Simulation of flames and smoke spreading in an underground garage under different ventilation conditions

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Abstract. Garages are significantly endangered by the formation and spread of fire. Additionally, some building equipment or installations located in a garage such as air outlets from ventilation installation could significantly deteriorate the fire situation. To determine the influence of the AHU (Air Handling Unit) outlet inside the garage on fire spreading, a simulation was carried out using the FDS (Fire Dynamic Simulator) in the PyroSim computer software. The investigated underground garage consists of 11 separated parking bays. The following conditions of a fire source were assumed: a car with a petrol engine, a fire area - 10 m², a range of fire - 12 m, and a total power of fire - 4 kW. The simulations were carried out for two fire scenarios: 1) normal condition (AHU is disabled), and 2) airflow from an AHU outlet (5,200 m³/h). The results show a negative effect of an AHU on fire spreading. The temperature and the concentration of smoke during fire are 2-3 times higher than if an AHU operates. In both fire scenarios, the safe temperature for humans, i.e. 60°C at a height of 2 m above the floor level has been exceeded in less than 4 minutes.

1. Introduction

Safety of people in the parking lot requires certain precautions and an analysis of fire effects at the design stage of the parking lot. Different fire events need, however, some further research and analysis because a single set of fire scenarios is not sufficient for all types of buildings due to their different designs and purposes.

Vehicles themselves pose the greatest fire threat. The conditions that favour fire development in parking buildings include [1]:

- Cars in crowded parking lots are parked close to one another, which increases the risk of fire spreading from car to car.
- New cars have more plastic elements than older ones. Plastics ignite faster and give off more heat.
- Plastic fuel tanks are easily damaged at high temperatures causing fuel leaks in tanks, formation of easily burning fuel patches and spread of fire to places far away from a source of leaks.

Technical infrastructure is another no less important aspect of fire scenarios. The buildings erected in previous decades often undergo modernisation and their installations are adapted to more demanding requirements. Consequently, technical devices can be installed at not original spots. Such devices can be air handling units or external units of split air conditioners. No adequate precautions or safety measures may significantly worsen fire conditions, which can hinder efficient emergency evacuation.
The main hazards are thermal factors and direct flame effects on people near fires and a strong effect of toxic combustion products in smoke on the human body. The presence of smoke is associated not only with hazardous substances but also a decreased amount of oxygen content in the room affected by fire. Another factor affecting the safety of people in rooms filled with smoke is reduced visibility, which, in turn, hinders and slows down evacuation of the building and exposes its users to higher amounts of poisonous compounds [2].

Statistics conducted over many years show that in the event of a fire, inhaled smoke and toxic gases are a greater threat to human life than a rapid increase in temperature and flames. Every year, from about 2/3 to 3/4 of all fatalities in fires is caused by effects of smoke [3]. Smoke is the most commonly identified cause of death in a fire and accounts for even 34% of all deaths in fires. Another 18% of deaths were attributed to both injuries caused by burns and harmful effects of smoke and 24% of them were caused by burns alone [4].

Computer simulations like a modelling of properties of materials exposed to high temperatures [5] or a classic modelling of activated sludge bioreactors [6-7] are extremely helpful tools to investigate not only fire and smoke spread but also various physical phenomena. CFD (Computational Fluid Dynamics) programmes are usually used to simulate changing dynamics. CFD software is used in a wide range of dynamic simulations, including fire events [8], air distribution in the room [9-10] or ventilation heat exchanger analysis [11].

2. Materials and methods

2.1. Building characteristics

The research object is the garage located on the 2nd floor (underground floor) in one of the Lublin University of Technology buildings. Figure 1 shows its actual space layout. This garage has 11 parking bays separated by partitions (bay no 6 is walled-up and is not used). Their areas are 13.1 m² (bays 2 and 7), 15.9 m² (10 - 12), 18 m² (5, 8) and 18.4 m² (1, 3, 4 and 9). The total area of the parking bays is 183.5 m². The height of the parking spaces measured from the floor to the ceiling is also different and amounts to 2.63 m for bays 1 - 8 and 4.60 m for bays 9 - 12.

Briefly described in Table 1, the building structure is made of typical non-flammable building materials. The garage floor is at a level of −6.64 m. The central manoeuvring yard of an area of 208 m² and a height of 4.60 m is between the parking bays and connected with the parking bays by entry holes of (2.34×2.40 m).

| Construction item                        | Density [kg/m³] | Specific heat [kJ/(kg K)] | Conductance [W/m·K] | Emissivity [-] | Absorption coeff. [1/m] |
|------------------------------------------|----------------|---------------------------|---------------------|----------------|------------------------|
| ceiling                                  | 2500           | 0.840                     | 1.7                 | 0.85           | 5 \times 10⁴         |
| floor - concrete (stands)                | 3050           | 0.880                     | 0.29                | 0.9            | 5 \times 10⁴         |
| floor - cobblestones (central square)    | 2630           | 0.840                     | 0.9                 | 0.9            | 5 \times 10⁴         |
| walls                                    | 2500           | 0.840                     | 1.7                 | 0.85           | 5 \times 10⁴         |
| columns and beams                        | 2500           | 0.840                     | 1.7                 | 0.85           | 5 \times 10⁴         |

The total volume of the garage is 1,560 m³. The ceiling above the garage is supported by numerous construction beams that can be important during a fire (smoke and hot air removal may be difficult). In the garage, there is one main gate (5.76×3.63 m) and one passage to the building at the opposite side of the garage, closed with a metal door (1×2 m). In the simulation, the garage gate and the door remain closed during a fire.
The garage is ventilated by a gravitational ventilation system. The ventilation grates (14×14 cm) are mounted 10 cm below the ceiling in each parking bay. The garage also has two air handling unit exhausts. One of them is a square of 70x70 cm. For the calculations, the stream of air supplied to the garage through this exhaust was assumed to be 3,200 m$^3$/h. The second exhaust is connected to the ventilation unit located in the discussed garage inside parking bay 5. This exhaust has a diameter of 55 cm and the airflow to the garage is 2,000 m$^3$/h.

2.2. Numerical model
Air temperature changes and smoke distribution during a fire were measured in a series of simulations. The numerical models of the analysed object and fire simulation were created using the FDS software and a specialist PyroSim graphical user interface by Thunderhead Engineering.

The first step was to create a model of the object and determine the fire properties of individual building structural elements and equipment. The FDS software allows selecting types of materials, specifying their properties such as density, specific heat, conductivity and emissivity and determining the absorption coefficient. The entire space of the object was covered by a computational grid. Due to the geometry of the building, the computational grid was divided into 3 parts: i) the central square and bays 9-12; ii) bays 1-5; iii) bays 7 and 8 to avoid unnecessary computational cells. The whole computational mesh contains 137,501 cells (0.25×0.25×0.25 m).

2.3. Simulation parameters
15 (S1-S15) virtual sensors for reading temperature and smoke concentration at given points were mounted in the garage space at a height of 2 m above the floor to efficiently check whether the air parameters in the individual areas of the garage for a certain time frame of fire allow safe evacuation. The air temperature at this height should not exceed its safe value for humans, i.e. less than 60°C.
The following initial parameters were established inside the garage: ambient temperature as 20°C, ambient pressure as 1,013.25 hPa, and relative humidity as 40%. A fire source was a car. The international NFPA 204 standard [12] was followed for the assigned fire parameters: fire surface 10 m², fire circumference 12 m, unit heat release 400 kW/m², and total fire power 4,000 kW.

To make the fire simulation realistic, fire development was assumed in accordance with the curve described by the relationship \( Q = \alpha_g \cdot t^2 \) where: \( Q \) – fire power [kW], \( \alpha_g \) – coefficient describing the fire power increase [kW/s²], \( t \) - time [s]. The fire simulated in the analysed building was defined as "fast", and thus the \( \alpha_g \) coefficient of 0.04689 kW/s² was used to determine the increase slope of fire power.

Depending on the scenario, the defined fire source was opposite parking bays 4 (scenario 1) and 10 (scenario 2). The bays differ in height and are 2.63 and 4.6 m, respectively. The entry holes between the bays and the manoeuvring yard have the same dimensions. Therefore, the examination focused on the influence of the height of the given parking space on the smoke spread and the influence of air blown into the garage space through the two described earlier AHU outlet grates: fires in bays 4 (scenario 3) and 10 (scenario 4). The simulation time for all scenarios was 600 seconds.

3. Results and their analysis

The results were investigated for fire development and spread of its products depending on the height of the parking bay with the fire source and the operating AHU installation in the garage. The readings of the defined virtual sensor were presented. Notably, the measurement results of these sensors are instantaneous values and the inertia is very large due to substantial fluctuations in the readings. The plane graphs with the temperature distribution were also presented.

The airflow to the garage through the AHU resulted in an about 80 second faster increase in the temperature of 60°C at each of the measuring points at the same fire power. The height of the bay with the fire source practically does not affect the rate of fire development and the final indications of the temperature sensors. The graphs below show a comparison of the readings of these sensors for scenarios 1, 2, 3 and 4 in the 600 second simulation.

![Figure 2. Comparison of the temperature sensor readings in the 600 second simulation.](image)

As can be seen in Figure 2, the temperatures are much higher for the scenarios with air supplied to the bay than the scenarios with no air supplied to the garage with the air handling units. The reason for this is the continuous flow of oxygen supporting the combustion process of both combustible materials to the place of fire and after-burning particles carried with smoke.

It is clear from the graphs showing the horizontal distribution (Figure 3) of temperatures in the garage in the 360 second simulation that the operation of the AHU outlet can move the hot air, especially the one accumulated around the entry hole of the parking bay 1. This is clearly depicted in Figure 4 where the yellow arrows show the direction of the air flow from the outlets.
Figure 3. Temperature (°C) distribution at a height of 2 m in the 360 second simulation.

Figure 4. Temperature distribution in the 480 second simulation for scenario 3.

The smoke concentration for scenarios 3 and 4 compared to scenarios 1 and 2 is higher directly in the area of the bay entry hole and directly above the fire source. At this point, if the air handling unit works, the smoke concentration reaches even 100%/m, but does not exceed 90%/m if there is no airflow.
The smoke concentration is, however, lower for scenarios 3 and 4 at the points distant from the fire source. The graphs in Figure 5 show the changes in smoke concentration depending on the scenarios at the measuring points above the manoeuvring area. These points were taken as representative because they are at equal distances from the places where the fire was located in each of the scenarios.

![Figure 5: Smoke concentrations at the virtual measuring points of S6, S13 and S14 for the 120, 240, 360, 480 and 600 second simulations.](image)

The smoke concentrations in scenarios 1 and 2 are very similar so it can be concluded that the different heights of parking bays do not have a significant influence on the smoke concentration in the garage. However, the air flow into the garage space causes changes in the sensor readings. The charts corresponding to scenarios 3 and 4 show greater fluctuations in the smoke concentrations due to the
increased air movement. The smoke concentrations despite the initial fluctuations are ultimately lower than those in scenarios 1 and 2 because the AHU makes the smoke mix with the ventilation air blown into the garage and the smoke concentration is reduced.

The air inflow adversely affects the room temperature by increasing it significantly. In scenarios 1 and 2, as a result of buoyant forces, smoke accumulates under the ceiling, creating a layer above the floor without smoke. This layer decreases as the fire develops. The visualisation of the spread of smoke shows that such a layer does not form in scenarios 3 and 4. The air supplied into the garage with the AHU causes the smoke to move from the upper to lower parts and, consequently, cover the entire garage space in a much shorter time. The spreads of fire and smoke for scenarios 2 and 4 are compared in Figure 6.

The difference in the smoke spread is evident from beginning of the simulation. In scenario 2, the smoke moving from the parking lot accumulates under the ceiling of the central manoeuvring yard and forms a regular shape. In scenario 4, it is dispersed by a stream of inflowing air and spreads irregularly over the entire volume of the garage.

4. Summary and conclusions
The following conclusions can be drawn from the literature related to fire events in parking lots and the results of the simulations of fire development in the underground garage carried out with the FDS software:

- The height difference of 1.97 m between parking bays 1 – 8 (2.63 m) and 9 – 12 (4.6 m) do not significantly affect the development and course of the fire.
- The temperatures and smoke concentrations during a fire are significantly higher in the case AHU air supply so the AHU needs to be disabled in a fire to improve safety.
- In each of the tested scenarios, the previously defined temperature limit safe for humans, i.e. 60°C at a height of 2 m above a floor level was exceeded after a time period not longer than 3 min 40 s. This time should be sufficient for people to leave the garage space but is relatively insufficient to evacuate property like cars.
- In the event of a fire of a passenger car, it takes 7-8 minutes only to make the entire garage space be filled with smoke and toxic compounds, which can significantly hamper efficient emergency evacuation by rescue teams.

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