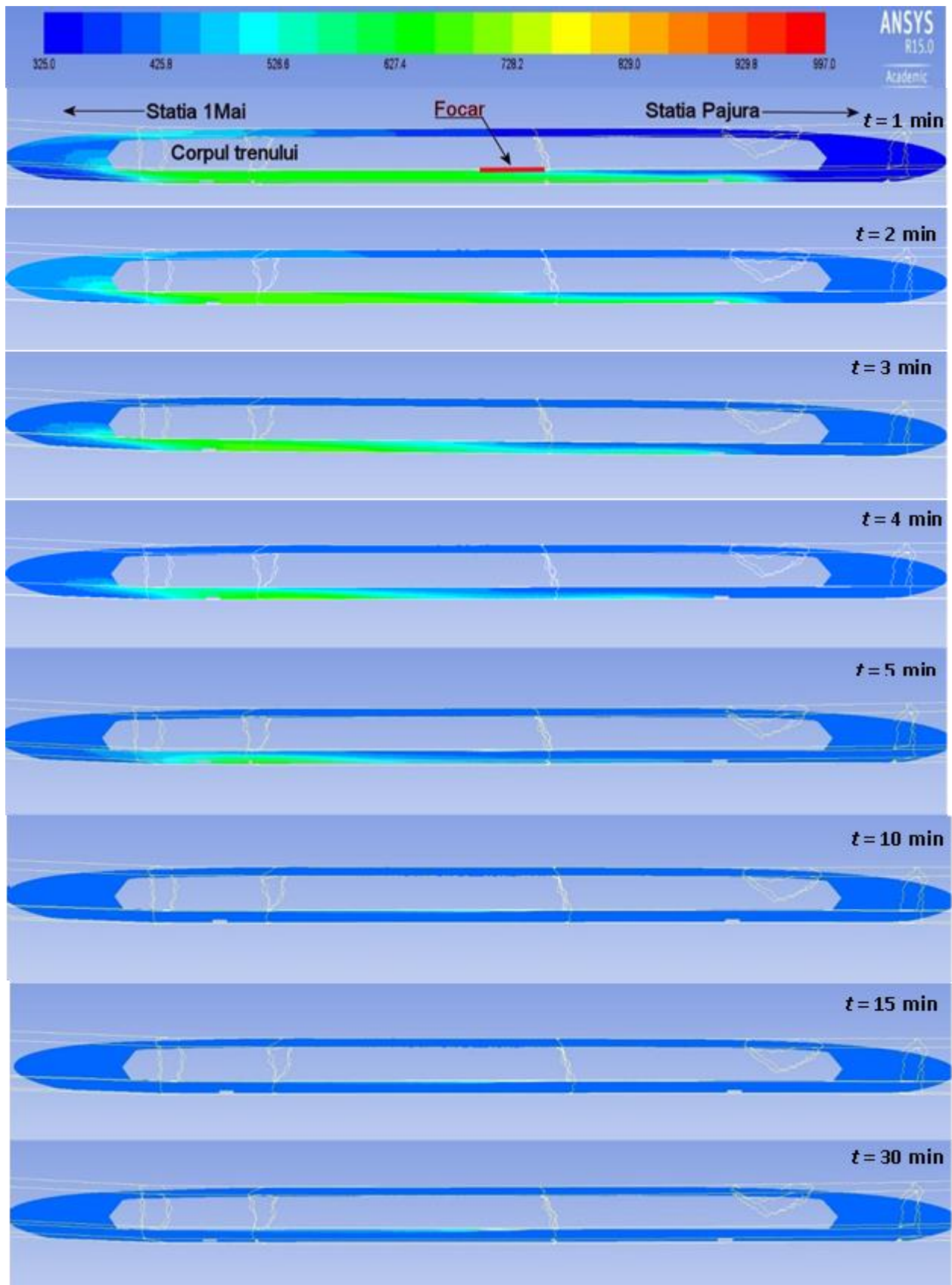


Fig. Section through the seat of fire area –CO₂ concentration (ppm)

The analysis of the air velocity fields in the longitudinal section capturing the end of the train in the direction of station 1Mai illustrates the obstacle effect of the train on the longitudinal ventilation in tunnel 1, as well as the fact that the numerical model is stable and the air flow is constant.

The temperature fields and pollutant concentrations in the same section reveal that the air with higher temperatures and higher concentrations of CO and CO₂ is evacuated to the 1Mai subway station, in the area where it does not risk endangering people's lives, being in the opposite direction from the direction of passengers evacuation.

Fig. 17 shows the longitudinal section of the end area of the train in the direction of Pajura station and a portion of the tunnel. As can be seen, the right side of the section includes a region of tunnel 1 (arranged between the train body and Pajura station), then passes through the train body (uncolored region of sections) and finally the space between the tunnel walls and the train is captured.

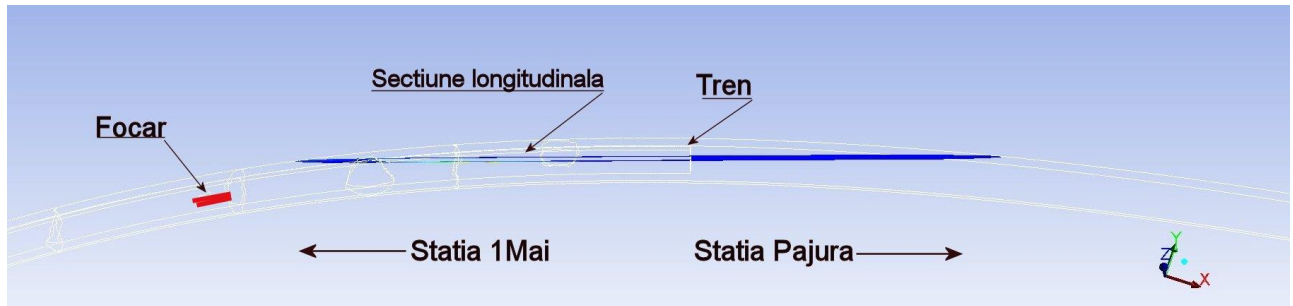


Fig. 16 Longitudinal section through tunnel 1 – end of train towards Pajura station

Fig. 18 shows the air velocity fields in this section and highlights the blocking effect of the train stopped in the tunnel on the air flow. It is observed again that the air velocity towards Pajura station does not exceed 3 m/s, which is enough to properly ventilate the tunnel but without hindering the evacuation of people.

Fig. 19 - Fig. 21 indicates that the smoke does not reach this area because the air temperature and pollutant concentrations are within normal limits. This approach, according to which hot air is an indicator of the presence of smoke, was proposed by Meng et al [79]. In addition, Chen et al. [53] considers that the presence of high concentrations of CO and CO₂ would signal the presence of smoke.

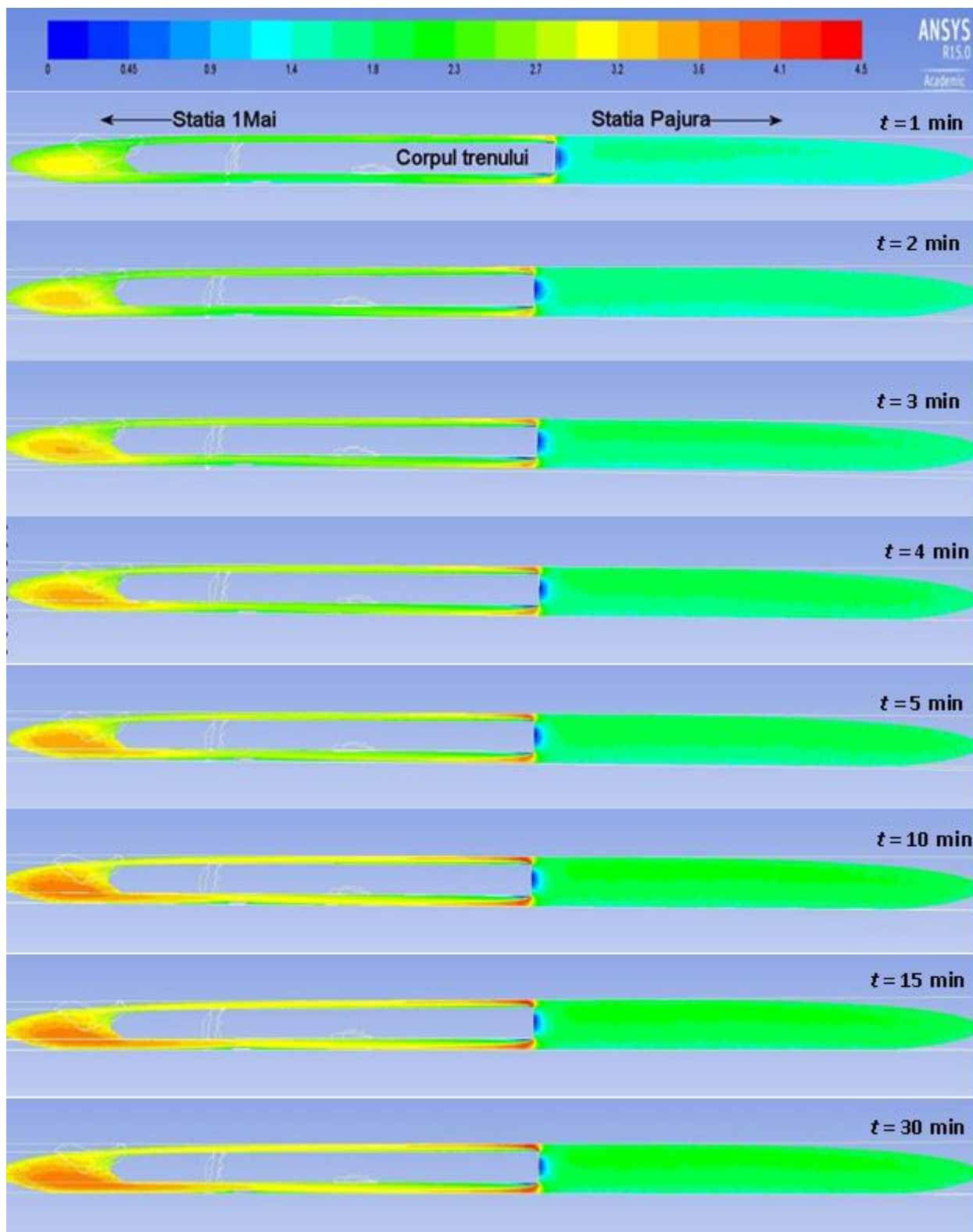


Fig. 17 Section through the end of the train in the direction of Pajura station – air velocity (m/s)

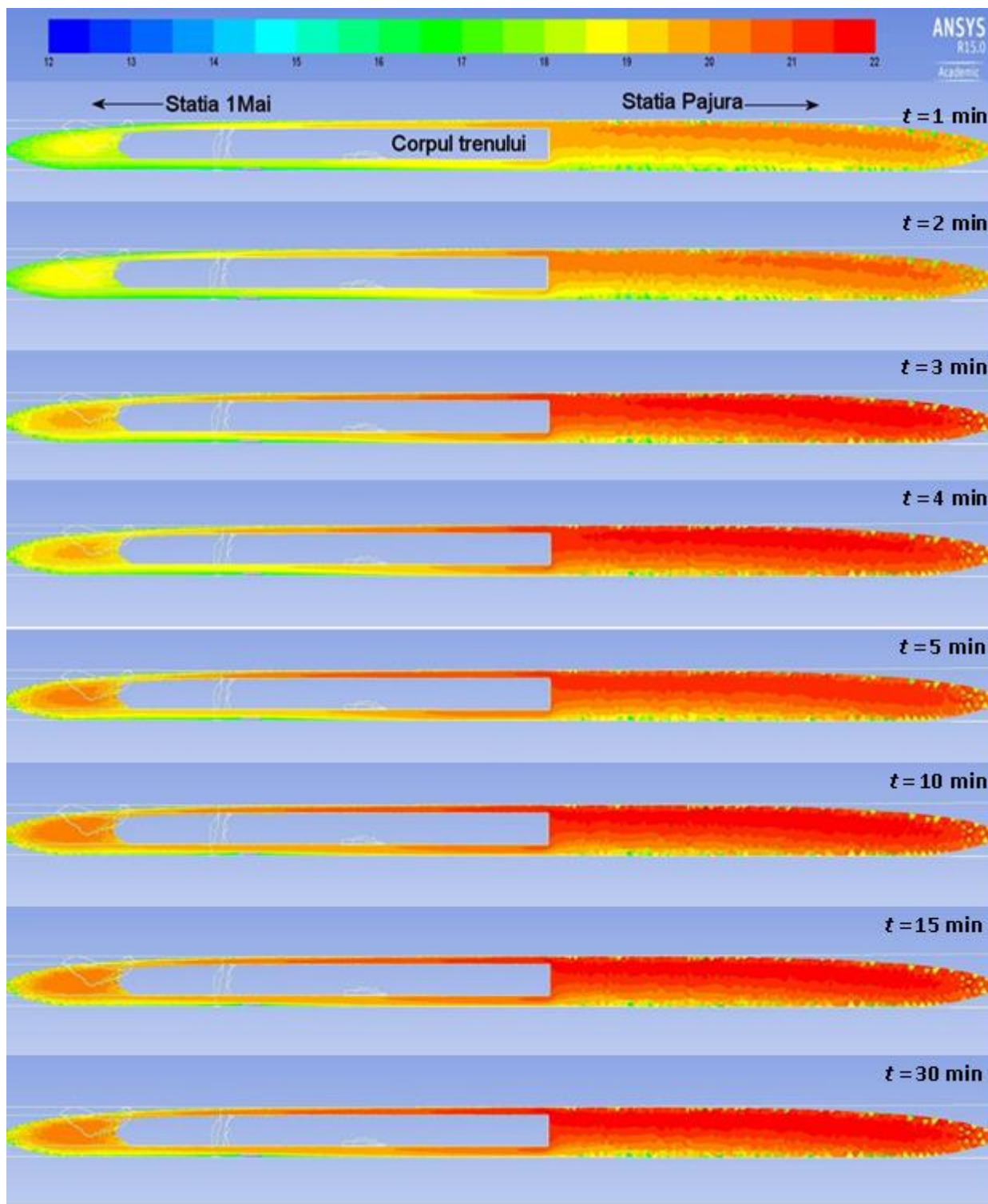


Fig. 18 Section through the end of the train in the direction of Pajura station – air emperature (°C)

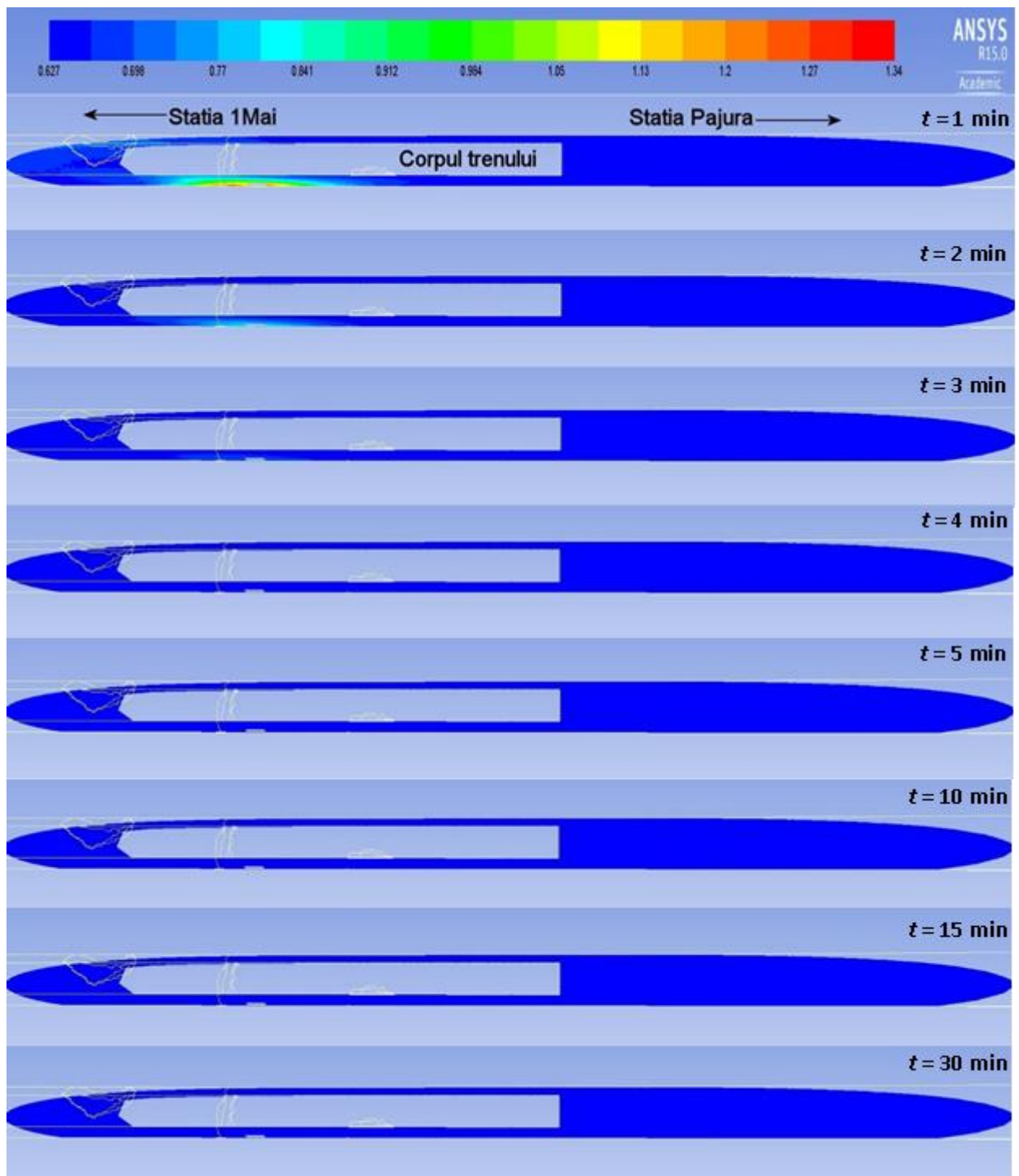


Fig. 19 Section through the end of the train in the direction of Pajura station – CO concentration (ppm)

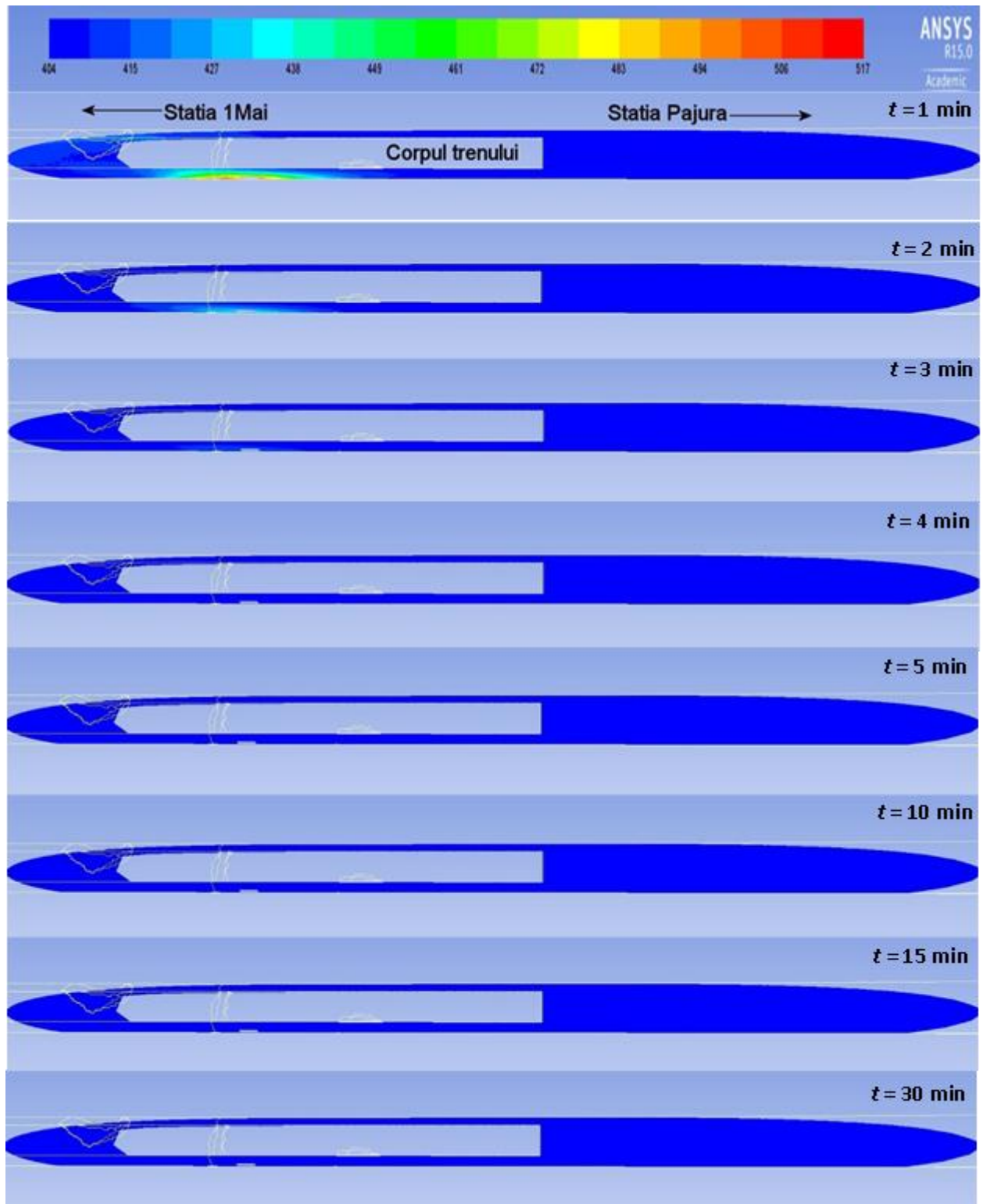


Fig. 20 Section through the end of the train in the direction of Pajura station –CO₂ concentration (ppm)

The air temperature fields and pollutant concentrations in the longitudinal section drawn through end-of-tunnel Pajura ventilation plant confirm that high temperatures and CO/CO₂ concentrations near the fire source do not reach Pajura station, thus creating the conditions for the safe evacuation of

passengers from the tunnel. The air velocity remains at a level (3.5 m/s) that does not prevent the process of evacuating people towards Pajura station.

3.7. Synthesis and conclusions

In this chapter, the operation of the proposed ventilation system for a configuration consisting of two subway stations connected by two tunnels was checked, in the case of the most unfavourable scenario of initiation of an emergency situation (fire train stopped into a curved and inclined tunnel). In this sense, the way of constructing the geometry at 1: 1 scale, the realization of the discretization network, the imposed boundary conditions, the modelled physical phenomena, the simulation procedure and the results obtained both in steady state and in transient mode were presented.

According to the fire scenario, with the transition of the simulation to transient mode, the fire source was introduced as a source of heat and pollutants (CO and CO₂).. The results are presented minute by minute for the first 5 minutes after the fire broke out, respectively after 10, 15 and 30 minutes, to highlight the effect of emergency tunnel ventilation on the evacuation of hot air and pollutants. These are presented in the form of fields of air velocity, air temperature and CO/CO₂ concentrations of the air in longitudinal sections through the tunnel, in 4 important areas on the passenger escape route (the middle area of the train where the fire outbreak was located, the end of the train in the direction of the 1Mai station and in the direction of the Pajura station, respectively the end-of-tunnel Pajura ventilation plant). As no high concentrations of CO and CO₂ or high temperatures (maximum 35°C) are identified in the tunnel section between the fire and Pajura station (passenger evacuation route), we can conclude that the proposed ventilation system ensures optimal conditions for the emergency evacuation of passengers from the tunnel.

4. Construction of the CFD numerical model for the emergency situation of a train on fire stopped in a subway station

4.1. Configuration of the subway station

The main objective of this study is to verify the operation of the proposed ventilation system for a subway station with two underground levels equipped with PSD (platform screen doors) in the emergency situation of a burning train stopped in the station.

It is mentioned that the analysed subway station is similar to the one in the previous study, but it is considered that in this situation it is equipped with PSDs, which separate the tunnel from the platform and prevent injuries caused by falling passengers on the tracks.

4.2. Emergency scenario

The emergency scenario in this case starts from the presumption that a train caught fire between two stations, but the driver manages to get the train to the next station (Pajura) to get off the passengers, according to the procedures indicated in [59].

The nature of the fire is supposed to be similar to that taken into account for the previous scenario, namely a mechanical or electrical failure located under the chassis of the train, close to the middle of its length, which leads to the initiation of a fire under the chassis. On the other hand, in order to simulate the situation corresponding to one of the most dangerous scenarios regarding the penetration of smoke and hot gases into the subway station (worst case scenario), this time the seat of fire was placed on the side of the train, in the middle of its length, as can be seen in Fig. 22.

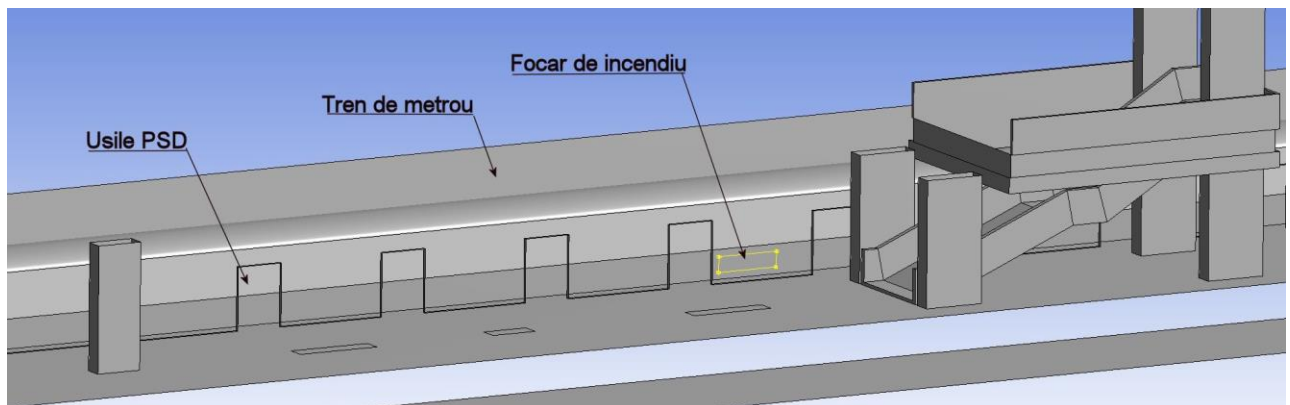


Fig. 21 Position of the seat of fire

Regarding the maximum heat release rate (HRR) specific to the fire source, a maximum value of 10 MW was used in this study to verify in emergency conditions the operation of the subway ventilation system in correlation with the PSD system.

Similar to the previous study, the heat release rate had a t^2 -type intensification pattern, so that the maximum HRR and pollutant emissions increased in the first 10 minutes of the simulation, as in the case of a real fire. The modelling of the fire development curve and the obtaining of equivalent CO and CO₂ emissions was done in the same way as in the previous study, which is why the method will not be detailed again. The maximum concentrations of pollutants obtained in the SDS are shown in Fig. 23.

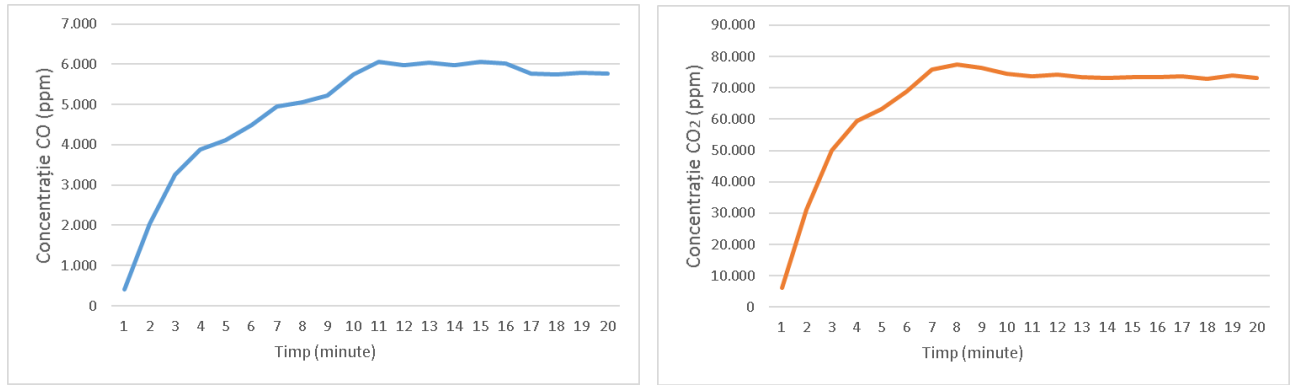


Fig. 22 CO and CO₂ concentrations obtained in the FDS simulation

4.3. Ventilation system

The ventilation of the Pajura metro station is ensured by a general ventilation plant with a flow of 200,000 m³/h in normal regime, respectively 400,000 m³/h in emergency regime. The general ventilation plant can be used for both introduction and extraction of air and is dimensioned to maintain a maximum temperature of 25°C in the subway station in the summer. Fresh air is introduced into the station through two air ducts, arranged on either side of the island-type platform, above the train tracks. These air ducts are equipped with 80 circular ventilation devices, with a diameter of 30 cm, 40 on each side of the platform. (Fig. 23).

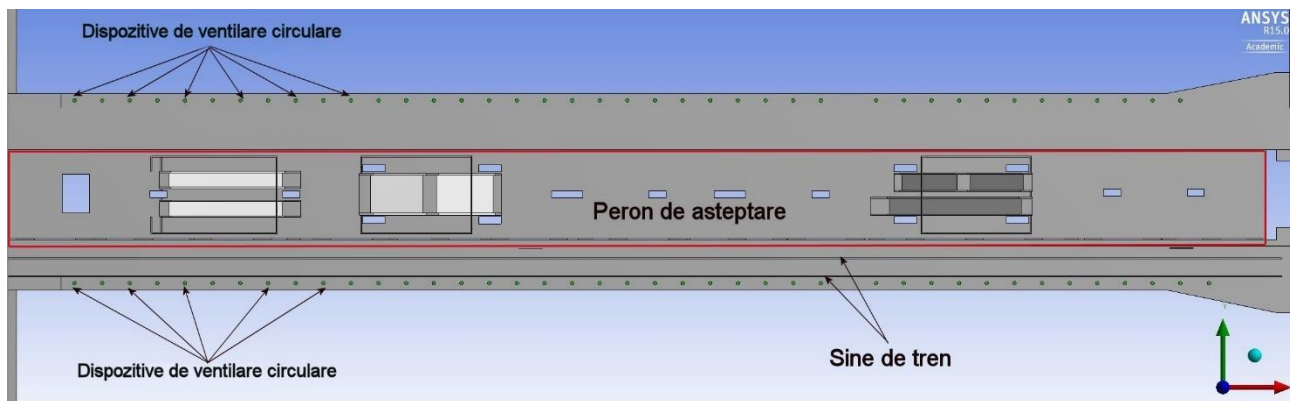


Fig. 23 Displacement of air ventilation devices in the station

In addition, in order to prevent the dispersion of dust particles caused by the movement of subway trains and to take over the heat released during braking at stations, a ventilation system has been provided for the area under the platforms. This system is extracting air from the track with a maximum flow of 20,000 m³/h.

4.3.1. Normal operation mode

The normal operation of the ventilation system assumes that in summer the fresh air is introduced through the general ventilation plant of the station and is evacuated through the end-of-tunnel ventilation plants located in tunnels, and in winter the inlet-outlet circuit is reversed to use the heat emissions from tunnel to heat the air directed to the stations.

4.3.2. Emergency operation mode

If a burning train arrives in the station, the priority is to evacuate the passengers to the surface and then to organise the intervention of the private fire service and the professional emergency services to extinguish the fire. In this sense, the general ventilation system from the station switches to emergency mode (air exhaust with a flow rate of 4000,000 m³/h), all PSD doors on the side with the train on fire open, and those on the opposite side remain closed (Fig. 25). In this way, an attempt is made to prevent the spread of smoke and hot gases from the tunnel on the platform, the aim being to evacuate the smoke through the 40 ventilation devices above the train and the 15 suction devices of the ventilation system located in the area under the platform.

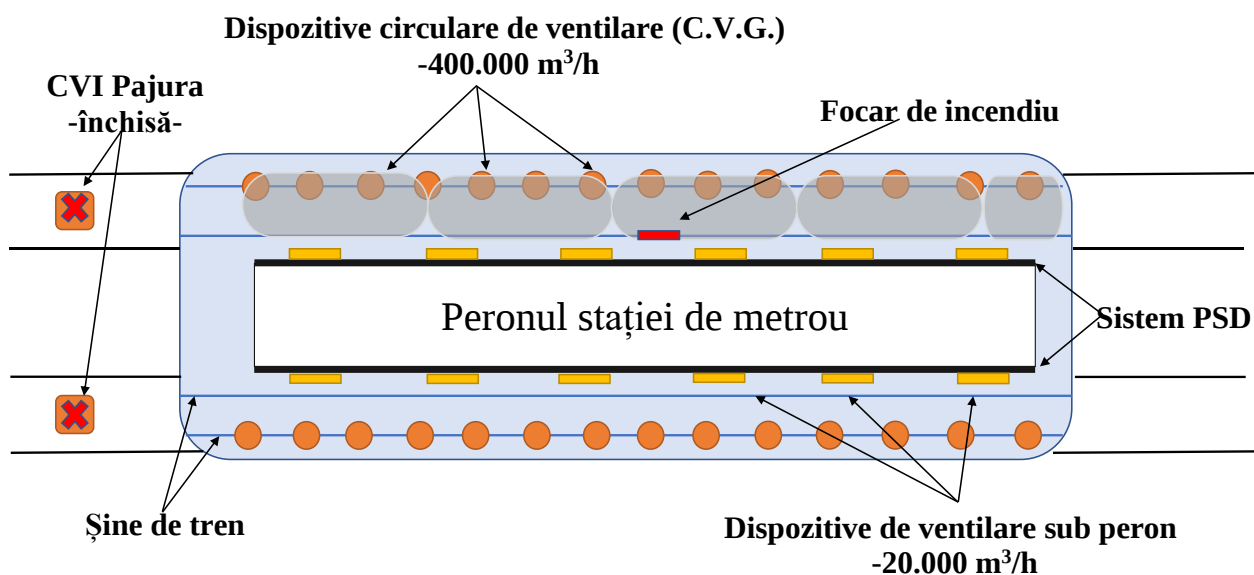


Fig. 24 Emergency functioning of the ventilation system

4.4. Construction of the numerical model

4.4.1. Geometry

The geometric model of the subway station was taken from the previous study, the difference being the addition of PSD doors and ventilation devices for the area under the platform.

4.4.2. Mesh

The mesh is unstructured, consisting of finite volumes of tetrahedral shape, as in the case of the network presented in the previous chapter. Both global control and local control functions were used in its construction, the following elements of geometry being chosen for local discretization:

- The area near the air evacuation devices from Pajura station;
- The area near the air evacuation devices in the area under the platform;
- The area near the seat of fire;
- The area near the train tracks.

Following the application of the global and local control functions of the discretization domain, 14,164,713 mesh cells were obtained.

4.4.2.3. Quality control of the spatial discretization elements

As in the case of the first simulation, the quality of the discretization network is verified by the skewness criterion. Based on this criterion, the degree of deformation of the generated elements is

evaluated. The results of this verification for the discretization network performed in this study are presented in Table 6.

Table 6 Number of mesh cells and their quality

Number of elements	Percentage from the total volume		Skewness value	Qualitative evaluation of the mesh
$1,81 \cdot 10^6$	13,4 %	71,7 %	0,0495	Very good quality
$3,95 \cdot 10^6$	29,7 %		0,148	
$3,91 \cdot 10^6$	28,6 %		0,247	
$2,65 \cdot 10^6$	17,7 %	25,6 %	0,346	Good quality
$1,29 \cdot 10^6$	7,92 %		0,445	
$4,07 \cdot 10^5$	2,22 %	2,66 %	0,544	Satisfactory quality
$1,07 \cdot 10^5$	0,39 %		0,643	
$3,58 \cdot 10^4$	0,05 %		0,742	
$1,06 \cdot 10^4$	0,0016 %		0,841	Week quality
$1,15 \cdot 10^3$	0,000088 %		0,94	Very week quality

It is observed that the mesh network is made up of 71.7% elements with an asymmetry factor of less than 0.25, so with elements of very good quality. 97.3% of the obtained elements have a skewness factor of less than 0.5, which means that the vast majority of discretization elements have a good quality and the network can be used later to perform numerical simulation.

4.4.2.4. Verification of results independency from the mesh

In order to verify that the mesh network does not influence the obtained solutions, a test of the discretization level was performed. In this sense, through the variation of the global and local control functions available, 3 discretization networks were created with a number of 10 million, 14 million and 18 million elements. The local control functions targeted the same areas, which were considered important for describing the flow of air through the calculation field. For each of the 3 discretization networks, a stationary simulation was performed, and the evolution of two parameters (air velocity and temperature) was registered in a point in the calculation range, considered representative (point located in the middle of the station, between the PSD and the resistance pillar, 1.8 m from the floor).

The 3 discretization networks were compared based on the air velocity fields in a cross section through station, as well as by the evolution of the 2 air parameters at the mentioned point in the last 1,000 iterations.

Fig. 27 shows the air velocity fields in a cross section through the station and it can be seen that the first velocity field is different from the next two and has much higher air velocities than the next two figures (the uncoloured areas in the first figure are due to the velocity scale not exceeding values greater than 0.28 m/s).

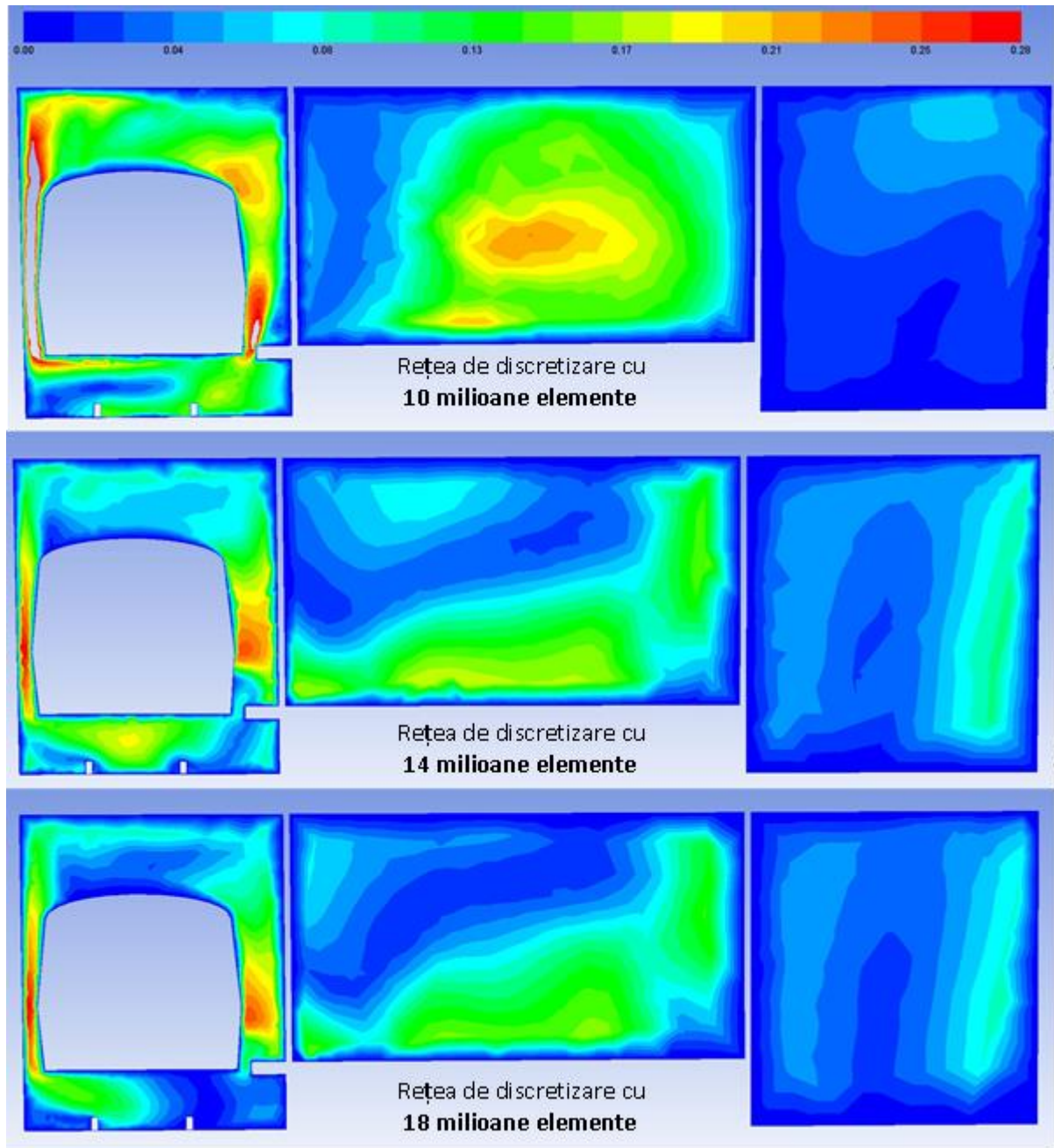


Fig. 25 Air velocity fields (m/s) in the same longitudinal section through the station with 3 different meshes

In Fig. 28 and Fig. 29 it is observed that, in the case of the discretization network with 10 million elements, both the velocity and the air temperature at the test point show big differences compared to the other two discretization networks. In addition, the difference between the average air velocity of the network with 14 million elements (0.064 m/s) and the air average velocity of the network with 18 million elements (0.053 m/s) is only 17%, and in terms of air temperature the difference is even smaller, about 1%. Therefore, we can consider that by increasing the number of elements of the mesh from 14 to 18 million elements no major improvements are made in terms of air flow, which is why the discretionary network with 14 million elements was used to conduct the study.

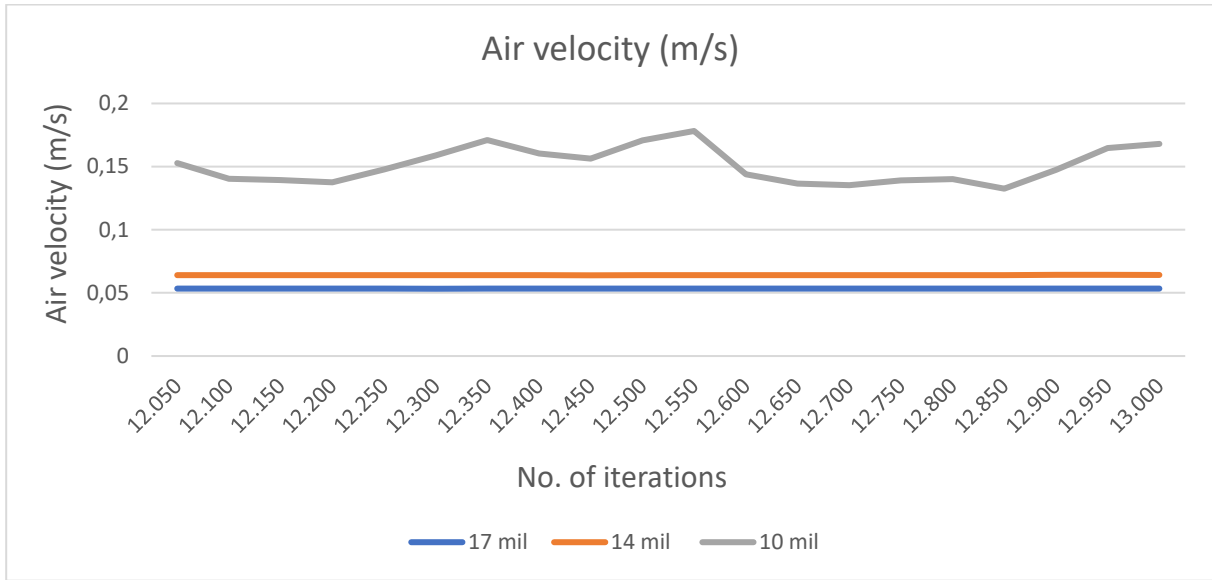


Fig. 26 Air velocity in the same point for 3 different meshes (m/s)

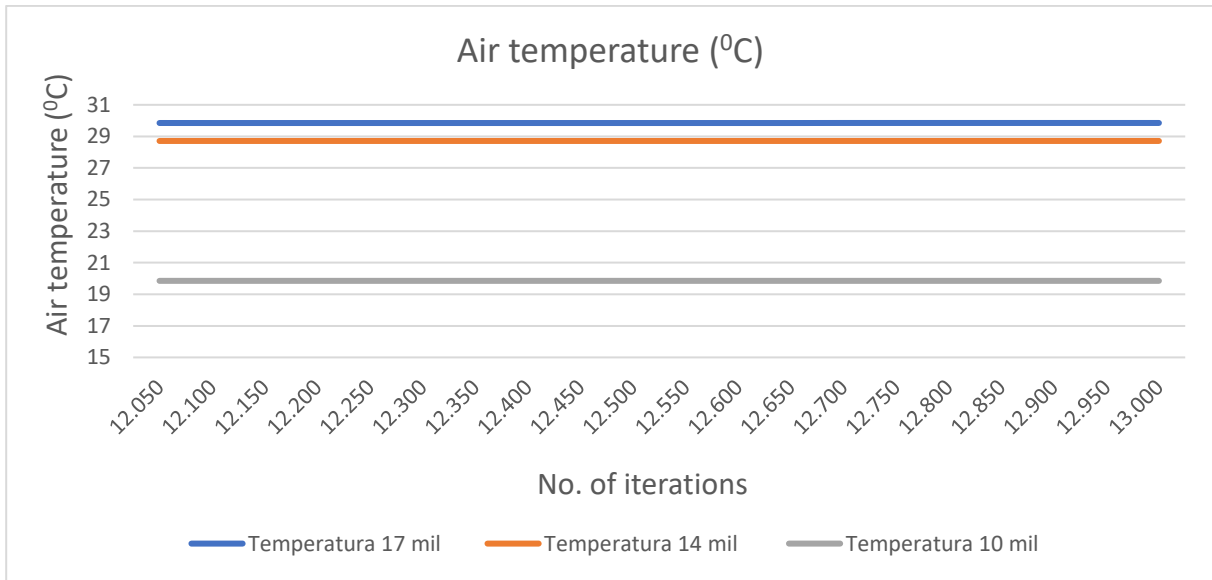


Fig. 27 Air temperature in the same point for 3 different meshes (°C)

4.4.3. Modelling of turbulent flow and near solid borders flow

Based on the considerations set out in Chapter 3.4.3, the RANS turbulence model with two $k-\epsilon$ equations was chosen for implementation, together with the *Standard wall function model*.

The mean values of the dimensionless distance y^+ obtained in this study are presented in Table 7.

Table 7 y^+ values obtained in the study

	Seat of fire	Walls of the metro train	Walls of the metro station	Walls of the air extracting devices under the platform
y^+ values	5,64	36,52	33,23	44,43

In the Ansys Fluent 15.0 user manual [67] it is recommended that the dimensionless distance y^+ when using wall functions be in the range 0-5 or 30-300, a condition that is also observed in the present study.

4.4.4. Modelling of radiative heat transfer

The discrete ordinate (DO) radiation model was chosen for the study because it is more versatile than the other models and can be used for the entire range of optical thicknesses. It allows you to solve a wide range of problems, from radiative transfer from wall to wall to combustion problems and solve radiation for semi-transparent surfaces. The calculation cost is modest for normal angular discretization and memory is reduced as long as fine angular discretization is not performed. [69].

4.4.5. Modelling of pollutants dispersion

The study defined a mixture of air, CO and CO₂ in different concentrations, depending on the development phase of the fire. The method presented in the previous study was used to solve the corresponding mass conservation equations for CO and CO₂ (Chapter 3.4.5).

Data obtained from measurements at several subway stations in Taiwan were used to initialize pollutant concentrations in the subway station, as well as for air entering the computational field through tunnels connecting to the next subway stations [75].

4.4.6. Boundary conditions

The boundary conditions used in the study describe the actual operation of the ventilation system in the event of a burning train stopped at the station. Starting from the air flows provided by the general ventilation system of Pajura station (CVG) and the central ventilation system of the area under the platform, the air velocities in the ventilation devices of the two systems were determined and were used as a limit condition. In order to maintain the mass balance of air flows, the openings at the limit of the computational field are considered to be at atmospheric pressure. Given that the tunnel air and the outside air have different mass fractions of pollutants, the corresponding values of air temperature and pollutant concentrations that can enter the calculation range if negative backflow pressures are calculated have been set

The boundary conditions used are shown in Table 8.

Table 8 Boundary conditions used in this study

Parameters	Values	Observations
Stations wall temperature	20 ⁰ C	[76]
Metro train wall temperature	17 ⁰ C	
Air temperature in the station, at initialisation	20 ⁰ C	
CO ₂ concentration in the station, at initialisation	692,5 ppm	[75]
CO concentration in the station, at initialisation	2,447 ppm	
CO ₂ concentration of the backflow air	403,7 ppm	[73]
CO concentration of the backflow air	0,627 ppm	[74]
Temperature of the backflow air	30 ⁰ C	Summer scenario
Air velocity through the ventilation devices within the station	- 4,84 m/s	Corresponding to an air flow of 200.000 m ³ /h
Air velocity through the ventilation devices under the platform	- 1,54 m/s	Corresponding to an air flow of 20.000 m ³ /h

4.4.7. Numerical solution

As in the previous study, a pressure solver was implemented, which uses the finite volume method to discretize differential equations and an algorithm for independent solving of moment and pressure

conservation functions - SIMPLE, which is recommended for use in case of complex geometries, with mesh networks with a high skewness factor (maximum skewness of 0.928 in this study).

The time step used to calculate the solution was fixed at 0.5 seconds, and the maximum number of iterations to solve each time step was 15 iterations.

The main elements related to the numerical solution within the developed CFD model are presented in Table 9.

Table 9 Numerical solution settings

Solver	Pressure based (velocity formulation: absolute)
Velocity-pressure coupling	SIMPLE algorithm
Spatial discretisation (gradient)	• Least squares cell based; • Pressure: second order; • Velocity, turbulence, CO, CO₂, energy: second order upwind • Under-relaxation factors: ○ pressure: 0,3; ○ density: 0,5; ○ body forces: 0,5; ○ velocity: 0,4; ○ turbulent kinetic energy: 0,4; ○ rate of dissipation: 0,4; ○ turbulent viscosity: 0,5; ○ CO/CO₂/ 0,5; ○ energy: 0,5;
Solving the discretised equations system	Gauss-Siedel with multigrid algebraic methods (convergence acceleration)
Transient simulations	First order implicit (number of iterations / time step: 20) Time step: 1 second.

4.5. Simulation procedure

The simulation performed respects the operation of the ventilation system of the subway station both in normal conditions and in emergency situations. Moreover, special attention was paid to switching from one mode of operation to another. In this sense, the simulation was performed first in steady state to describe the standard mode of operation of the ventilation system, then, based on the results of this simulation in steady state (now considered initialization values) the simulation was launched in transient mode, with introduction of heat source and pollutants (fire source)

The transient simulation lasts 20 minutes, the evolution of the fire over time in terms of heat source and pollutant emission (CO and CO₂) being presented in Chapter 4.2.

4.5.1. Steady state simulation

The first simulation was performed in steady state, without fire source, with the general ventilation system from the subway extracting air with a flow rate of 200,000 m³/h. The objective of this simulation is to generate a stable air flow regime in the computational field, these data will be the initialization dates of the simulation in transient regime.

In order to verify the stability of the model, 3 control points were established in the calculation field, in which the values for the 3 parameters were monitored: air speed, air temperature and CO

concentration in the air. Given that the values of these parameters do not show significant changes in the last 1,000 iterations, the air flow was considered stable and the simulation was performed in transient mode.

4.5.2. Transient simulation

Odată cu trecerea simulării în regim tranzitoriu a fost introdus focarul de incendiu ca sursă de căldură și poluanți (CO și CO₂), conform scenariului descris la capitolul 4.2.

În cadrul modelului numeric dezvoltat, focarul a fost reprezentat ca o suprafață de formă dreptunghiulară cu lungime de 2 m și lățime de 0,5 m dispus pe partea laterală a trenului, la mijlocul lungimii acestuia. Suprafața respectivă este atât sursă de căldură cât și de poluanți. Modelarea transportului și difuziei de CO și CO₂ în domeniul simulat s-a realizat prin introducerea a două ecuații de conservare a fracției de masă CO și CO₂ în modelul CFD.

Folosind un pas de timp de 0,5 secunde și un număr de 15 iterații/pas de timp au fost rulate peste 47.000 de iterații, într-un timp de calcul CPU de aproximativ 320 ore (în medie 16 ore CPU pentru fiecare minut), pentru a simula curgerea aerului prin stație timp de 20 de minute.

Verificarea stabilității modelului de calcul se realizează prin analizarea bilanțului debitelor masice de aer din domeniul de calcul în diferite momente ale simulării. Acest bilanț reprezintă diferența dintre debitele de aer care intră în domeniul de calcul și debitele de aer care ies din domeniul de calcul.

În Table 10 se poate observa că bilanțurile debitelor de aer masice obținute în simulare prezintă valori foarte bune, eroarea (neînchiderea) maximă fiind de ordinul 10⁻⁶.

With the transition to simulation in transient mode, the fire source was introduced as a source of heat and pollutants (CO and CO₂), according to the scenario described in Chapter 4.2.

In the numerical model developed, the fire source was represented as a rectangular surface with a length of 2 m and a width of 0.5 m arranged on the side of the train, in the middle of its length. That surface is a source of both heat and pollutants. Modelling of CO and CO₂ transport and diffusion in the simulated field was performed by introducing two conservation equations of the mass fraction of CO and CO₂ in the CFD model.

Using a time step of 0.5 seconds and a number of 15 iterations / time step over 47,000 iterations were run, in a CPU computation time of approximately 320 hours (average 16 CPU hours per minute), to simulate the flow of air through the station for 20 minutes.

The verification of the stability of the calculation model is performed by analysing the balance of mass air flows in the calculation range at different times of the simulation. This balance represents the difference between the flow rates of air entering the domain and the flow rates of air leaving the domain.

In Table 10 it can be seen that the mass air flow balances obtained in the simulation have very good values, the maximum error (non-closing) having 10⁻⁶ order.

Table 10 Air mass flow rates obtained in the simulation

	Steady state	Minute 1	Minute 2	Minute 3	Minute 4	Minute 10	Minute 15	Minute 20

Air mass flow rate [kg/s]	$-8,23 \cdot 10^{-7}$	$3,24 \cdot 10^{-7}$	$3,3 \cdot 10^{-7}$	$3,95 \cdot 10^{-6}$	$4,73 \cdot 10^{-6}$	$3,48 \cdot 10^{-6}$	$4,01 \cdot 10^{-6}$	$3,21 \cdot 10^{-7}$
Volume percentage	$2 \cdot 10^{-8} \%$	$2,3 \cdot 10^{-7} \%$	$2,37 \cdot 10^{-7} \%$	$2,83 \cdot 10^{-6} \%$	$3,4 \cdot 10^{-6} \%$	$2,5 \cdot 10^{-6} \%$	$2,9 \cdot 10^{-6} \%$	$2,3 \cdot 10^{-7} \%$

4.6. Results from the transient simulation

The results of the transient simulation are presented minute by minute for the first 5 minutes after the fire broke out, as these are the most important minutes for the emergency evacuation of passengers from the subway station. The results of the simulation after 10, 15 and 20 minutes, respectively, are also presented to highlight the effect of emergency ventilation on the evacuation of hot air and pollutants and to have an overview of the emergency situation at the station throughout. simulation.

The results are presented in the form of cross-sections that capture the air flow, temperature and concentrations of CO and CO₂ in the area near the fire source and through PSD.

Fig. 30 and Fig. 31 show the temperature fields obtained during the simulation, in a cross section through the area of the fire outbreak, executed in the left limit of the outbreak (direction of propagation of hot air and pollutant concentrations). It can be seen that in the area on the train wall where the outbreak should be represented, it is missing from the image. This is because the temperature in the seat of fire is higher than the maximum temperature on the scale used to represent the temperature variation. It is very important to mention that the effect of the PSD system on limiting the propagation of hot air in the subway station is noticeable. If this dividing wall were missing, the hot air would reach the platform area and prevent the evacuation of passengers from the station. This is why the US Fire Safety Standard for Fixed Transit and Passenger Rail Systems (NFPA 130) [77] requires that the fire resistance and structural strength of PSD systems be close to those of the subway train.

The maximum air temperature in the area of the outbreak is between 900⁰-1100⁰ C, in accordance with the temperature levels determined experimentally in the EUREKA study [80] for fire outbreaks with similar HRR values to those in this paper.

Fig. 32 and Fig. 33 show the CO concentration fields obtained during the simulation in the same cross section through the focus area (maximum values of 6,450 ppm) and it is observed that they resemble the temperature fields, the carbon monoxide reaching to occupy all the space between the PSD system (which limits access to polluted air in the station) and the train body.

Fig. 34 and Fig. 35 show the CO₂ concentration (maximum 77,000 ppm) fields obtained during the simulation in the same cross section through the focus area. However, the carbon dioxide, having a higher density than the air, arrives in the first 2 minutes under the train and is driven by the upward movement of the air towards the ventilation devices above the train, then follows the same distribution model as carbon monoxide.

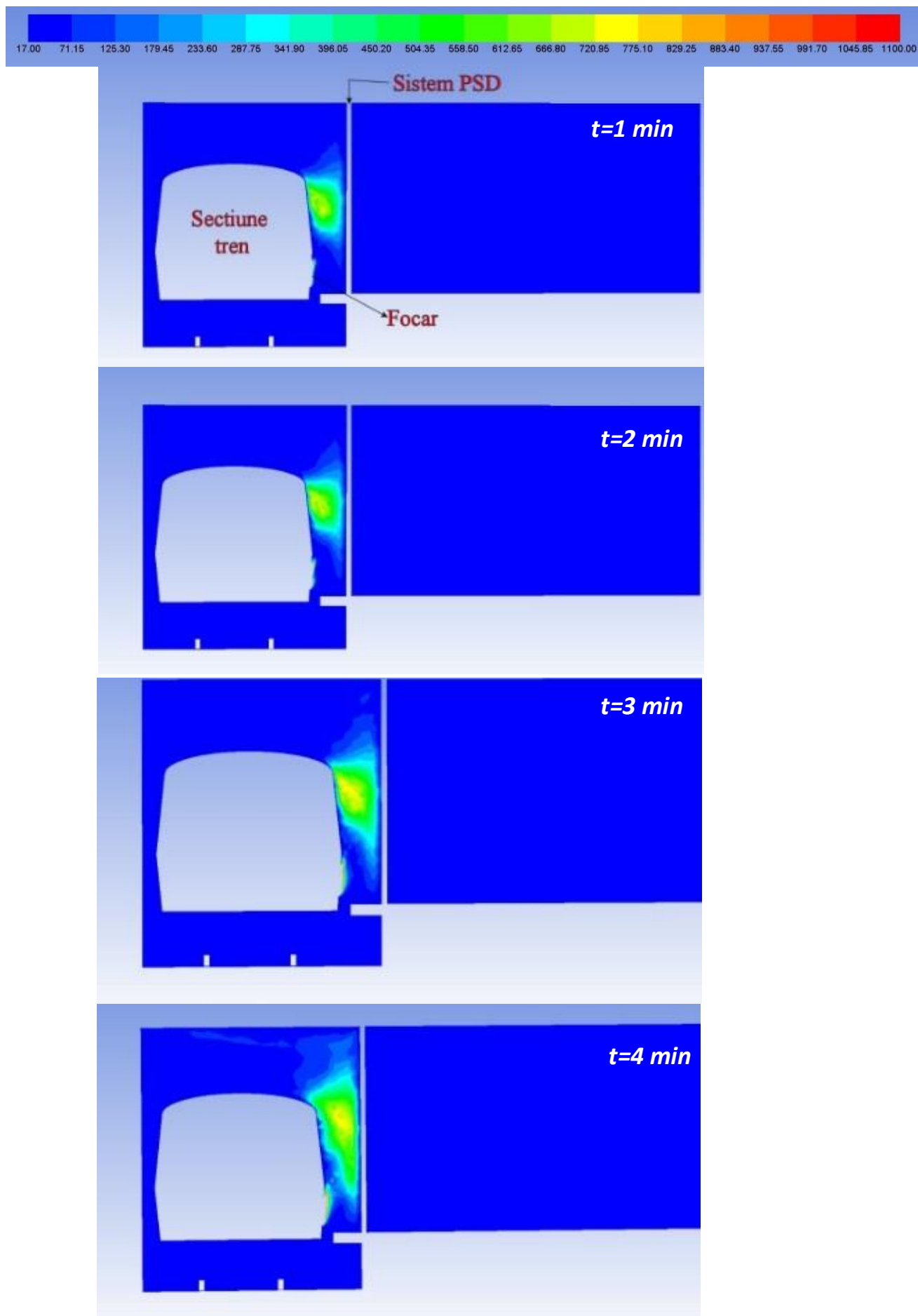


Fig. 28 Cross-section through the fire source – air temperature fields - minutes 1-4 ($^{\circ}\text{C}$)

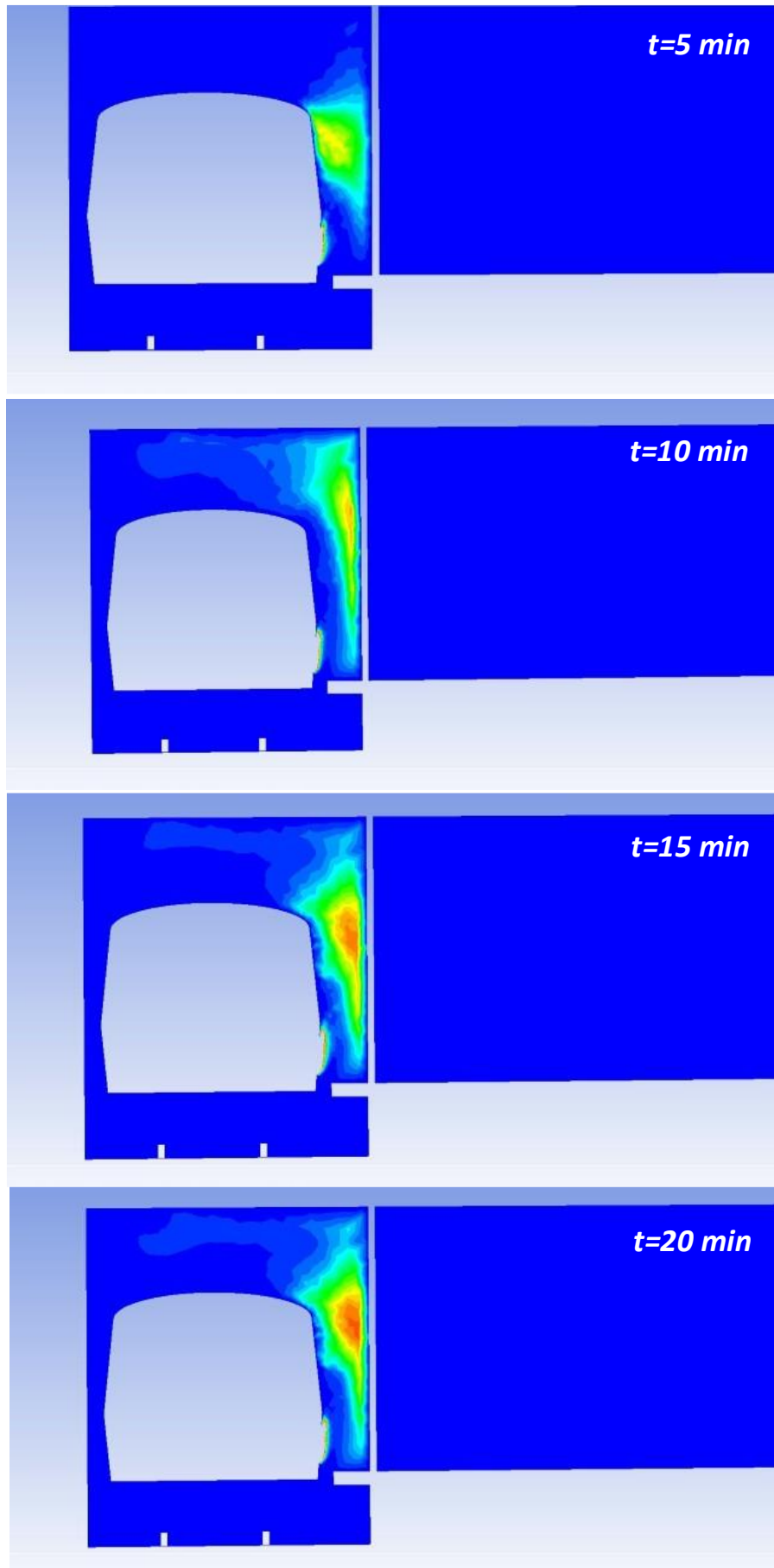


Fig. 29 Cross-section through the fire source – air temperature fields - minutes 5-20 ($^{\circ}\text{C}$)

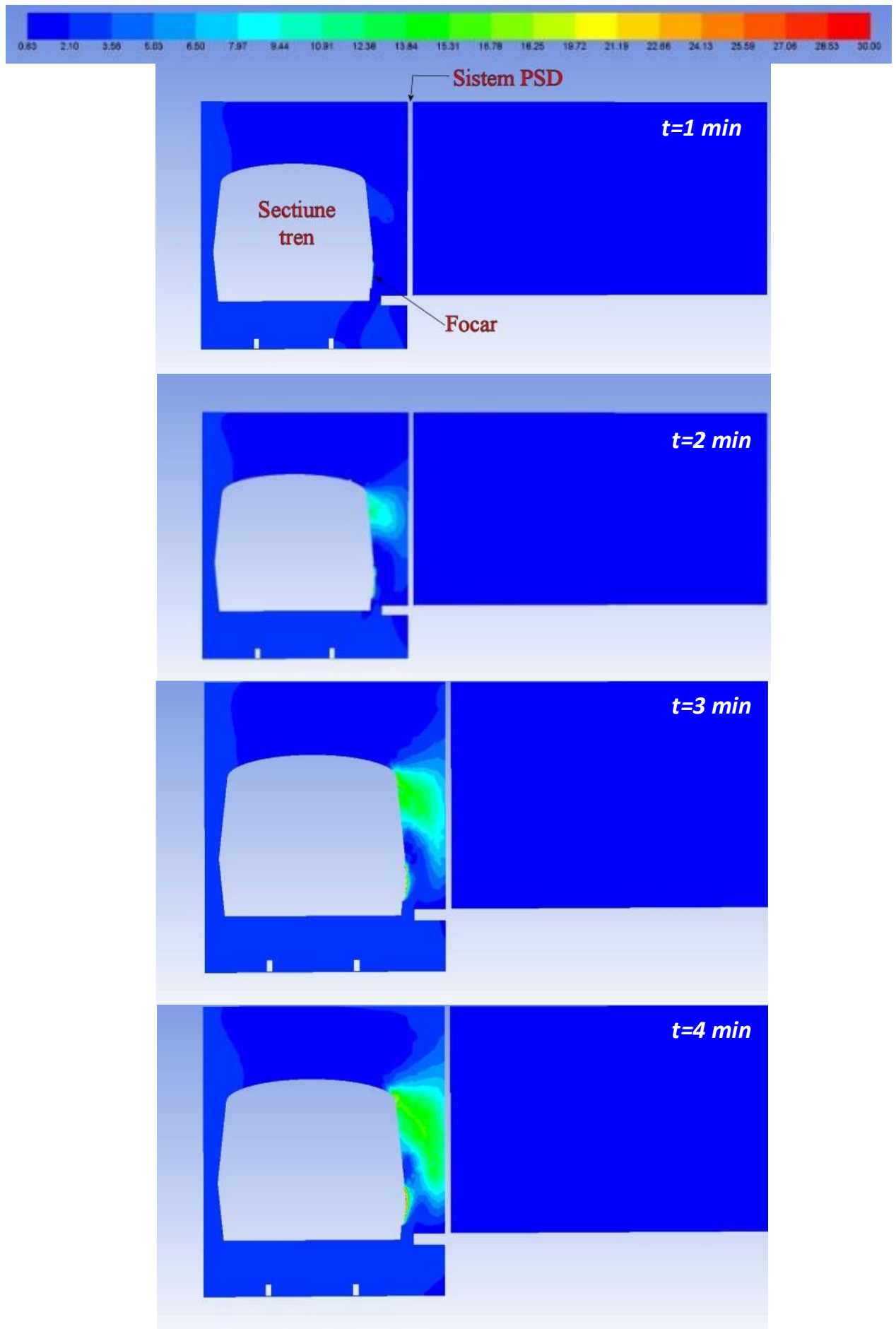


Fig. 30 Cross-section through the fire source – CO concentration fields - minutes 1-4 (ppm)

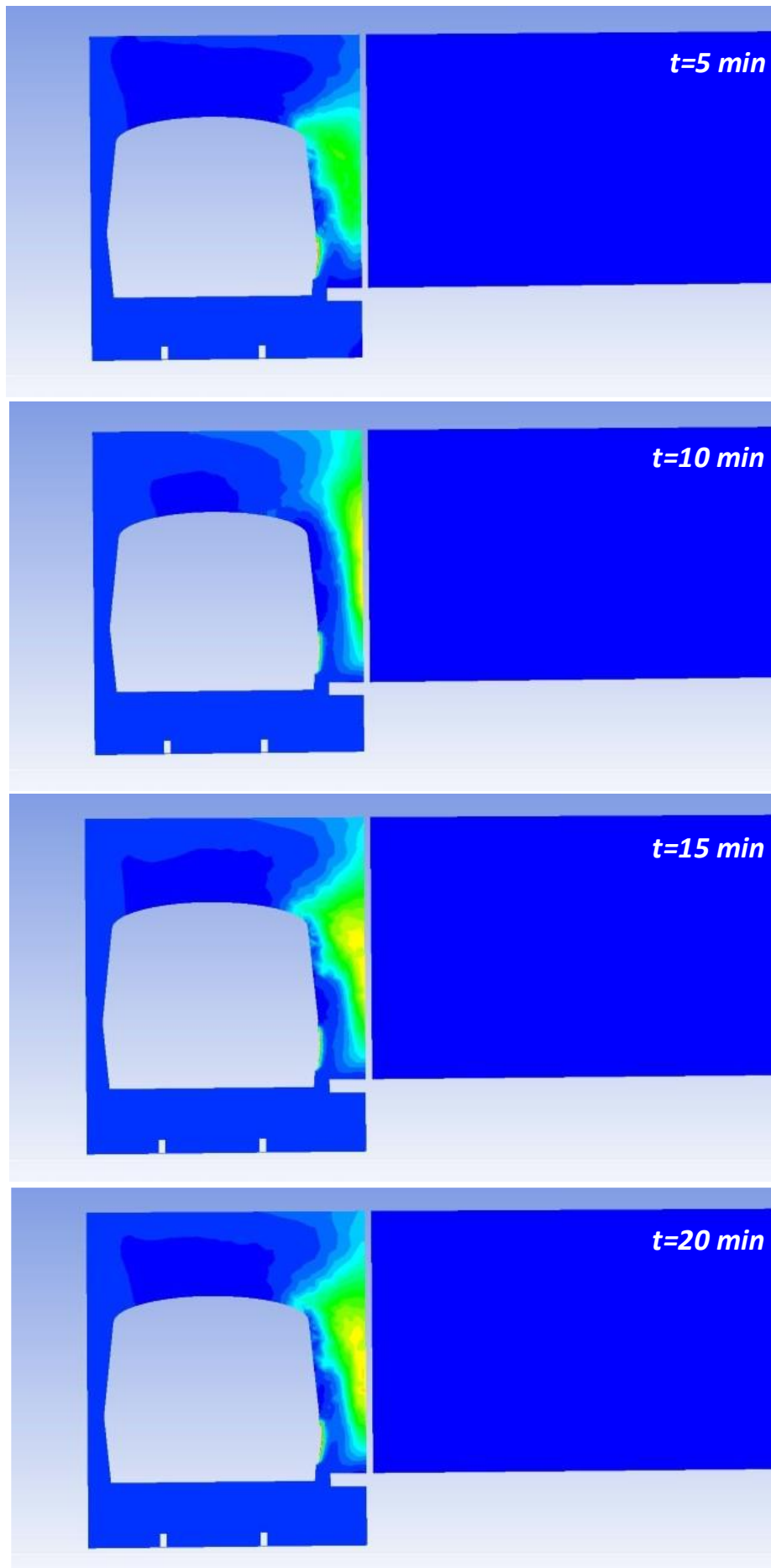


Fig. Cross-section through the fire source – CO concentration fields - minutes 5-20 (ppm)

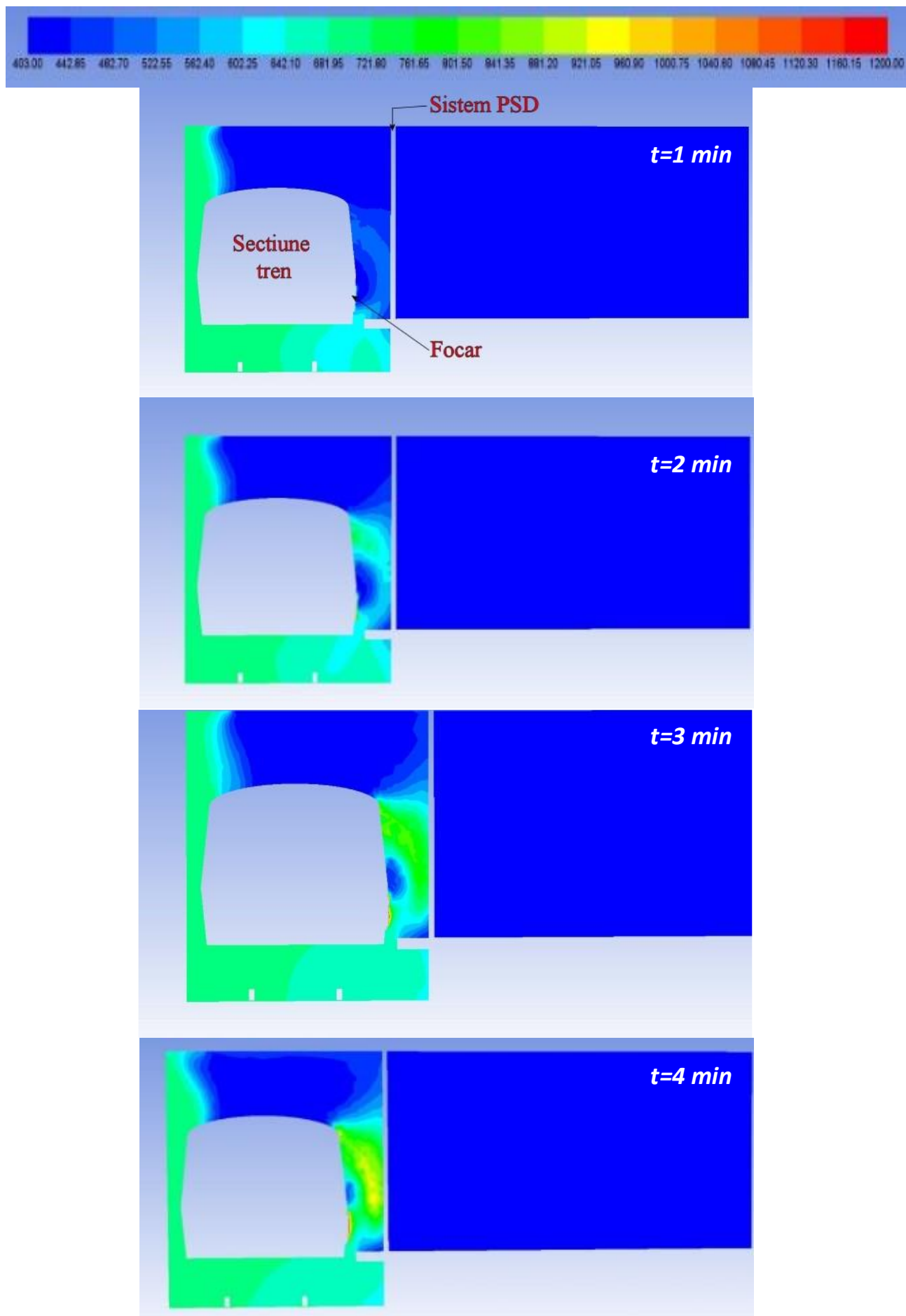


Fig. 31 Cross-section through the fire source – CO₂ concentration fields - minutes 1-4 (ppm)

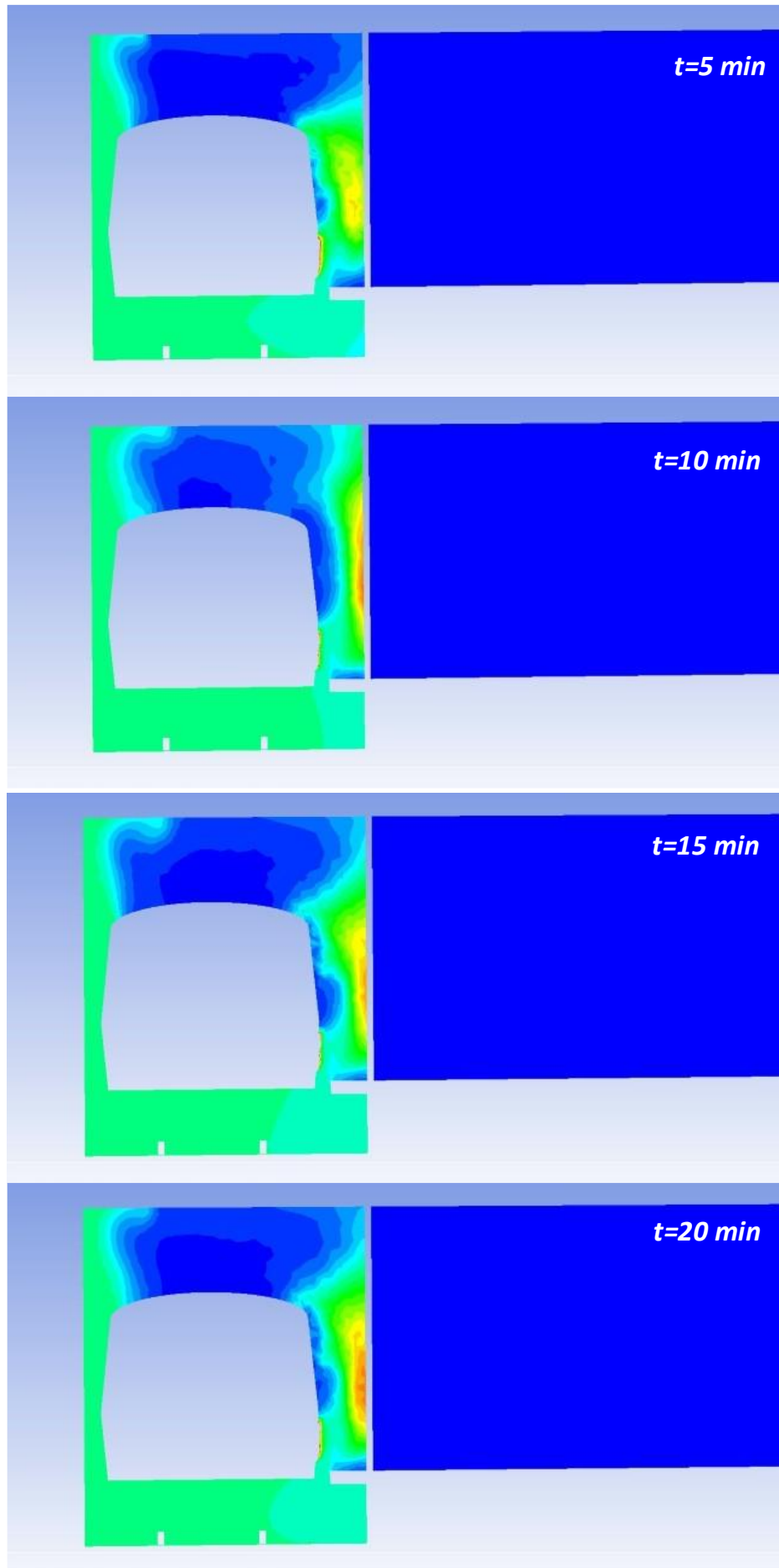


Fig. 32 Cross-section through the fire source – CO₂ concentration fields – minutes 5-20 (ppm)

Fig. 36 - Fig. 41 show the air temperature fields, CO concentration, respectively CO₂ concentration through the PSD door to the left of the fire source, the one through which the highest chances for hot air or pollutants to enter the station.

As can be seen, the PSD frame that is at the top of the door and rises to the ceiling has a role as important as the part between two consecutive doors, as it is a physical barrier that blocks the access of smoke generated by fire to space platform. As they are approximately 2 m from the fire source, the temperature and CO/CO₂ concentration fields in this section highlight the buoyancy effect of the smoke generated by the fire.

Although no ventilation system under the platform is included in this cross-section, the effect they have on hot air and pollutants near the hearth can be seen. By their action, the ventilation devices of the area under the platform help to limit the access of smoke in the area of the platform.



Fig. 33 Cross-section through the PSD door near the fire – air temperature fields - minutes 1-4 ($^{\circ}\text{C}$)

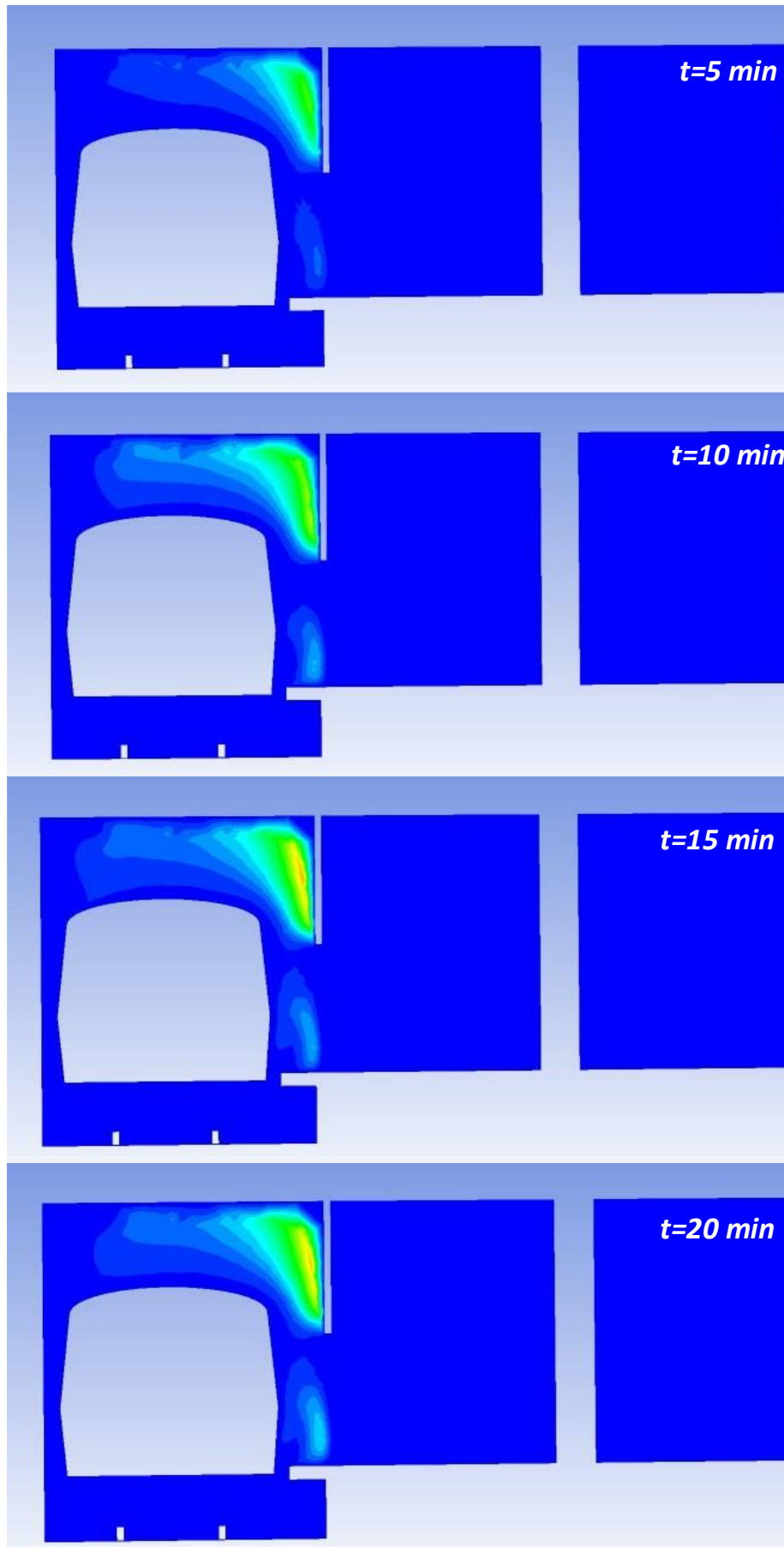


Fig. 34 Cross-section through the PSD door near the fire – air temperature fields - minutes 5-20 ($^{\circ}\text{C}$)

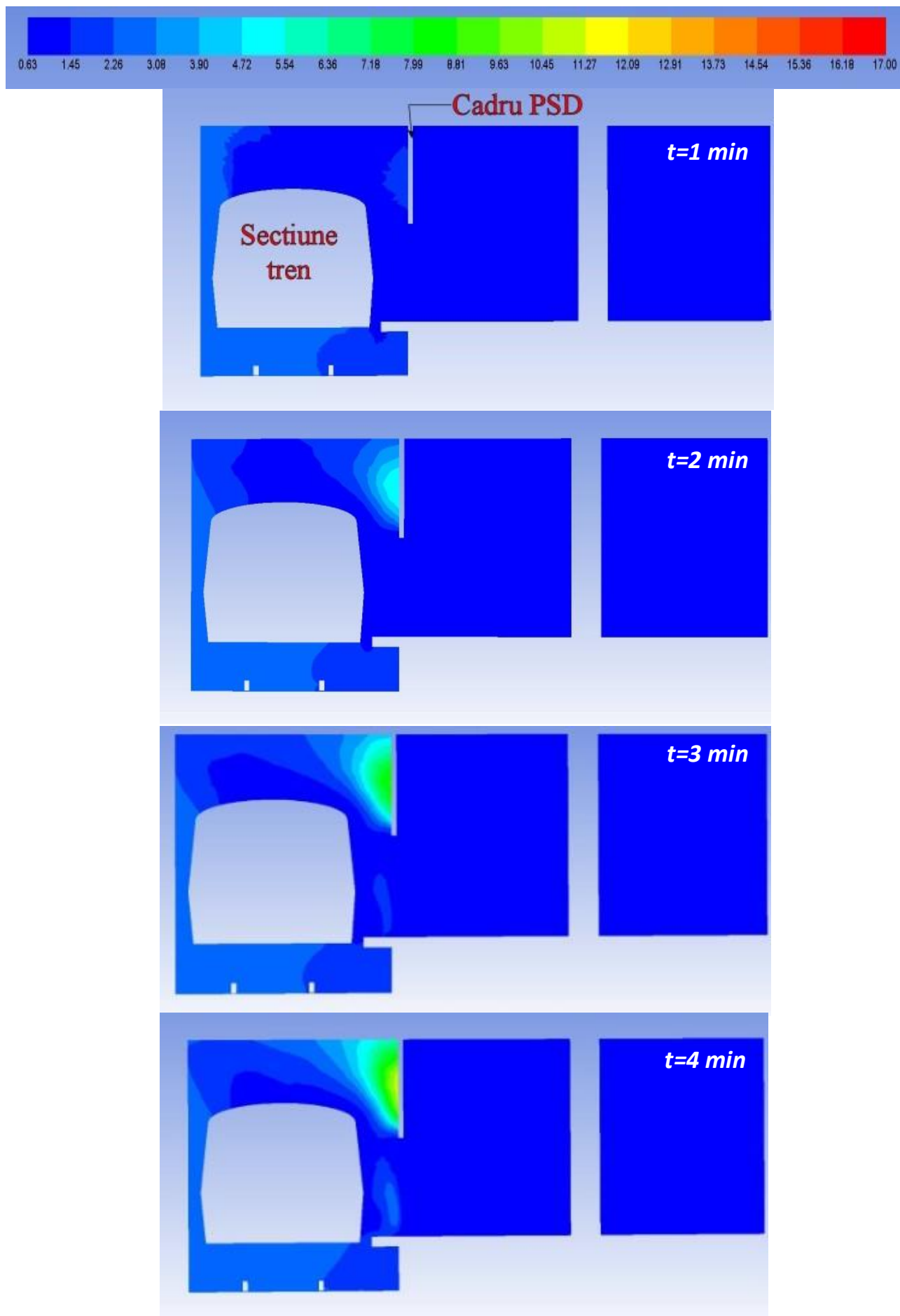


Fig. 35 Cross-section through the PSD door near the fire – CO concentration fields - minutes 1-4 (ppm)

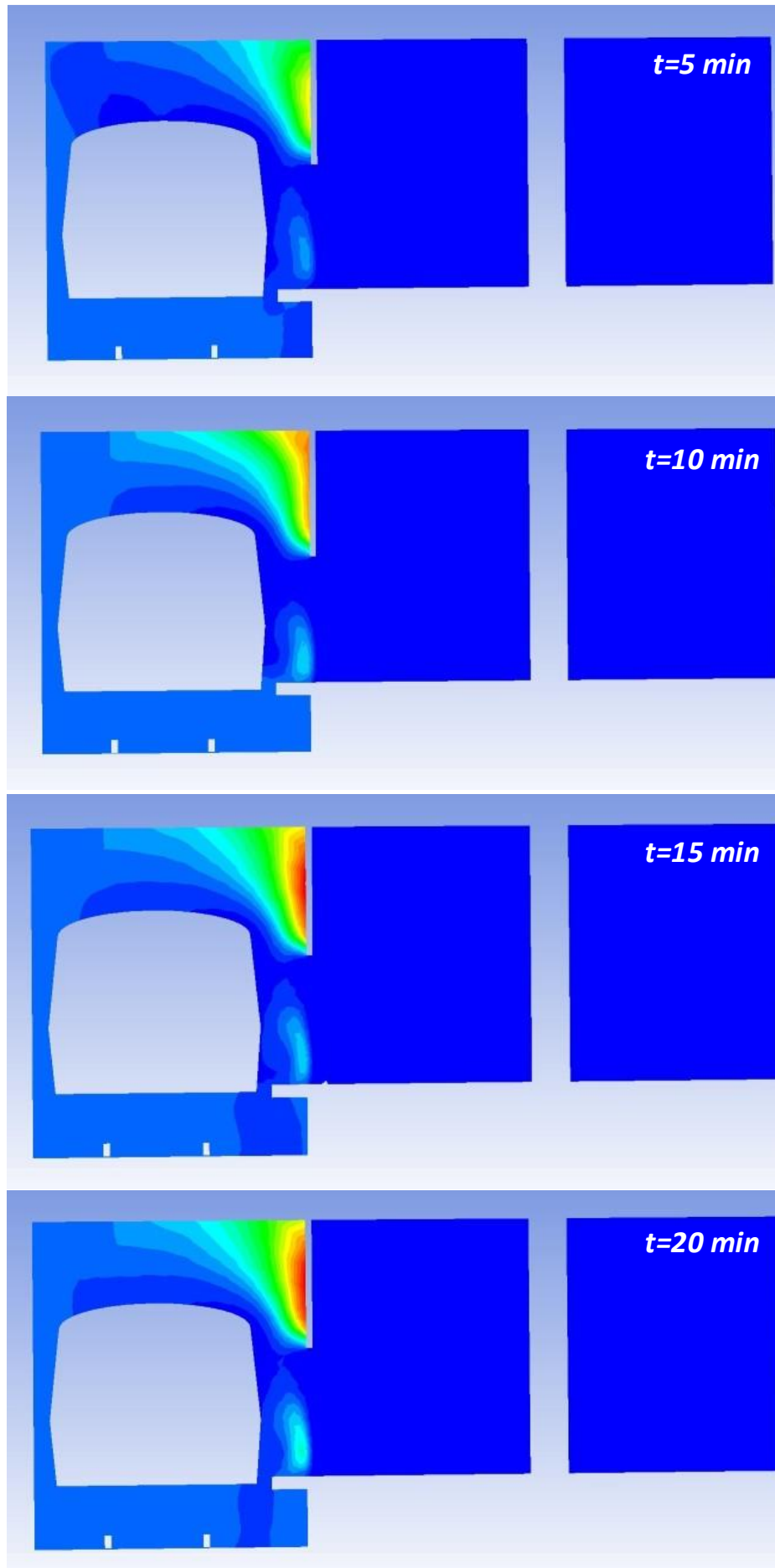


Fig. 36 Cross-section through the PSD door near the fire – CO concentration fields - minutes 5-20 (ppm)

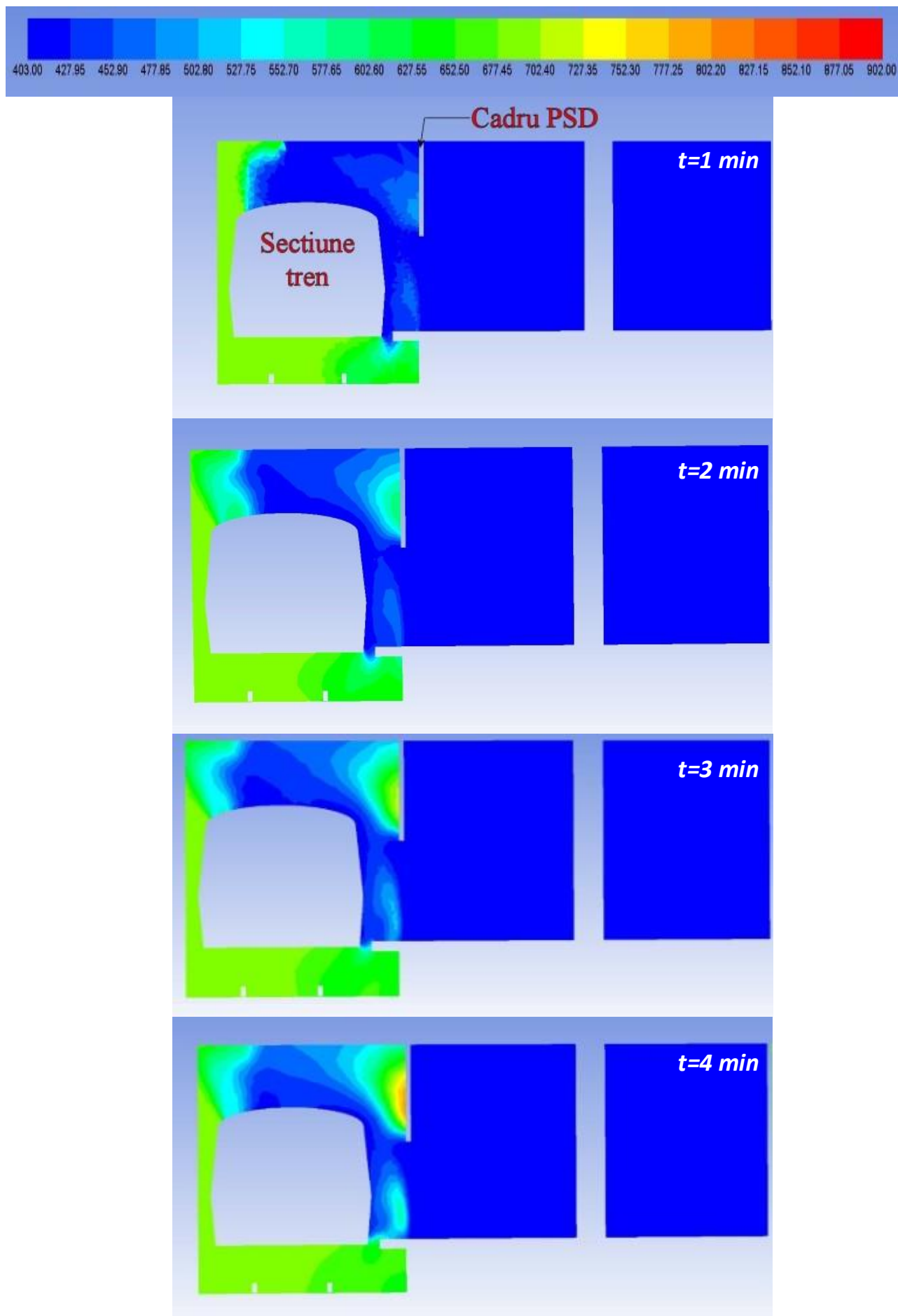


Fig. 37 Cross-section through the PSD door near the fire – CO₂ concentration fields - minutes 1-4 (ppm)

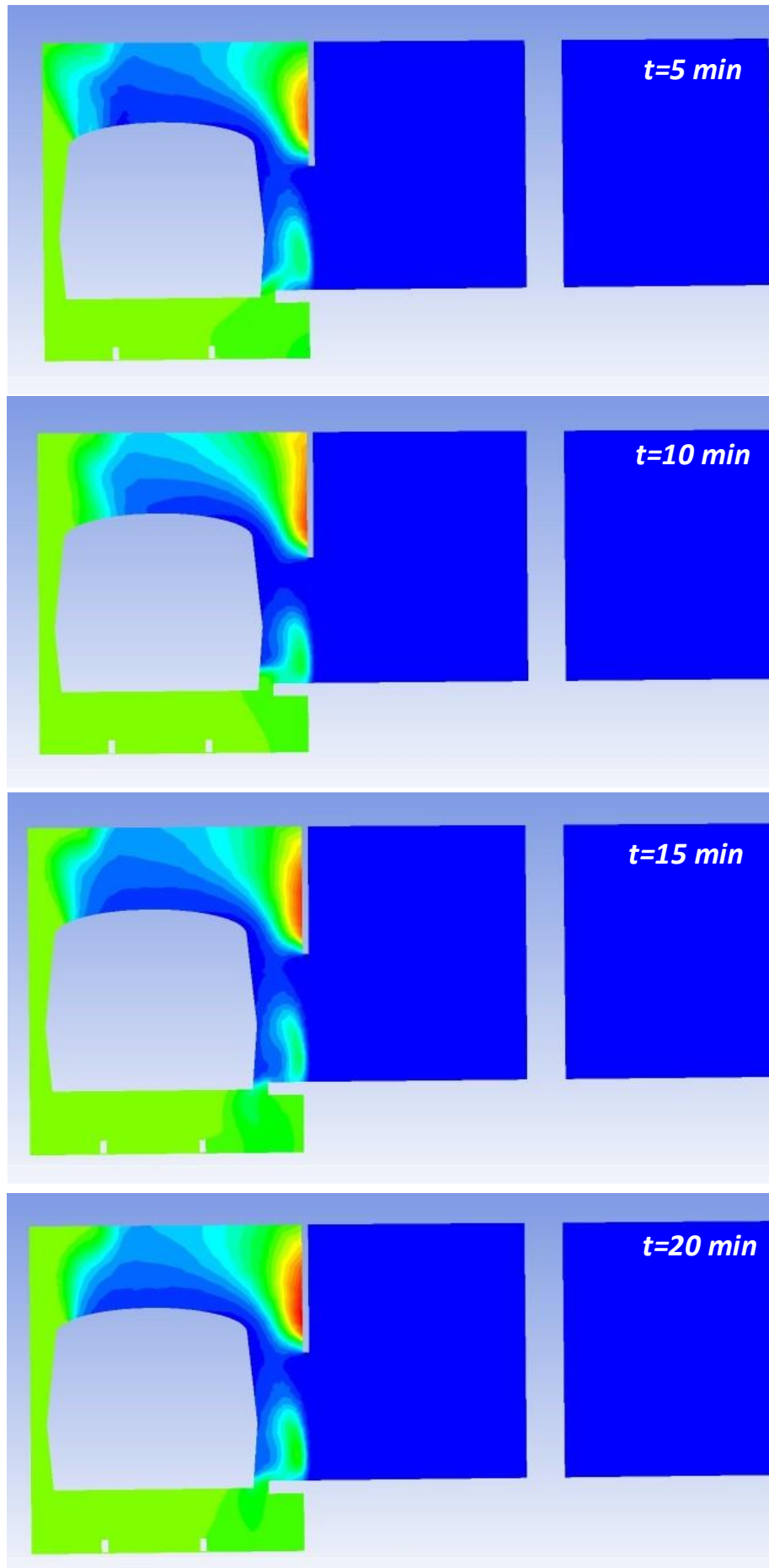


Fig. 38 Cross-section through the PSD door near the fire – CO₂ concentration fields - minutes 5-20 (ppm)

4.7. Synthesis and conclusions

In this chapter, the operation of the proposed ventilation system for a subway station with two underground levels equipped with PSD type doors was verified for the scenario of a burning train stopped at the platform. In this sense, the way of constructing the geometry at 1: 1 scale, the realization of the discretization network, the imposed boundary conditions, the modelled physical phenomena, the simulation procedure and the results obtained both in steady state and in transient mode were presented.

The steady-state simulation was performed to stabilize the air flow through the calculation domain before introducing the fire as a source of heat and pollutants (CO and CO₂). The velocity fields obtained in a longitudinal section through the centre of the circular ventilation devices located above the train tracks in the metro station, as well as in a horizontal plane through the ventilation devices of the area under the platform confirm that the flow regime is stable and the results can be used as initialization values for the transient simulation.

According to the fire scenario, with the transition to simulation in transient mode, the fire source was introduced as a source of heat and pollutants, located in the middle of the length of the train, on its lateral side. The results of the transient simulation are presented minute by minute for the first 5 minutes after the fire broke out, respectively after 10, 15 and 20 minutes, to check if the hot air or pollutants generated by the fire reach the platform area. The results are presented in the form of fields of air velocity, air temperature and CO/CO₂ concentrations of air in longitudinal sections (through the circular ventilation devices arranged above the train rails) and transversal (through the fire source and through a PSD door).

The cross-sections through the fire source reveal that the maximum air temperature in the area between the fire and the PSD system is 900⁰-1100⁰C, in accordance with the results obtained experimentally in the EUREKA study [80]. Also, the temperature and pollutant fields presented highlight the effect that the PSD system has in limiting the spread of hot and polluted air in the area of the platform, where in the first 10 minutes the emergency evacuation of people takes place.

In the cross section and the horizontal plane through the PSD door it is observed that the hot air and the high concentrations of pollutants propagate above the door and are retained in the tunnel by the PSD system that occupies the space between the door and the ceiling. Also, the speed vectors highlight the air circulation from the station to the tunnel, as a result of the extraction of air from the tunnel through the circular ventilation devices located above the train. In addition, at the bottom of the sections, the effect of the operation of the ventilation system of the area under the platform is observed, which amplifies the air circulation from the station to the tunnel. **Therefore, in the scenario proposed in this study, the PSD door system has a particularly important role and contributes significantly to limiting the spread of smoke from the tunnel to the subway station.**

5. Personal contributions

This doctoral thesis covers a complex and strongly interdisciplinary field, addressing topics related to fire safety engineering (characteristics of a fire source, fire effluents, emergency evacuation of passengers etc.), civil engineering (ventilation in normal and emergency situations, the arrangement ventilation plants, the location of ventilation devices in the subway station, etc.), as well as CFD modelling and simulation.

In this sense, a first element of originality of the thesis is the collection, centralization and processing of information on technical prescriptions, norms and national and international standards on the safe operation of subway networks. For this bibliographic study, information was requested from private and state-owned companies that manage the metro networks of the largest cities in Europe (Metro Madrid, Hamburg Hochbahn AG, Norwegian Railway Authority, RATP Group – Paris, ATAC S.p.A. – Roma, UITP - International Association of Public Transport) and outside Europe (MTR Corporation Hong Kong, National Research Council Canada, National Fire Protection Association - USA, Ministry of Land, Infrastructure, Transport and Tourism - Japan). The collected information resulted in a comparative study on the technical regulations that must be met by the administrators of subway networks to ensure the safe evacuation of passengers from subway stations and tunnels in case of fire, the conclusions being presented in Annex no. 1.

The personal contribution of the first two chapters of the thesis is that the latest information and numerical studies on fires in tunnels and subway stations have been identified, classified and synthesized. Thus, the current state of knowledge in the field of doctoral thesis was presented and a review article was prepared on numerical studies regarding the operation of ventilation systems specific to subway networks in emergency situations, which was presented in the second conference of the UTCB Doctoral School (2019).

Given that the field of CFD modelling and simulation is extremely complex, with many fields of study and engineering applications, the personal contribution in the third chapter lies in collecting and synthesizing essential theoretical information on performing a numerical simulation of airflow through a complex domain.

Probably the most important element of originality in the thesis is the realization of the 3D geometry of the subway network consisting of two subway stations and the connecting tunnels between them, as well as the development of the numerical CFD model for this configuration. The novelty and specificity of this approach consists in the fact that the tunnels are curved, and one of them is inclined with a slope of 3.1%. This tunnel configuration is the least studied, being both rare and difficult to reproduce experimentally and there are a small number of articles that present numerical simulations of fires in such tunnels. Numerical models developed in this doctoral thesis may be the basis for other simulations targeting different emergency scenarios, new ventilation solutions, the influence of constructive changes on the comfort or safety parameters of the station, etc.

Although PSD security doors are built in most of the new subway stations, there are not many studies that address their impact on passenger safety in the event of a fire in a subway station. Moreover, the study presented in Chapter 5 is the first study on the impact of PSD doors in a subway station in Bucharest, thus representing a major original contribution to the thesis at the national level. The study can be extended to other subway stations in Bucharest or even to new subway networks, such as the subway network that will be built in Cluj-Napoca.

Another original aspect of the numerical studies presented is the way in which the fire outbreak was simulated. Thus, the mass concentrations of monoxide and carbon dioxide produced by the combustion of a PMMA fire source characterized by a heat release rate of 30 MW and 10 MW, respectively, were extracted from Fire Dynamics Simulator and used as input data in Ansys Fluent 15.0 for the description of the fire.

The results of the research carried out during the doctoral study program, both those related to the conclusions of the bibliographic study and those related to the results of numerical simulations, were disseminated as follows:

1. Review of numerical studies on ventilation systems for subway networks in emergency situations

- Authors: Vladimir Kubinyecz și Cătălin Teodosiu.
- Presented at the 2nd Conference of the UTCB Doctoral School (2019).
- Published in *IOP Conference Series: Earth and Environmental Science*, Volume 664, Issue 1, pp. 012093 (2021), DOI: 10.1088/1755-1315/664/1/012093.

2. Verification of ventilation system efficiency in a curved subway tunnel in case of fire using numerical modeling

- Authors: Vladimir Kubinyecz și Cătălin Teodosiu.
- Presented at "10th International Conference on Energy and Environment" (2021).
- Published in *IEEE Xplore* în 29 November 2021, DOI: 10.1109/CIEM52821.2021.9614790.

3. Numerical study on smoke evacuation from a curved subway tunnel

- Authors: Vladimir Kubinyecz și Cătălin Teodosiu.
- Presented at the 4th Conference of the UTCB Doctoral School (2021).

4. Numerical evaluation of emergency ventilation system design in a curved and sloped subway tunnel in case of fire

- Authors: Cătălin Teodosiu, Vladimir Kubinyecz și Raluca Teodosiu.
- Pending approval to be published in *Environmental Engineering and Management Journal*.

6. Concluzii și perspective

The general objective of the doctoral thesis is to develop numerical models that can verify the operation of ventilation systems in emergency situations represented by a train on fire stopped in the tunnel between two stations, as well as a train on fire stopped on the platform in a subway station.

Following the bibliographic study, it was concluded that most research related to subway tunnel fires concerns straight tunnel configurations, with inclined and curved tunnel configurations being the least investigated, although the degree of inclination of tunnels influences the distribution of smoke and hot gases because of the specific thermal phenomena that occurs (“buoyancy effect” and “stack / chimney effect”), and the asymmetry of the walls of a curved tunnel influences the movement of smoke and decreases the efficiency of longitudinal ventilation. Regarding the study of fires in subway stations, the studied bibliography reveals that PSD doors contribute to increasing the comfort of passengers in subway stations and contribute to faster evacuation of smoke generated by fires, also increasing the time available for evacuation of passenger in emergency situations.

Regarding CFD simulations, based on the analysis performed and the results obtained, it can be stated that the developed CFD numerical model is reliable and can be used successfully in predictions on investigating the efficiency of ventilation systems in case of emergencies that may occur in subway networks.

In this regard, the numerical study on the evacuation of smoke from an inclined and curved tunnel found that the proposed ventilation system ensures the optimal conditions for the safe evacuation of passengers, as no high concentrations of pollutants or high temperatures were identified on the escape route of passengers (maximum temperature of 35⁰C and CO concentrations below 2000 ppm, respectively CO₂ below 60,000 ppm).

Also, in the numerical study on smoke evacuation from a subway station with two underground levels, it was observed that, although the PSD doors near the burning train are permanently open, the hot air (temperatures between 900⁰-1100⁰C) and high concentrations of pollutants (values of 6,450 ppm for CO and 77,000 ppm for CO₂ in the space between the fire source and the panel of the PSD system) propagate above the door and are retained in the tunnel by the PSD system occupying the space between the door and the ceiling. In addition, the results presented showed the circulation of air from the station to the tunnel, as a result of the extraction of air from the tunnel through the circular ventilation devices of the general ventilation system of the station.

It should also be noted that the CFD models developed can still be used to simulate other emergency scenarios. With regard to the scenarios analysed in this thesis, all the data indicate that the proposed mode of operation for the ventilation system of the subway network ensures the necessary conditions for emergency evacuation of passengers from the tunnel (in the case of a scenario involving a burning train stopped in the tunnel) and from the subway station (for the scenario with a burning train stopped at the platform in the station provided with PSD type systems).

Taking into account the workload for the construction of the geometry, the realization of the mesh network and the identification of the appropriate numerical solving methods for the two CFD numerical models, the time allocated to the study of possible ventilation scenarios was limited. A possible continuation of the two studies is, as mentioned above, the investigation of different emergency scenarios. For example, starting from the first numerical model, one can study the

consequences of changing the ventilation direction from the tunnel (from 1Mai station to the Pajura station) or changing the position of the train stopped in the tunnel. The effect of the 3-minute delay required to change the direction of rotation of the ventilation plants fans on the spread of smoke on the passenger exhaust route could also be studied. Regarding the second numerical model presented, starting from the same emergency scenario, the effect of opening the PSD doors on the opposite side or starting the end-of-tunnel ventilation plant near the station could be studied. It could also be analysed how the smoke is extracted in case of a fire on the subway platform, correlated with the opening / closing of PSD doors, as well as the implementation of other forms of ventilation devices (not only the circular ones used in the present study).

Given that the design rules for specific subway constructions and installations for fire prevention and extinguishing were issued in 2002 and do not refer at all to PSD door systems, the conclusions of the study presented in this thesis may be the basis for updating the respective legal documents. Moreover, following the model of relevant legislation in other countries (eg Italy and the USA), we consider it appropriate to be mandatory to perform numerical simulations to verify fire safety scenarios for all new subway constructions and optimize safety solutions for those already in operation.

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