PERFORMANCE OF VENTILATION AND SMOKE EXHAUST SYSTEMS IN CASE OF FIRE IN UNDERGROUND PARKING LOTS: CASE STUDY

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Abstract. The purpose of this study was to analyse a ventilation system with impulse fans, which acts to ensure optimal air parameters and to evacuate smoke in case of fire in an underground car park. Given the number of parameters to be taken into account in the spread of smoke, there is a high chance of introducing calculation errors if only conventional methods are used. In this study, CFD simulations were used to compare the various stages of operation of the ventilation system, as well as their effectiveness in the proposed scenarios. In the case of the ventilation scenario, the concentration of carbon monoxide (CO) reached maximum values of 360 PPM, exceeding the maximum allowed value of 100 PPM, this endangering the users of the underground car park. In the second phase, we analysed the operation of the ventilation system simultaneously with that of the impulse fans for the two targeted functions and in this case the maximum concentration reached was 60 PPM, which indicates that this system configuration fulfils the function for which it was designed. The results showed, in the case of the scenarios, that the addition of impulse fans as complementary elements to the ventilation system substantially improved the reduction in the concentration of carbon monoxide (CO) and increased fire visibility in the parking lot.

Keywords: underground parking, ventilation, jet fan, smoke.

1. Introduction

For modern buildings, the installation of a mechanical ventilation system is essential to ensure the necessary level of air quality and thermal comfort. In addition to ensuring an optimal indoor environment, an important aspect of mechanical ventilation systems is to ensure protection in the event of a fire.
Fires in underground car parks are dangerous due to smoke that can flow quickly through the compartment, almost without any restrictions. These compartments have a large surface area, and their small height reduces the depth of the smoke-free bottom layer. Fire sources can be very difficult to fight, as smoke can easily fill the entire compartment and affect vision.

Combustion products from a fire are the most serious pollutants that can occur in underground parking lots. The knowledge gained by studying the consequences of fire on human beings implies that combustion products can be even more dangerous to human health than other fire-related phenomena. Combustion products from fire reduce the oxygen content of the air, suppress the ability of people to think clearly, reduce the visibility and ability to orient evacuees, and create preconditions for panic. In addition, they directly affect human health in two different ways - through flue gases and toxic gases (CO). [1], [7]

Carbon monoxide (CO) is considered to be the most dangerous combustion product, with a lower poisoning threshold of only 0.01 to 0.02% by volume. At a concentration of over 1% of the volume, man loses consciousness and death occurs in three minutes. Carbon monoxide poisoning is a common cause of fire death. [11], [15], [16]

Over time, the parking lots were ventilated using the traditional method of ventilation with air ducts that took up a lot of space. There is now an innovative new approach, known as impulse ventilation, which eliminates the need to use air ducts and uses special impulse fans, thin, efficient, and powerful, which has made this system very popular in recent years. These fans are positioned in places where smoke or polluted air is expected to stagnate, this being highlighted with the help of CFD simulations.

This system uses the principle of adding momentum to the air to push it to a pre-designated extraction point and to ensure that there are no dead zones for vapor and smoke to stagnate and collect in those areas.

This ventilation system can be used as a normal ventilation system, necessary for the removal of air pollutants, but also as an emergency ventilation system used for the evacuation of flue gases in case of fire.

In the case of underground car parks, the normal ventilation system aims to remove the air polluted by the flue gases generated by the movement of cars, to prevent damage to the health of people inside the car park. The emergency ventilation system is used to fight fires by evacuating excessive heat and flue gases from the fire. Both ventilation systems simultaneously provide fresh air inside the car park to increase the safety of evacuees and emergency crews during evacuation. [4], [8], [9], [18], [19]

From a technical point of view, it is possible that the two ventilation systems, normal ventilation, and emergency ventilation, can be combined into a single physical system, taking into account that such a system must meet the requirements of both types of individual ventilation. This system will have two stages of airflow control, the first stage
serving the normal ventilation system, and the second stage will be used in the event of a fire.

However, in Romania, there is no standard for the design of fire safety systems involving impulse fans, and during the design process, the provisions of standard EN 12101-3 on ventilation systems with impulse fans were observed. [5], [10]

The purpose of this study was to design and analyze a ventilation system with impulse fans for an underground car park. The studied ventilation system has the following functions: ensuring air quality and maintaining optimal comfort parameters by reducing the concentration of carbon monoxide (CO) and the evacuation of flue gases and excessive heat in case of fire.

2. Numerical modelling

The numerical simulation was performed in the (Autodesk CFD, Ansys, SimScale) modelling environment, and the purpose of the study is to determine the behaviour of a ventilation system with impulse fans operating in an underground car park, to identify possible methods of streamlining the system. [2], [3], [6], [13], [17], [19]

For the analysis of the scenarios considered in the present study, a P2 type underground parking lot with a capacity of 250 vehicles was used. The car park has a single level located in the basement of an office building, with an area of 6750 m² and a height of 3.5 m, resulting in a total volume of 23625 m³. The car access to the car park is made from the street level, through a two-way ramp of the following dimensions: 17.6 m x 5.0 m and a slope of 5%. The building is located in an area with low traffic, free from high pollution factors.

The ventilation system designed for underground parking is a ventilation system with impulse fans, which serves two main functions: the first function is to ensure ventilation of the parking lot to reduce the concentration of pollutants, and the second is to evacuate smoke in case of fire. The designed ventilation system has two operating stages, the first stage is used for normal ventilation and the second stage is used for emergency parking ventilation. The two operating stages will convey different airflows according to the regulations of each of the functions.

The introduction, respectively the evacuation of the air necessary for the ventilation is made using three discharge openings and three exhaust outlets, having the dimensions of 2.0 m x 1.0 m. long of the parking lot and the outlets were located in the upper part, opposite the discharge ones. The ventilation system considered in the present study is a vacuum ventilation system, in which the exhaust airflow is higher than the introduced airflow, thus ensuring the circulation of contaminated air to the outside.

To improve the movement of air masses in the parking lot, the technical characteristics of the Flakt Woods Standard 315, 0/7 / 0.09 kW F300 impulse fan, with a diameter of
315 mm and a length of 2.2 m. It has two operating stages that will serve the two functions of the system. To streamline the ventilation system, the CFD simulations from this study will be used, with the help of which we will determine the optimal arrangement of the impulse fans inside the parking lot.

Fig. 1 – Simulation - Ventilation system

Because the ventilation system studied serves two separate functions, this system was dimensioned using the regulations of both individual systems. Considering the aspects mentioned above, four analysis scenarios resulted using CFD simulations as follows:

For the normal ventilation system, designed to ensure optimal air parameters in the parking lot, we considered the following scenarios:

A. Operation of the ventilation system using the first stage of operation.

B. Simultaneous operation of the ventilation system and pulse fans also adjusted to the first stage of operation.

For the emergency ventilation system, used for smoke evacuation in case of fire, we considered the following two scenarios:

C. Operation of the ventilation system using the second operating stage.

D. Concomitant operation of the ventilation system and the second-stage pulse fans.

Case A and B

To simulate the ventilation system, an airflow of 79300 [m³/h] was considered to be evenly distributed over the three air intake grids, resulting in a flow on each grille of
The exhaust flow of 26435 [m$^3$/h] is, in turn, evenly distributed over three air exhaust grilles, resulting in a flow of 29075 [m$^3$/h] / grille.

For mixing and directing the air in the parking lot we considered the Flakt Woods Standard impulse fan - with a length of 2.2 m and a diameter of 315 mm. It has two operating stages, and in the case of this scenario the first operating stage with the following characteristics was used: impulse force - 5.7 [N], airflow - 0.61 [m$^3$/s]. The total amount of carbon monoxide (CO) released inside the car park for the situation where 50% of the vehicles are considered to be moving is 7.53 [kg/h]; The computational range used to simulate the ventilation system is Hex-dominant and consisted of 4.9 million cells. As a model of turbulence, we used the k-model model. For the simulation of house B, the same settings of the simulation from the first case were kept, the new calculation field being made up of 6.7 million cells.

**Case C and D**

To simulate the smoke exhaust system, an airflow of 120,000 [m$^3$/h] was considered to be evenly distributed on the three air intake grids, resulting in a flow on each grid of 40,000 [m$^3$/h]. The exhaust flow of 150,000 [m$^3$/h] is in turn distributed evenly on the three air exhaust grilles, resulting in a flow on each grid of 50,000 [m$^3$/h]. For mixing and directing the air in the parking lot we considered the Flakt Woods Standard impulse fan - 2.2 m long and 315 mm in diameter. It has two operating stages. In the case of this scenario, the second stage of the operation was used, which has the following characteristics: impulse force - 22 [N], airflow - 1.2 [m$^3$/s]. We considered as a smoke source a fire in a car with a length of 5 m and a width of 3 m, resulting in a smoke emission surface of 15 m$^2$. It was positioned in the center of the parking lot, at a height of 1 m from the floor. The dimensions of the fire are those recommended in the BS7346 standard for steady-state simulations. According to Table 3.1 of the British standard BS7346, a steady-state car fire has a heat release rate (HRR) equal to 4MW.

### Table 1

**Recommended values for designing fires in the Steady-State state**

| Fire parameters       | Parking without sprinkler system | Parking with sprinkler system |
|-----------------------|----------------------------------|------------------------------|
| Dimensions            | 5 m x 5 m                        | 3 m x 5 m                    |
| Perimeter             | 20 m                             | 16 m                         |
| Heat release rate     | 8 MW                             | 4 MW                         |

The calculation range used to simulate the smoke exhaust system consisted of 4.9 million cells and is Hex-dominant. As a model of turbulence, we used the k-$\varepsilon$ model.
3. Results

In table 2, figures S1-a to S1-f show the movement of air through velocity planes at different heights and how it influences the concentration of carbon monoxide (CO) inside the underground car park.

**Table 2**

*Case A Operation of the ventilation system using the first operating stage*

| S1-a | Speed plan at 0.75 m (m/s) |
|------|--------------------------|
| S1-b | CO concentration plan at 0.75 m (PPM) |
| S1-c | Speed plan at 1.75 m (m/s) |
| S1-d | CO concentration plan at 1.75 m (PPM) |
To represent the velocity planes to use a color map distributed in the range 0 - 2 m/s, and for the planes representing the carbon monoxide (CO) concentration to use a colouring in the range 0 - 100 PPM for an obvious problem for areas. In figures S1-a, S1-c, S1-e it is observed until the distribution of air inside our parking lot is uniform, which led to the creation of an air recirculation area. In the area where the air stagnates and, as can be seen in Figures S1-b, S1-d, S1-f, the concentration of carbon monoxide (CO) creates, exceeding a maximum permissible value of 100 PPM in a range of 20 for a minute. In areas in the care of concentration at a deposit of more than 100 PPM, especially in the famous colouring in the intensity of red, can be maximum at 358 PPM.

In view of the above, it follows that the use of a ventilation system without impulse fans does not ensure that the concentrations of pollutants produced by motor vehicles are kept within optimal limits. It is therefore necessary to increase the air mixture in these recirculation zones in order to reduce the risk of developing high concentrations of carbon monoxide (CO). In order to make the ventilation system more efficient, we considered the installation of impulse fans in the parking lot in problematic areas, of air stagnation, to improve its mixture inside and to direct the air currents to the exhaust ports. Figure 2 shows the areas of air stagnation. At the same time, the path of the air movement represented by the velocity vectors can be observed. To improve air movement in problem areas we introduced 11 impulse fans.
According to Figure 2 we added to the initial geometry the proposed impulse fans and we generated a new calculation field that will be used in the second scenario of this case.

Figures S2-a to S2-f show the movement of air through velocity planes at different heights and how it influences the concentration of carbon monoxide (CO) inside the underground car park.

| Table 3 |
| --- |

*Case B - Concomitant operation of ventilation system and stage I fan blowers*

| S2-a Speed plan at 0.75 m (m/s) | S2-b CO concentration plan at 0.75 m (PPM) |
With the improvement of the air movement in the parking lot, it can be observed the decrease of the carbon monoxide (CO) concentration below the maximum allowed values of 100 PPM in an interval of 20 minutes, this showing from figures S1-b, S1-d, S1-f. The maximum value reached in the concentration of carbon monoxide, in this case, was 66 PPM, and the average value inside the car park is 50 PPM.

In view of the above, it appears that the solution analyzed in the second scenario of the ventilation installation provided an optimal air flow to reduce the concentrations of pollutants below the maximum allowed level. Therefore, the introduction of impulse fans operating simultaneously with the ventilation system is a valid and efficient solution in order to reduce the concentrations of pollutants released by vehicles when traveling in parking lots.

An important aspect for the design of a ventilation system with impulse fans that has a high efficiency in operation is the study through CFD simulations of the positioning of the constructive elements of the installation and the analysis of the air masses produced by these elements, in order to implement the optimal solution.
Figures S3-a to S3-f show the movement of air through the velocity planes at different heights and how it influences the dissipation and concentration of smoke inside the underground car park.

Table 4  
*Case C - Operation of the ventilation system on the second stage a*

| S3-a Speed plan at 0.75 m (m/s) | S3-b CO concentration plan at 1.5 m (%) |
|---------------------------------|----------------------------------------|
| S3-c Speed plan at 1.75 m (m/s) | S3-d CO concentration plan at 2.25 m (%) |
Although in this case a much higher air flow was used than in the case of the previously studied ventilation system, in figures S1-a, S1-c, S1-e it is observed that the movement of air inside the parking lot is not uniform, aspect which leads to the creation of air recirculation areas. If in these areas, where the air stagnates, a fire develops, the accumulation and concentration of smoke in that area increases rapidly, which is seen in Figures S1-b, S1-d, S1-f. In this scenario, the area where the smoke concentration reaches a percentage of 100% is 292 m². Figures 3 and 4 show that the clear height under the smoke blanket is quite low (1.4–1.6 m) in areas with high smoke concentration. These issues make it impossible for fire crews to remove the source of the smoke and evacuate people who are near the fire or who are located on the opposite side of the exit.

Fig. 3 – Longitudinal section of fire - smoke concentration

Fig. 4 – Fire cross section - smoke concentration

In view of the above, it follows that, in the present case, the ventilation system without impulse fans does not ensure a reduction in the smoke concentration in order to allow the safe conduct of the activities of the intervention crews and the safe evacuation of parking users.
It is therefore necessary to increase the air mixture in the recirculation areas, in order to reduce the risk of developing high concentrations of smoke and to avoid dangerous situations.

As a consequence, it is recommended to make the ventilation system more efficient by adding impulse fans in problem areas, to stagnate the air, in order to improve its mixture in the car park and to direct the air currents towards the exhaust outlets.

As the air recirculation areas are similar to those identified in the previous simulations, the same arrangement of the impulse fans will be used.

Figures S4-a to S4-f show the movement of air through the velocity planes at different heights and how it influences the dissipation and concentration of smoke inside the underground car park.

Table 5
Case D - Simultaneous operation of the ventilation system and impulse fans on the second stage of

| Case | Description | Height | Concentration (%) |
|------|-------------|--------|-------------------|
| S4-a | Speed plan at 0.75 m (m/s) | 0.75 m |  |
| S4-b | CO concentration plan at 1.50m (%) | 1.50 m |  |
| S4-c | Speed plan at 1.75 m (m/s) | 1.75 m |  |
| S4-d | CO concentration plan at 2.25 m (%) | 2.25 m |  |
Figures S4-a, S4-c, S4-e shows a considerable improvement in the movement of air inside the parking lot after the placement of the impulse fans. The air flow speed in the parking lot is on average 1.2 m/s, as shown by the figures mentioned.

With the improvement of the air movement in the parking lot, it can be observed the decrease of the smoke concentration and the limitation of the areas where the smoke concentration reaches a maximum percentage, this emerges from figures S4-b, S4-d, -f.

The area of the areas where the smoke concentration reaches a percentage of 100% decreased considerably reaching 39 m², compared to the previous scenario when the area where the smoke reaches maximum concentrations was 292 m² - this aspect can be seen in Figure 5.

Taking into account the results of the CFD simulation, it results that the solution analysed in this scenario successfully meets the requirements for reducing the smoke concentration, ensuring the necessary visibility conditions for specialised intervention crews and for the safe evacuation of parking users.

For the design of a ventilation system with impulse fans that have a high efficiency in operation, it is very important to analyse through CFD simulations the positioning of
the constructive elements of the installation and the movement of air masses generated by these elements, in order to implement the optimal solution.

4. Conclusions

The CFD simulations provided an in-depth understanding of how the ventilation system works, providing an opportunity to analyse the movement of airflow, velocity fields, pollutant concentration, smoke concentration and the impact of the positioning of ventilation elements in the parking lot. These issues have led to the identification of ways to streamline this system.

In the first phase, we analysed the operation of the system without impulse fans for the two functions concerned. The results of both simulations indicated that the air distribution in the parking lot is not uniform, which implies the appearance of air recirculation areas. In these areas the air stagnates, becoming dangerous areas where the concentrations of pollutants or smoke even exceed the maximum allowed values.

In the case of the ventilation scenario in these areas, the concentration of carbon monoxide (CO) reached maximum values of 360 PPM, exceeding the maximum allowed value of 100 PPM, this endangering the users of the underground car park.

In the case of the smoke evacuation scenario, it was observed that the occurrence of a fire in the perimeter of these areas can lead to rapid accumulation of smoke and, at the same time, rapid increase of smoke concentration to maximum values, which affect visibility inside and prevent crew intervention. Firefighters or evacuating people inside the parking lot.

In conclusion, in the two cases considered of the ventilation system without impulse fans, the operating and safety requirements regulated by the regulations in force were not met.

In order to make the ventilation system more efficient, we considered adding impulse fans to the parking lot in order to improve the air movement and to ensure the requirements regulated by the two functions of this system.

Based on the results of the two initial simulations, the areas where the air stagnates and its better circulation are identified, this aspect allowed the optimal choice of the number of impulse fans and their optimal arrangement for obtaining an increased efficiency. We considered adding a number of 11 impulse fans that work simultaneously with the ventilation system.

In the second phase, we analysed the operation of the ventilation system simultaneously with that of the impulse fans for the two targeted functions. The results of the simulations indicated a considerable improvement of the air movement in the parking lot due to the optimal positioning of the impulse fans. This has led to the removal of air stagnation areas. As a result, pollutant and smoke concentrations have decreased.
In the case of the ventilation scenario, the maximum concentration reached was 60 PPM, which indicates that this system configuration fulfils the function for which it was designed.

In the case of the smoke evacuation scenario, the decrease of the smoke concentration was observed and implicitly of the areas where maximum concentrations are reached, resulting that even in this situation the analysed system fulfils the function for which it was designed.

In conclusion, the use of the impeller fan ventilation system fulfils the functions of normal ventilation and emergency ventilation required in its design, as well as the regulated safety requirements.

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