REVIEW OF TECHNICAL STANDARDS AND CALCULATION METHODS FOR DIMENSIONING OF SMOKE AND HEAT CONTROL SYSTEMS IN CASE OF FIRE IN UNDERGROUND CAR PARKS

ПРЕГЛЕД ТЕХНИЧКИХ СТАНДАРДА И ПРОРАЧУНСКИХ МЕТОДА ЗА ДИМЕНЗИОНИСАЊЕ СИСТЕМА ЗА ОДВОЂЕЊЕ ДИМА И ТОПЛОТЕ У СЛУЧАЈУ ПОЖАРА У ПОДЗЕМНИМ ГАРАЖАМА

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<https://doi.org/10.240/ptk.018.30.1.195>

Smoke and heat exhaust ventilation systems create a smoke free layer above a floor by removing smoke. They can, therefore, improve conditions to allow the safe escape and rescue of people, to protect property and to permit a fire to be fought while still in its early stages. Ventilation systems for smoke removal also serve simultaneously for heat exhaust and can exhaust hot gases released by a fire, thus controlling the temperature in the room affected by the fire. The paper reviews international and domestic standards as well as domestic regulations that are relevant for the fire protection of underground car parks. Recommendations and calculation methods for dimensioning of mechanical smoke and heat exhaust ventilation systems in case of fire in underground car parks are discussed in the paper. Calculation examples of dimensioning of these systems for different case studies are also included in the paper.

Key words: car park fires, smoke and heat exhaust systems, calculation methods

Улога система за одвођење дима и топлоте у случају настанка пожара је да обезбеде услове за безбедну евакуацију и спасавање људи, да заштите покретну и непокретну имовину и омогуће интервенцију ватрогасаца и гашење пожара у раној фази његовог настанка. Ови системи истовремено служе за одвођење врелих гасова који настају у пожару, односно за контролу температуре у простору захваћеном пожаром. У раду је дат преглед међународних и домаћих техничких стандарда, као и домаћих правилника који регулишу ову област противпожарне технике. Приказане су препоруке и прорачунске методе за димензионисање система механичке вентилације за одвођење дима и топлоте у случају пожара у подземним гаражама. У раду је такође дато неколико прорачунских примера за димензионисање ових система у различитим карактеристичним случајевима.

Кључне речи: пожар у подземним гаражама, системи за одвођење дима и топлоте, прорачунске методе

1. Introduction

Underground car parks are challenging for fire protection engineers because of their location, specific fire load and ventilation needs. The causes of fire in these objects are mainly the consequences of the technically defective vehicles or electric installations. Due to the presence of flammable materials on vehicles (plastics, textiles, and tires) and various fuels fires in underground car parks are spreading rapidly. There is also a potential danger from explosions. The proper dimensioning and selection of the smoke and heat control equipment and systems in underground car parks limits the spread of smoke and toxic combustion products. Furthermore, these systems increase visibility and allow quick and efficient intervention of fire-fighting units and safe evacuation of people. In this paper international and domestic standards and domestic regulations that are relevant for the fire protection of underground car parks are reviewed. Some recommendations and calculation methods for dimensioning of mechanical smoke and heat control systems are given. Calculation examples of dimensioning of these systems for different case studies are also included in the paper.

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2. Review of technical standards and regulations

In 2005 the Rulebook of technical requirements for the fire and explosion protection of car parks [1] was issued in Serbia. The Rulebook is derived from the national Law of fire protection and its application is mandatory for [2]. According to the Rulebook car parks are classified as over ground, underground and combined over and underground car parks. Underground car parks are those that are below the level of the terrain, including the partially underground car parks if they are below the ground level more than 1 m. Furthermore, car parks are classified as large (with usable area larger than 1,500 m²), medium sized (with usable area from 400 to 1,500 m²) and small car parks (with usable area up to 400 m²). Among other things, the rulebook prescribes the required number of entrances and exits, as well as requirements for approaching fire-fighting vehicles depending on the size of the car park. Automatically stable fire extinguishing systems (i.e. sprinklers) and stable fire alarm systems must be provided in large and medium-sized garages [1]. The main benefit of sprinklers is to control the size of fire to be dealt by the fire and rescue service.

Ventilation of underground car parks is usually recommended in order to limit concentrations of carbon monoxide (CO) and other vehicle emissions in the day to day use of car parks and to remove smoke and heat in the event of a fire. The same equipment is often used to satisfy both requirements. However, it should be noted that smoke and heat control systems usually require several times higher flow rates compared to ventilation systems that limits CO emission in car parks. For underground car parks mechanical or forced ventilation is mandatory [1]. Forced ventilation should be dimensioned to limit half-hourly average concentration of carbon monoxide below 100 ppm. In order to achieve this, the ventilation system must discharge at least 6 m³/h of air per square meter of useful car park area. In all car parks with forced ventilation detectors of carbon monoxide must be installed and permanently in operation. If the concentration of carbon monoxide in the air is higher than 250 ppm, the detectors automatically alert the alarm system which warns the car park users to turn off the vehicle engine and leave the car park. Methodology for dimensioning of ventilation systems with respect to carbon monoxide emissions in car parks can be found in textbook [3] or German engineers directive (VDI 2053) [4].

General conditions that ventilation and air conditioning systems must satisfy in terms of fire protection in Serbia are defined in the Rulebook of technical normative for ventilation and air conditioning systems [5].

In other countries, national laws and regulations are applied (i.e. German car park regulation: *Garagenverordnung* – GaVO) [6].

Technical standard SRPS CEN/TR 12101-5:2009 [7] gives recommendations and guidance on functional and calculation methods for smoke and heat exhaust ventilation systems for steady-state design fires. It is intended for a variety of building types and applications, including single-storey buildings, mezzanine floors, warehouses with palletized or racked storage, shopping malls, atria and complex buildings, car parks, places of entertainment and public assembly and un-compartmented space within multi-storey buildings. This standard is based on the text of British standard BS 7346-4:2003 [8]. The most relevant international standard for smoke and heat control systems applied in covered car parks is BS 7346-7:2013 [9]. This standard gives guidance on functional recommendations and calculation methods for smoke and heat control systems for covered parking areas for cars and light commercial vehicles. The recommendations in this standard are provided for smoke and heat control systems installed in car parks, with or without sprinkler protection.

In USA NFPA 92 [10] standard is commonly used. It establishes requirements for the design, installation, and testing of smoke control systems used to mitigate the impact of smoke from fire in general. Additionally, NFPA 92B, is standard for smoke management systems in malls, atria and large spaces [11].

3. Dimensioning of smoke and heat control systems

3.1. System configuration

Car park ventilation systems can be designed for one or more three purposes in the event of a fire: 1. To assist fire-fighters to clear smoke from a car park during and after a fire, 2. To provide clear smoke-free access for fire-fighters to a point close to the seat of the fire, 3. To protect means of escape from the car park.

The following types of ventilation might be considered as alternatives: 1. Natural ventilation, 2. Ducted mechanical ventilation, 3. Impulse ventilation, 4. Smoke and heat exhaust ventilation systems (SHEVS) [9].

In this paper only smoke and heat exhaust ventilation systems (SHEVS) will be considered. These systems serve to extract smoke and toxic gases from the car park level at which the fire appeared. There is a large number of different configurations/schemes of SHEVS that can be found in practice. Some of them are shown in Figure 1.

Figure 1. Schematic view of SHEVS configuration in underground car parks [3]
 (Key: 1 – car parking lots, 2 – smoke ventilation chamber, 3 – smoke extract fan, 4 – fire damper, 5 – vertical smoke manhole, 6 – horizontal smoke manhole)

If the ventilation chambers are installed at each level of the car park, the smoke and toxic gases that are generated in case of fire are discharged through the exhaust openings positioned on the ventilation duct and ejected through the extraction fan. Smoke and gases enter the ducts through a fire damper which is closed in normal operation. The damper is automatically opened in case of fire by remote control system (Figure 1a). In the same way, exhaust of the smoke and toxic gases can be achieved via fans located at the highest level of the car park or on a specially designed technical channel (Figure 1b). Smoke extraction can be carried out only through the vertical manholes. In this case, the fire dampers are mounted directly on the exhaust openings of the outlet smoke manholes (Figure 1c). The most preferable configuration of the smoke and heat control system is as shown in Figure 1f. This system combines general ventilation system and smoke and heat control system and thus requires less ducting and extraction fans. In this case it is necessary to mount a fan with speed control unit (two speed or modulating control). The fire dampers, that are normally closed, are positioned at each branch of the exhaust duct at each level. In this way, only the exhaust opening at the car park where fire appears can be opened while the exhaust openings on other levels can be closed.

On the other hand, fresh air supply is carried out through elevator shafts, stairways and corridors at the car park level at which fire can occur. In order to protect the means of evacuation from smoke and toxic gases penetration, a higher pressure should be provided at the side of escape routes (i.e. stairways, corridors) in relation to adjacent rooms where fire can occur. The value of the pressure difference should be from 20 to 80 Pa [1] if all doors and openings on the evacuation routes are closed. A minimum air velocity of 0.5 m/s through the opened door at the level where the fire occurs should be provided.

Smoke extraction fans must operate in case of fire and must withstand temperatures up to 400°C for 90 minutes [1]. In addition to the automatic control of the forced ventilation system and SHEVS, it is also necessary to provide the possibility of manual start-up from a safe place [1]. Ducts of SHEVS have to be fire resistant up to 90 min. Fire dampers also have to be fire resistant (up to 90 min) and equipped with automatic and remote control. Automatic commands are available through an automatic fire alarm installation, while remote commands are available from the control room and from the manual fire alarm tasters that are placed in the exit at each level of car park.

The discharge points for the smoke exhaust system should be located such that they do not cause smoke to be recirculated into the building, spread to adjoining buildings, or adversely affect the means of escape. The main extract system should be designed to run in at least two parts, such that the total exhaust capacity does not fall below 50% of the rates in the event of failure of any one part and should be such that a fault or failure in one will not jeopardize the others. The system should have an independent power supply, designed to operate in the event of failure of the main supply. Extract points should be arranged so that 50% of the exhaust capacity is at high level and 50% is at low level (Figure 2) and evenly distributed over the whole car park [9].

The system should be initiated by one or more of the following: smoke detection, rapid rate of rise heat detection, multi-criteria fire detection, a sprinkler flow switch, and a fire service override switch.

Care should be taken to ensure that there are no stagnant areas in either daily ventilation or smoke ventilation operational mode. Provision should be made for the supply of replacement air to the car park. The velocity of air within escape routes and ramps should not exceed 5 m/s in order to avoid impeding the escape of occupants of the building [9].

Figure 2. Typical mechanical ventilation using a ducted smoke clearance system: section view [9]
(Key: 1- 50% high level extract, 2- 50% low level extract)

3.2. Calculation of ventilation flow rate

Until recently common practice in Serbia was that the dimensioning of SHEVS was based on the recommended value of ventilation flow rate of 600 m³/h per one car parking lot [12].

Different approach would be dimensioning of SHEVS based on the flow rate of smoke that should be extracted from the car park in case of fire. This value can be calculated by the equation of Hinkley [3]:

$$M_f = 676.8 \cdot P_f y^{3/2} \cdot K_s \quad (1)$$

where

M_f – mass flow rate of smoke that is extracted from the car park [kg/h]

P_f – perimeter of fire in the initial stage [m]

$$P_f = 0.36 \cdot A^{1/2}, P_f \leq 12 \text{ m} \quad (2)$$

where

A – car park usable area [m²]

y – distance from the lower edge of smoke layer to the floor [m]

K_s – coefficient [-], $K_s=1$ or $K_s=1.2$, for the natural ventilation of smoke from in car parks with sprinkler system

In the similar way, based on the plume theory, where the entrainment of air into the plume (that is the amount of air mixing into the fire gases as they rise) is large for practical purposes the mass of the actual

products of combustion can be ignored. The smoky gases can be treated for calculation purposes as contaminated hot air. Furthermore, plumes above large fires are those where [7]:

$$y \leq 10 \cdot A_f^{1/2} \quad (3)$$

where A_f – plan area of fire [m^2]

Equation (3) has been validated experimentally for fires in large spaces with heat release rates between 200 and 1,800 kW/m^2 . The rate of air entrainment into a plume of smoke rising above a fire can be obtained using the following equation [7]:

$$M_f = 3600 \cdot C_e \cdot P_f y^{3/2} \quad (4)$$

where

C_e – coefficient is equal to 0.19 for large-space rooms such as auditoria, stadia, large open-plan offices, atrium floors etc., where the ceiling is well above the fire;

C_e – coefficient is equal to 0.337 for small-space rooms such as unit shops, cellular offices, hotel bedrooms etc., with ventilation openings predominantly to one side of the fire.

There is no information available to show how equation (4) can be modified to allow for the effects of sprinkler spray interactions. The demarcation between a large-space and small-space room is determined by the ability of the incoming air to flow into the rising plume from all sides. The narrower the room becomes, the less easily the air can flow behind the plume [7].

In temperature control designs the temperature of the smoke reservoir gases above ambient temperature (θ) is specified. The convective heat flux in the smoky gases entering the buoyant smoke layer is also known. The mass flow rate entering the buoyant layer is calculated using the following equation [7]:

$$M_f = Q_f / (c \cdot \theta_1) \quad (5)$$

where

c – specific heat of air at constant pressure [$\text{kJ}/(\text{kg} \cdot \text{K})$]

θ_1 – average temperature above ambient temperature of the gases in a buoyant smoke layer in a smoke reservoir [$^{\circ}\text{C}$]

For different building types default values of perimeter and heat release rates are given in standard SRPS CEN/TR 12101-5:2009 [7]. The convective heat flux (Q_f) carried by the smoky gases entering the smoke reservoir should be taken to be 0.8 times the heat release rate ($q_f \cdot A_f$) identified for the design fire, unless the designer provides evidence to support the use of a different value. For steady state design fires in covered car parks fire parameters are set out in Table 1. Minimum clear height above escape routes (y) is defined as 2.5 m or $0.8 \cdot H$ [m], whichever is the smaller [8, 9].

For selection of the appropriate fans, the mass flow rate of smoke determined from previous calculation of entrainment into the rising smoke plume can be converted to the corresponding volumetric flow rate using equation [7]:

$$V = M_f \cdot T_1 / (\rho_{\text{amb}} \cdot T_{\text{amb}}) \quad (6)$$

where

T_1 – absolute average temperature in a smoke reservoir's buoyant layer [K]

ρ_{amb} – density of air at ambient temperature [kg/m^3]

T_{amb} – absolute ambient temperature [K]

Time-dependent design fires should be based on an experimental test fire, which should be described and justified. Where the experimental data has been placed in the public domain, a reference to the publication should be used as justification. Functional recommendations and calculation methods for smoke and heat exhaust ventilation systems, employing time-dependent design fires are given in standard BS 7346-5:2005 [13].

Table 1. Steady state design fires [9]

Fire parameters	Indoor car park without sprinkler system	Indoor car park with sprinkler system	Two car stacker with sprinkler system
Dimensions/area	5x5m/25 m^2	2x5m/10 m^2	2x5m/10 m^2
Perimeter	20 m	14 m	14 m
Heat release rate	8 MW	4 MW	6 MW

Finally, dimensioning of SHEVS can be done by using the recommended value of air change rate. According to standard [9] the smoke and heat control system should be independent from any other system and be designed to operate at 10 air changes per hour.

According to the German car park regulation [6] automatic activation of smoke and heat control systems in case of fire is required, with minimal ventilation air change rate of 10 1/h.

4. Case study

Within the case study, three different underground car parks were considered, of which the first two are for residential buildings and the third for a commercial building. The usable areas of the car parks are such that all three categories are covered (small, medium and large sized). The second and third car parks are equipped with a sprinkler system. For each car park, the value of the ventilation flow rate is calculated in order to limit the concentration of CO according to the criterion of 6 m³/h of air per square meter of a useful car park area, which given in the rulebook [1]. The smoke and heat control system flow rate is then calculated according to three different methods: 1. Based on the recommended value of 600 m³/h per one car parking lot [12]; 2. Based on the equation (4); 3. Based on the recommended number of air changes of 10 1/h [9]. The results are summarized in Table 2.

Table 2. Ventilation, smoke and heat control system flow rates for three different car parks

Car park size by area [m ²]		Area [m ²]	Height [m]	Number of parking lots [-]	Ventilation flow rate [m ³ /h]	Smoke and heat control system flow rate [m ³ /h]		
						Method 1	Method 2	Method 3
Small	< 400	206	2.5	9	1,236	5,400	26,275	5,974
Medium	>400 < 1500	550	2.5	16	3,300	9,600	21,030	13,750
Large	> 1500	1578	3.6	44	9,468	26,400	29,390	56,808

From the results it can be concluded that smoke and heat control systems require several times larger flow rates than usual ventilation system which is in every day operation. In some cases this can be a limiting factor when fire protection engineers are considering the combined configuration of these two systems.

For smoke and heat control system the first method gives the smallest volumetric flow rates (5,400÷26,400 m³/h). The second method gives volumetric flow rates that are in range from 21,030 to 29,390 m³/h. It can be noticed that the calculated flow rates for small and large sized car parks do not differ considerably. Therefore, it can be concluded that according to this method only the parameters of design fire are relevant. The third method gives moderate values of flow rates for small and medium sized car parks (5,974 and 13,750 m³/h), but rather high value for large sized car park (56,808 m³/h). This is due to the large car park area and high ceiling level and consequently the increased space volume.

The last method with recommended air change rates may be the best option for the medium and large sized car parks. For small sized car parks it can lead to insufficient flow rates, as the fire load of a passenger car can be higher than in a large sized car park, due to the lack of a sprinkler system, with much smaller car park space volume. Finally, it can be recommended that it is important for fire protection engineers to verify the calculated flow rates for each specific case by using a multi-criteria approach.

5. Conclusion

Based on the review of international and domestic standards and domestic regulations, three different calculation methods that are commonly used in fire protection engineering for dimensioning of smoke and heat control systems are discussed in the paper. The calculation methods are applied to determine the smoke exhaust flow rates for three case study underground car parks with different areas and ceiling heights. The method which implies the recommended ventilation air change rate of 10 1/h may be the best option for the medium and large sized car parks. For small sized car parks it can lead to insufficient flow rates, as the fire load of a passenger car can be higher than in a large sized car park, due to the lack of a sprinkler system, with much smaller car park space volume. Therefore, it can be recommended that it is important for fire protection engineers to verify the calculated flow rates for each specific case by using a multi-criteria approach.

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