# ANALYSIS OF SMOKE STRATIFICATION AND SMOKE LAYER THICKNESS IN UNDERGROUND CAR PARKS

by

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*Fire accidents in underground car parks have a significant impact on the building structure and lives of people and firefighters. Different methods are used to obtain a reliable estimation of fire and hot smoke influence on the building structure. Numerical modelling is crucial in the fire design and is a useful tool to determine smoke stratification and clear layers for safe human evacuation and firefighter access. Smoke stratification can be checked separately for any time interval in any section of an underground car park, regardless of the underground car park architecture complexity. This paper describes numerical modelling of smoke stratification and movement in an underground car park. The results show smoke movement and smoke layer thickness during the evacuation time, and how they can help reduce the harmful influence of fire on the underground car park structure.*

Key words: *fire, smoke stratification, smoke movement, smoke layer thickness, underground car park, numerical modelling*

## Introduction

Fire accidents occur rarely, and people, in general, do not spend much time in underground car parks. However, in the unlikely event that one occurs, fire accidents can have a significant impact on the building structure and lives of people and firefighters. Hot smoke inhalation is the primary cause of death in fires. The exposure of the concrete construction of an underground car park to hot gases can cause concrete spalling and create dangerous conditions for people and firefighters.

The heat release rate (HRR) is the critical parameter to characterize a fire. The HRR is the rate at which heat is generated by fire and directly affects the absolute temperature values [1]. Different methods have been developed to estimate HRR. In underground car parks, the fire is likely to be in a car. Many different car fuel properties and characteristics influence the HRR. Furthermore, the HRR is affected by the behaviour of the burning car, and fire experiments have been carried out to establish this [2]. Analysis can provide a comparison between cars using different fuels, such as compressed natural gas, petrol [3] and liquefied petroleum gas (LPG) driven vehicles [4]. The accidental releases of LPG fuel [5] or air-conditioning refrigerants [6] can also cause dangerous conditions in underground car parks. It

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is crucial to estimate the HRR accurately [7]. Otherwise, the fire accidents may cause unexpected damage.

If installed, the mechanical smoke extract ventilation is switched-off during the evacuation time. Otherwise, mechanical smoke extract ventilation can cause turbulent smoke flow which can stop natural smoke movement and stratification. Therefore, the natural ventilation has an impact on the smoke flow and stratification in an underground car park. The lowest natural ventilation rate is when the difference between outdoor and the indoor temperature is small [8]. In the summertime, natural ventilation rate is significantly lower than in winter [9].

Numerical modelling is a useful tool to determine smoke movement and stratification, smoke layer thickness, temperature fields and visibility. It can also be used to simulate and model air stagnation areas, streamlines, fire growth and mechanical smoke extract ventilation efficiency. These parameters can be checked separately for any time interval in any section of an underground car park [10], regardless of the complexity of the underground car park architecture, although, the analysis results show the sensitivity on the implemented mesh size [11]. Furthermore, the results depend on the boundary conditions.

To design a mechanical ventilation system [12], to analyse the air stream driven by installed fans [13], to analyse the mechanical smoke extract ventilation system for smoke control [14], to optimise the mechanical ventilation system in an underground car park [15] or to study the smoke flow control [16], various numerical modelling software packages can be used. The behaviour of the underground car park structure when exposed to fire [17] and the fire influence on a concrete frame [18] are analysed. The influence of all vertical obstructions, columns, beams and partition walls can also be analysed [19].

The fire dynamics simulator (FDS) code was used to investigate smoke stratification, smoke movement and fire spread in underground car parks. The experimental results of HRR of a single car fire were compared [20]. In addition, FDS was used for parallel computer simulation of the smoke stratification [21], and various experimental parameters were implemented into the FDS numerical simulations [22]. The explosion caused by leaked LPG during the car servicing was analysed using numerical simulations [23].

In the year 2003, in the Norwegian tunnel Runehamar, five large-scale tests, four heavy goods vehicles mock-up and one pool fire test were carried out [24]. The results from the fire tests in Runehamar tunnel were used to validate the theoretical models and numerical simulation results [25].

After the evacuation time expires, if installed, the mechanical smoke extract ventilation is switched on. The system provides the extraction velocity, needed to establish a clear layer, with no smoke for safe firefighter approach before on-site arrival. In underground car parks with no installed smoke extraction systems, natural ventilation must provide a sufficient extraction velocity. Numerical modelling can be used to analyse the extraction velocity in an underground car park [26]. An empty underground car park is often assumed to simplify the numerical modelling setup, although, cars are obstacles to the smoke movement and stratification [27].

The timely fire detection is one of the most important issues [28]. Besides the smoke and flame detectors and other sensors, multi-model flame and smoke detectors can be used for the fire detection in underground car parks [29]. The main tasks of passive and active fire protection systems are life-safety and reducing damage to the buildings in the case of fire. Human behaviour and reactions in fires and psychological anxiety caused by the fire are identified as the key behavioural factors affecting the performance of humans in a burning building. Evacuation start time, which guarantees the safety of evacuees, is determined by many kinds of factors. All underground car park occupants must be able to safely find the exit during the evacuation period, including disabled people [30]. Risk perception and decision-making, along with psychological deviation and cultural background, are interactional factors that influence reactions in the case of fire before evacuation [31]. The use of stairs, evacuation elevators, sky-bridges and the characteristics of other vertical egress components are taken into account in modern egress designs [32].

Fire growth rates, slow, medium, fast or ultra-fast, are determined by a fire growth coefficient, which has a direct influence on smoke propagation and movement in enclosed spaces. Furthermore, smoke propagation can be easily calculated. However, the smoke layer thickness cannot be estimated. Therefore, numerical simulations, along with the results provided by experiments, are essential to determine smoke layer thickness. Numerical modelling results can be used to analyse evacuation procedures after a fire occurs and evacuation signs installation height in underground car parks.

## Numerical modelling setup

In-building experiments give a real insight into fire behaviour in underground car parks but are limited by safety and cost considerations. Simplified experiments can provide valuable data, but transfer and scaling from the model to the full-scale in most cases is impossible or unreliable. The numerical modelling has been carried out to estimate a smoke movement in a real underground car park to have the most realistic results as possible. Figure 1 shows underground car park layout.

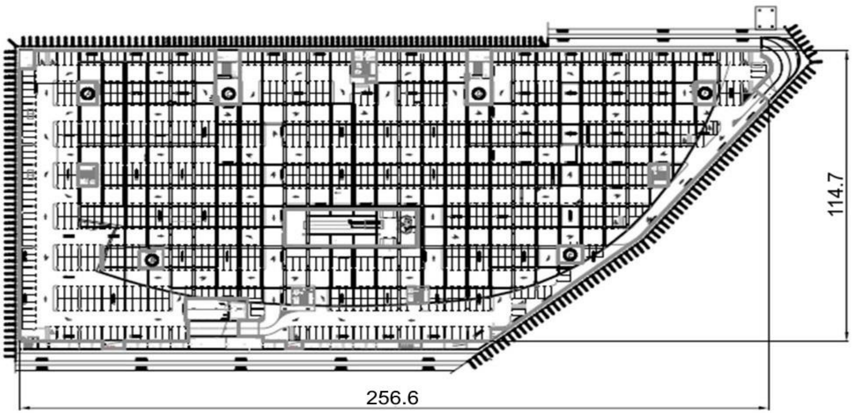


**Figure 1. Underground car park layout**

The analysis has been carried out using commercial CFD code ANSYS/FLUENT. The code is based on a finite volume approximation of Raynolds-averaged Navier-Stokes equations (RANSE). An additional scalar transport equation solved for smoke stratification and smoke movement.

Main underground car park geometric particulars, length, width, height are shown in tab. 1.

Smoke stratification and smoke movement are being predicted in large spaces of an underground car park. Thus, the far-field smoke behaviour is of most interest. Of course, the numerical mesh resolution and mash aspect ratio have a significant influence on the accuracy of prediction for RANSE model. Explicit marching scheme was applied. The mesh used for

**Table 1. Main underground car park geometric particulars**

| Ordinal | Title | Symbol | Value | Unit |
|---|---|---|---|---|
| 1 | Length | $L$ | 265 | m |
| 2 | Width | $B$ | 115 | m |
| 3 | Height | $h$ | 2.90 | m |
| 4 | Net parking area | $A$ | 24100 | $m^2$ |
| 5 | Volume | $V$ | 70000 | $m^3$ |

computations was of an unstructured polyhedral type, consisting of approximately 2.4 million cells [33]. The results were compared with previously published experimental and the literature data. No significant differences in the results were found. The quality of the mesh, in this case, is satisfactory for this analysis.

The heat release and smoke movement were computed for the full-scale object. The initial temperature was 15 °C. The constant temperature was set for whole underground car park structure. At the start of the simulation, calm conditions at the ambient temperature were imposed. No ventilation flow was imposed at the beginning. Standard wall function was used.

Fire simulation was conducted using a volumetric heat source model. This model simulates fire as time-varying heat and mass source over prescribed volume, imposing uniform scalar distribution. Smoke stratification and smoke movement were predicted in large spaces of the underground car park. Thus, the far-field smoke behaviour is of most interest. Therefore, the use of the volumetric heat source model was the preferred approach here. Since radiation heat transfer was not taken into account, temperatures are absolute and most likely are not representative.

Computational domain took into account the complexity of the underground car park geometry, and the influence all vertical obstructions, columns and partition walls had on the smoke movement. Total analysis time is three minutes. This time is considered as the people evacuation time when the maximum fire HRR is achieved. In 60 seconds the maximum HRR is achieved and last for next 120 seconds. The analysis is characterized by an intense heat release and smoke movement inside a computational domain due to natural convection.

During the analysis, a time step was constant and set to 0.1 seconds and is good regarding stability [19, 33]. The transport of species, velocity and temperature fields in the computational domain, were solved iteratively. A maximum number of iteration during one-time step was 10 and held constant during the analysis. Numerical simulation setup characteristics are shown in tab. 2.

All HRR modelling parameters are shown in tab. 3.

The fire heat release rate $Q(t)$ is given by:

$$Q(t) = \alpha t^2 \tag{1}$$

Part of released heat $Q(t)$ is transferring by the radiation to the surrounding concrete walls. It is absorbed without being reflected back to the flow domain (radiation losses). The radiation decreases the HRR value. The radiation heat transfer was not considered in the analysis. The radiation loss value is expressed by a radiation loss ratio; heat lost due to radiation is relative to the produced heat. The fire shape is assumed to be a cylinder to coarsely match the shape of fire. Fire volume is 11.5 $m^3$. The computational domain outline is shown in fig. 2, and computational domain detail and fire shape are shown in fig. 3.

The fire is situated at the position shown in fig. 4, marked with the circle. The influence of other active fire protection systems, primarily, sprinkler installation, is not considered in the numerical modelling setup. Otherwise, the fire will not reach the maximum HRR value. Natural ventilation influence on the smoke movement is also not considered.

Numerical modelling was divided into two steps. First, the fire was modelled in steady state form using the maximum HRR and smoke production values for worst case scenario. In the second stage, the time-dependent analysis was used to verify the solution. The analysis demonstrates that conditions do not worsen over time.

Total time of three minutes (180 seconds) was chosen according to the real evacuation time from underground car parks. The more smoke produced, the worse conditions are in an underground car park. Usually, the evacuation time is 3 or 4 minutes after the fire occurred. After the evacuation time expired, the smoke extraction system is switched on.

**Table 2. Numerical simulation setup – main characteristics**

| | |
|---|---|
| Spatial discretization | Three dimensional |
| Fire model | Volumetric heat source |
| Species transport | Two component mixture (gas-air) |
| Natural convection | Full buoyancy effects |
| Thermal conductivity | Mass weighted mixing law |
| Type of flow | Viscous turbulent |
| Turbulence model | *k*-*ε* turbulence model |
| Time modelling scheme | Unsteady |

**Table 3. Heat release rate modelling parameters**

| Ordinal | Name | Symbol | Value | Unit |
|---|---|---|---|---|
| 1. | Maximum heat release rate | $Q_{max}$ | 8 | MW |
| 2. | Time instant – growth stage is terminated | $t_g$ | 60 | s |
| 3. | Time instant – before extinction stage begins | $t_e$ | 180 | s |
| 4. | Growth coefficient | $\alpha$ | 2,200 | $Ws^{-2}$ |
| 5. | Radiation loss ratio | – | 0.25 | – |

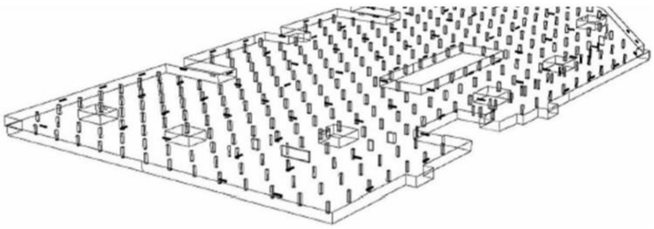

**Figure 2. Computational domain outline**

## Results

In the beginning, after the fire occurs, the fire produces a buoyant smoke plume. The plume rises above the source of fire until it reaches the underground car park ceiling. Smoke movement is shown in the figs. 5-8. After 50 seconds, due to the pillar's position in the underground car park, the smoke is moving in the form of a shamrock pattern. The underground car park has no beams, and besides pillars, no obstacles to smoke movement are present. The smoke is spreading uniformly in all directions from a fire. The smoke reached the boundary wall in the middle of the underground car park between 60 and 70 seconds after the fire occurred. That obstacle stops smoke movement in that direction and channels it to move mainly in the x-direction. After approximately 150 seconds, the smoke reached the outside boundary wall. From that moment on, the smoke can spread only in the x-direction.

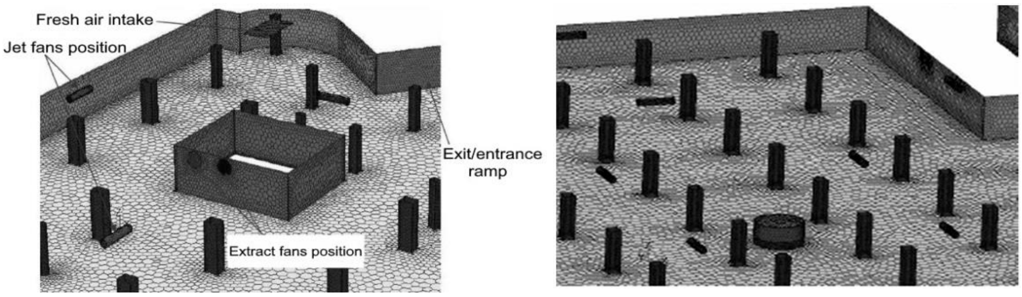


**Figure 3. Computational domain detail and fire shape**

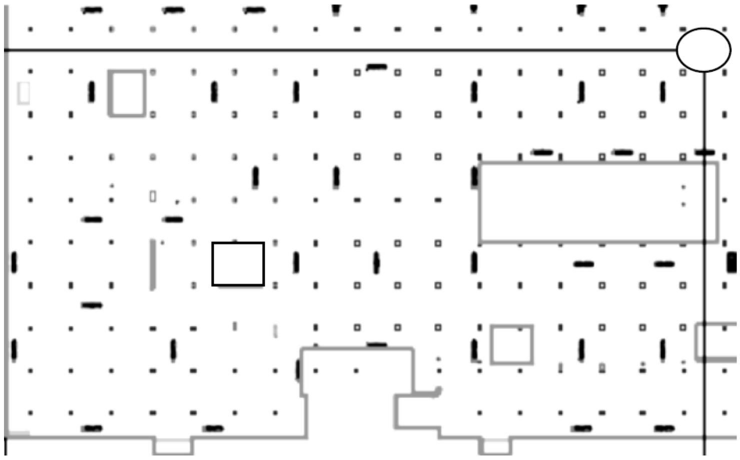

**Figure 4. Fire position in the underground car park**

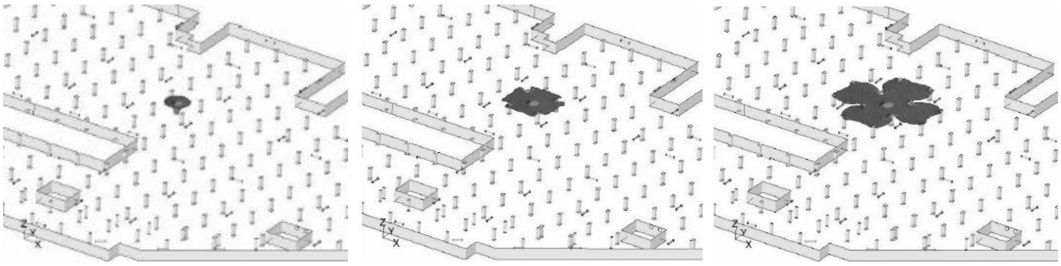

**Figure 5. Smoke movement after 30, 40, and 50 seconds**

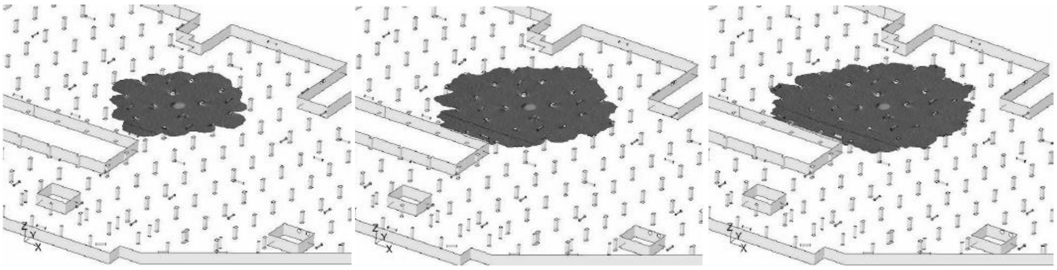

**Figure 6. Smoke movement after 60, 70, and 80 seconds**

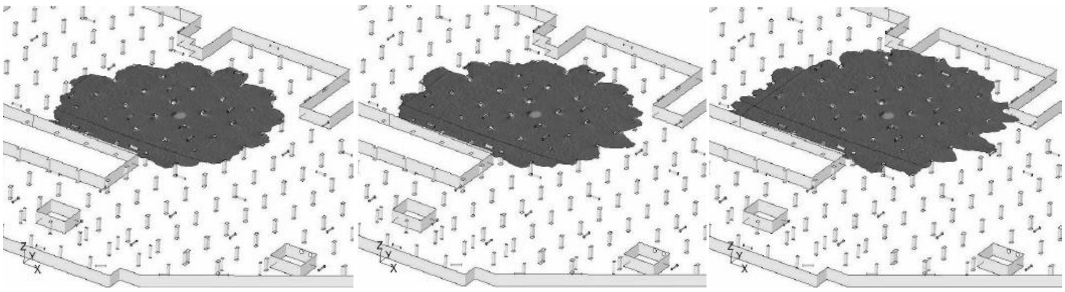

**Figure 7. Smoke movement after 90, 100, and 120 seconds**

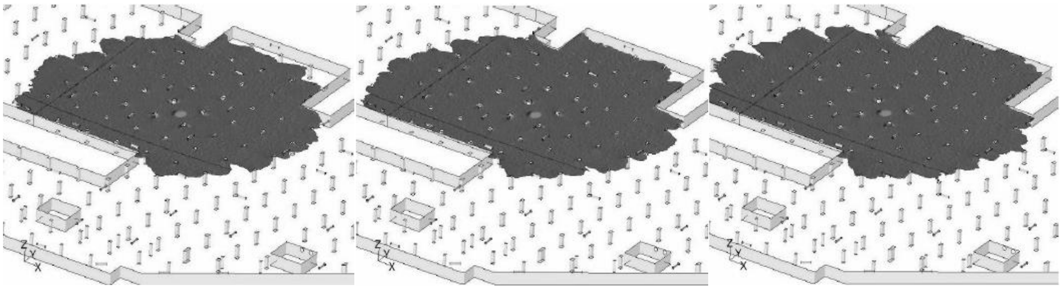

**Figure 8. Smoke movement after 150, 160, and 180 seconds**

In tab. 4, the underground car park surface filled with smoke as a function of time is shown. After 50 seconds, 280 $m^2$ of an underground car park is full of smoke. It is 1% of whole underground car park area. In the next 20 seconds, in total 70 seconds, after the fire occurred, approximately 1000 $m^2$ of an underground car park is filled with smoke, meaning 4% of the whole underground car park surface. This means that smoke filled almost four times more underground car park surface in 20 seconds. After 180 seconds, approximately 3,100 $m^2$ (13%) is full of smoke. Smoke movement velocity is 0.75 m/s.

**Table 4. Area filled with smoke**

| Time [s] | Area [$m^2$] | Area [%] |
|---|---|---|
| 0 | 0 | 0 |
| 35 | 56 | 0.2 |
| 50 | 280 | 1.0 |
| 70 | 1,000 | 4.0 |
| 90 | 1,400 | 6.0 |
| 120 | 1,850 | 8.0 |
| 150 | 2,700 | 11.0 |
| 180 | 3,100 | 13.0 |

The smoke velocity is crucial. The occupants have a limited time to find an exit from an underground car park. Some occupants will not start to run immediately after a fire alarm is switched on. Some of them will try to escape driving the car. Disabled people, the elderly, children, people with mental disorders, dementia, people needing an escort, *etc.* must have enough time to escape. If smoke covers the evacuation signs and moves fast, the occupants will not be able to find an exit during the evacuation period.

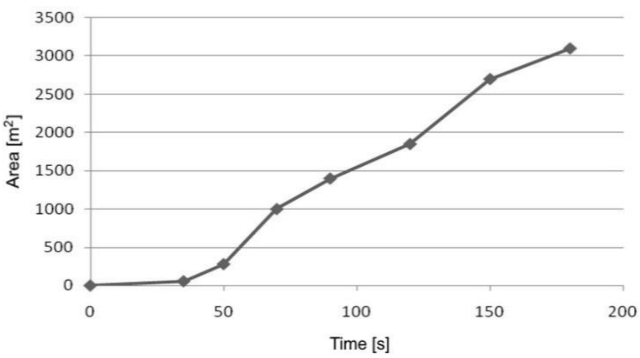


**Figure 9. An area filled with smoke as a function of time**

Figure 9 shows that approximately 50 seconds after a fire occurs, an area filled with smoke increases almost linearly.

Clear layer, from the floor up, with no smoke, is also crucial for safe human evacuation from an underground car park. It guarantees the safety of evacuees because breathing the hot and toxic gasses may cause death. Furthermore, it helps the firefighters during their intervention. Figure 10 shows a cross-section, in the x-direction, of smoke layer thickness at the distance of 10 meters from a fire in all directions. Underground car park height is 2.9 m. Therefore, a minimum clear layer with no smoke is approximately 2.4 m. That is enough for safe human evacuation from an underground car park.

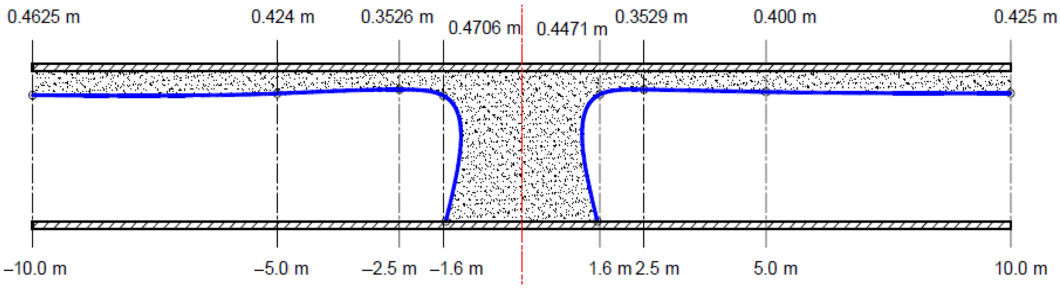


**Figure 10. Smoke layer thickness**

However, for safe human evacuation, the fire escape routes must be appropriately marked. Opaque smoke reduces visibility. Therefore, the evacuation signs must be visible during the evacuation period. Otherwise, people are not able to follow escape routes, and they will find themselves in dangerous conditions. The smoke layer thickness analysis shows the evacuation signs must be installed at least 500 mm beneath the ceiling. Only, in that case, will they be visible to the evacuees.

The numerical modelling results show a small smoke layer thickness difference between left and right sides (in the $x$-direction), shown in fig. 11.

The temperature, after 180 seconds the fire occurred, reached approximately 1400 K (1100 °C) above the seat of the fire, and nearly up to 600 K (330 °C) at 10 meters distance. Temperature contours are shown in fig. 12.

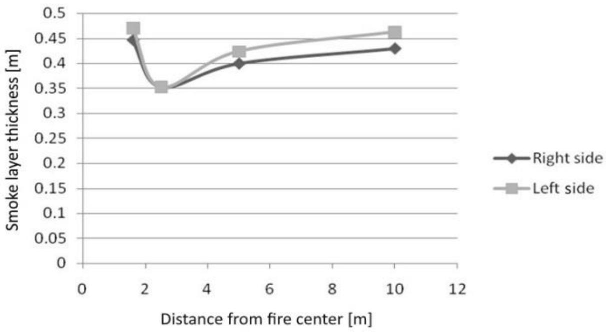


**Figure 11. Smoke layer thickness, right and left from a fire**

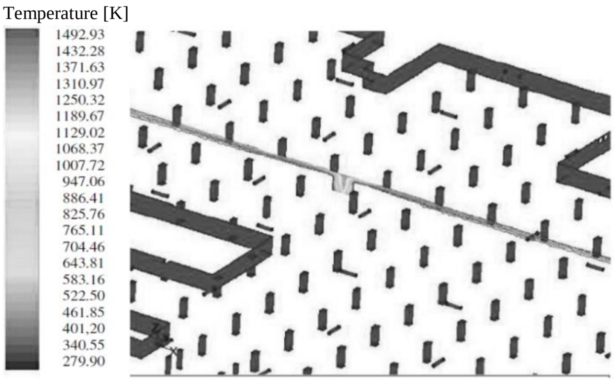


**Figure 12. Temperature contours, 180 seconds after the fire occurred** (*for color image see journal web site*)

## Conclusions

The numerical modelling results show that after 180 seconds approximately 13% of an underground car park is filled with smoke. Smoke movement velocity is 0.75 m/s, and smoke layer thickness reaches up to 0.5 m beneath the underground car park ceiling. An area filled with smoke increases almost linearly approximately 50 seconds after a fire occurs. Fire flame shape was regular and in accordance with isolated fire constrained by the underground car park ceiling, in the $z$-direction. The smoke stratification resulting from the fuel combustion shows the regular shape. The smoke movement is locally disturbed by vertical pillars.

People have sufficient time to evacuate from an underground car park. The underground car park height with no smoke is minimum 2.4 meters in all underground car park areas filled with smoke. Therefore, evacuees can breathe normally during an evacuation. The visibility is good, and people can follow evacuation signs to the exit. Due to the smoke layer thickness, evacuation signs should not be installed directly on the underground car park ceiling to avoid obscuring the sign and endangering safe human evacuation. The evacuation signs must be installed at least 500 mm beneath the ceiling. In that case, they are visible to the evacuees.

After 180 seconds the fire occurred, temperature values reached approximately 1100 °C above the seat of the fire, and nearly up to 330 °C at 10 meters distance. Therefore, the occupants must find an exit as soon as possible. Otherwise, they will be exposed to high temperatures.

The results show that timely fire detection is essential and that people must obey the fire signals and follow the instructions otherwise, the crucial time for evacuation will be lost. After 180 seconds, installed the mechanical ventilation is switched-on. At the beginning, this causes turbulent air and smoke flow. No clear layer with no smoke will exist anymore, and the visibility will be very poor. Therefore, all fire detection and fire protection systems must work properly and detect fire immediately after the fire occurs in an underground car park.

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