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PERFORMANCE ASSESSMENT OF MECHANICAL SMOKE AND HEAT EXHAUST VENTILATION SYSTEMS FOR UNDERGROUND CAR PARKS WITH NATURAL SOURCES FOR FRESH AIR SUPPLY USING COMPUTATIONAL FLUID DYNAMICS

BY

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Abstract. A particularly important role in the design of mechanical ventilation systems for the exhaust of smoke and heat from underground car parks is the sizing and location of sources for natural fresh air supply. Thus, the studies carried out were relevant to the fact that there are premises for an improvement of the functionality of these installations both from a technical and an economic point of view by sizing and arranging the gaps provided for the supply of fresh air, corroborated with the decision to use or non-use of impulse jet fans.

Keywords: CFD, Simulation, Underground, Car, Park, Ventilation.

1. Introduction

The need for technical and economic efficiency of mechanical smoke and heat ventilation systems in closed underground car parks has led the factors

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involved to make extensive use of combined systems that involve the natural supply of fresh air, along with the mechanical exhaust of smoke and heat. From this perspective, the problem of sizing and locating fresh air sources arises, so that the system works at optimal parameters.

However, in addition to the sources of natural fresh air supply provided according to specific standards, in most cases, closed underground car parks are also provided with other functional gaps without a specific role in the designed smoke and heat exhaust systems, which may interfere with their proper functioning. Relevant are the examples of partially open facades, courtyards of light, ramps for access of vehicles in the car parking and others.

This scientific paper proposes the experimental analysis using Computational Fluid Dynamics (CFD) of the impact generated on the functionality of mechanical smoke and heat ventilation systems in underground car parks, determined by the existence of other possible sources of fresh air in addition to those designed according to standards, and the identification of solutions to improve the performance of these systems through a correct disposing of the fresh air supply sources, related to the specifics of the chosen smoke and heat ventilation system.

2. Car park model and CFD details

2.1. Car park a computational domain

In order to meet the objectives of this scientific paper, it is proposed the CFD analysis of an underground car park with 90 parking spaces, with a free height of 2.50 meters, which has a usable area of approximately 2600 m² (52mx50m). For the air intake, two gaps were provided, each area of 4.05 m². It should also be noted that the car park is provided with a permanently open access ramp, which has an area of 12.5 m².

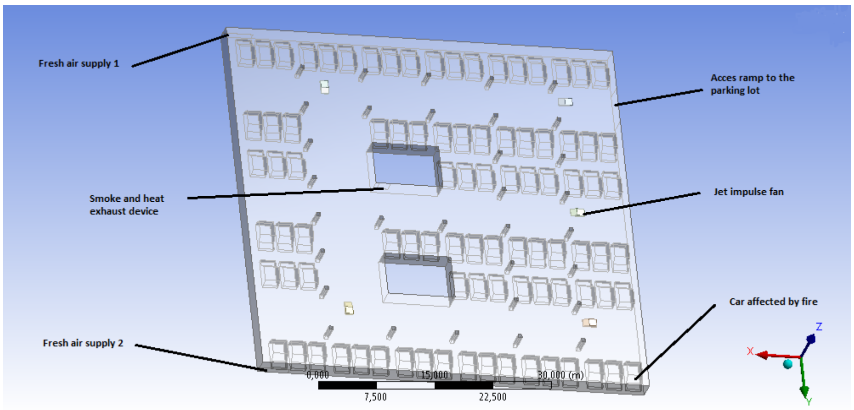


Fig. 1 – Design of car park.

In this paper, in order to respect the previously stated principles regarding discretization, a general discretization of 0.5 m was chosen, and in the areas where the defining elements of the smoke evacuation system appear, a twice more refined discretization was chosen, the values of the finite elements being 0.25 meters. This mesh is fine with respect to other similar studies (Viegas, 2006; Viegas, 2010).

Regarding the models used in the performed simulations, the following are relevant: Solver – pressure-based, velocity absolute values and steady state, Models – standard k-epsilon (2 equations) with enhanced wall treatment, discrete ordinates radiation model and species transport model. Also, the relevant properties of the fluid mixture (H2O, O2, CO2 and N2) in the car park are: density – ideal incompressible gas, specific heat – mixing law, thermal conductivity – mass weighted mixing law, viscosity – mass weighted mixing law and absorption coefficient – weighted-sum-of-gray-gases-model (WSGGM) domain based.

The solution methods that were chosen in the simulations are Pressure-Velocity Coupling – Simple Scheme and Spatial Discretization: gradient – least squares cell based, pressure – body forced weighted, momentum – first order upwind, turbulence kinetic energy – first order upwind, turbulence dissipation rate – first order upwind, H_2O – first order upwind, O_2 – first order upwind, CO_2 – first order upwind, energy – second order upwind, discrete ordinates – second order upwind.

2.2. Car fire and fans

The inlet temperature of the fresh air in the parking lot, but also the temperature of the fluid in the parking lot before the fire will be 300 K, 0.16 kg/s will be the amount of flue gas evacuated following the oxidation reaction produced (400 kW/m², CO_2 - molar fraction 0.35 and H_2O - molar fraction 0.65) at a temperature of 1200K (Teodosiu *et al.*, 2015), and also the normal concentrations of air components in the parking lot before the fire start will be N_2 – 79% and O_2 – 21% (the rest of the air components being assimilated in terms of their reduced impact on the simulation results). Also, the car affected by fire will be situated in the opposite corner from the fresh air supplies, to simulate the worse possible scenario. At the same time, the car park is equipped with a mechanical installation for the evacuation of smoke and hot gases provided with an exhaust flow of 900 m^3/h/vehicle (EN 12101, 2009), being provided a fan with a flow of 81000 m^3/h. Also, the impulse of the initial jet fans used have a force value per unit volume of 100 N/m, initially reduced to 80 N/m, and later to 60 N/m.

2.2. Simulation cases

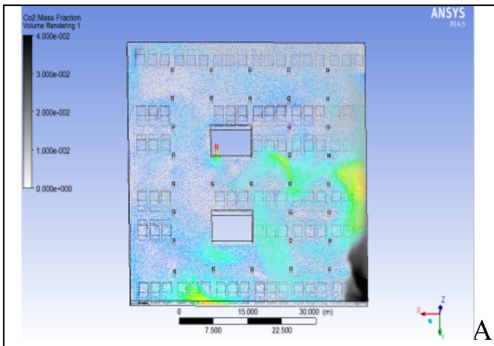
In this case, 2 simulations were performed using Computational Fluid Dynamics (CFD), in different configurations that involved alternating sources for fresh air supply, respectively the use of the conventional smoke and heat exhaust ventilation systems and subsequently improved systems by equipping the parking lot with 5 impulse jet fans with a role in the circulation of smoke and heat, and later with 8 such fans.

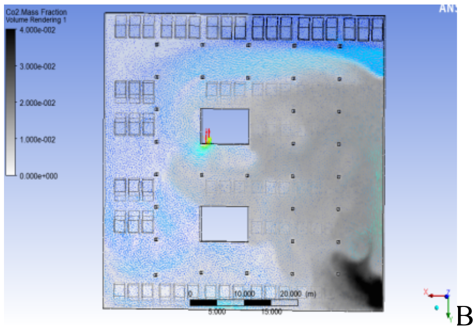
The performance criteria followed in the simulations will consist primarily in analyzing the concentration of carbon dioxide in the entire parking lot, the upper limit identified in terms of black coloration being set at the concentration value of 4%, in order to establish the visibility lever for parking users. Also, the pressure regime in the parking lot will be monitored in order to make an analysis on how it affects the flow of smoke and hot gases to the device provided for their evacuation, the limits of the analyzed range being (-5 Pa, 5 Pa / blue, red). And last but not least, the value of thermal radiation will be analyzed at a height of 2.5 meters, the upper limit identified in terms of red color being set at 2.5 kW/m^2, a performance indicator provided by specific standards, in order to prevent fire spread.

3. Results

The results obtained by analyzing the conventional system (without jet impulse fans) revealed that the best results from the perspective of reducing the concentration of carbon dioxide in the enclosure were identified in case A, respectively the one that assumes that both the gaps provided for fresh air supply and the access ramp in the parking lot are open. In case B, where the gaps for fresh air supply are closed and the only source of fresh air is the access ramp to the car park, there is an increase in the concentration of carbon dioxide on an area of about 50% of the entire underground car park. Moreover, in case C, which requires the access ramp to the car park to be closed and the gaps for fresh air to be opened, the results are even worse than in the previous case.

Analyzing the pressure regime, as well as the level of thermal radiation in the enclosure, resulting from the fire, the superior performances identified in case A are justifiable, compared to the other two cases, in the context in which it can be seen that in case A there is negative pressure in the vicinity of the fire and positive pressure in the rest of the room, which encourages the flow of combustion products to the flue. Or in the other two cases B and C, the constant negative pressure at the level of the entire car park generates the premises for the stagnation of the combustion products on the premises.





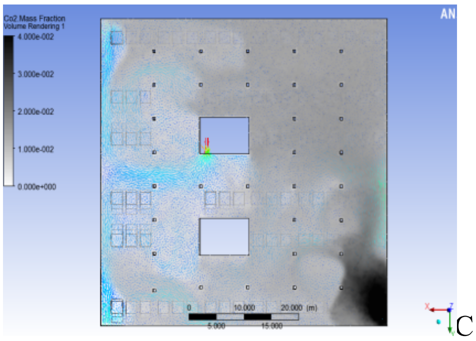
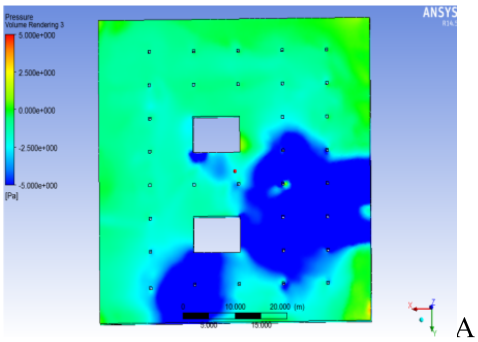
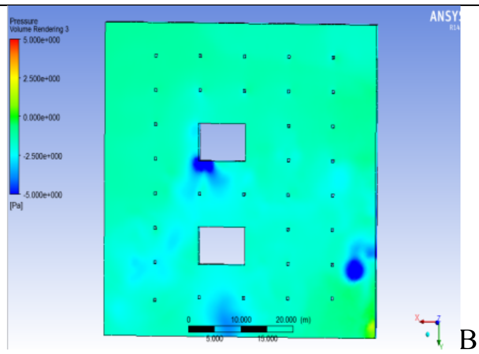


Fig. 2 – CO_2 mass fraction combine with velocity vectors in case A, B and C.





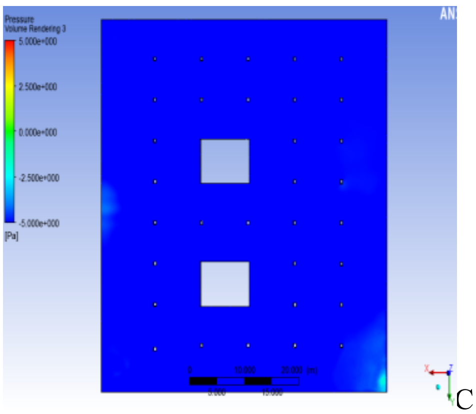


Fig. 3 – Pressure regime in case A, B and C.

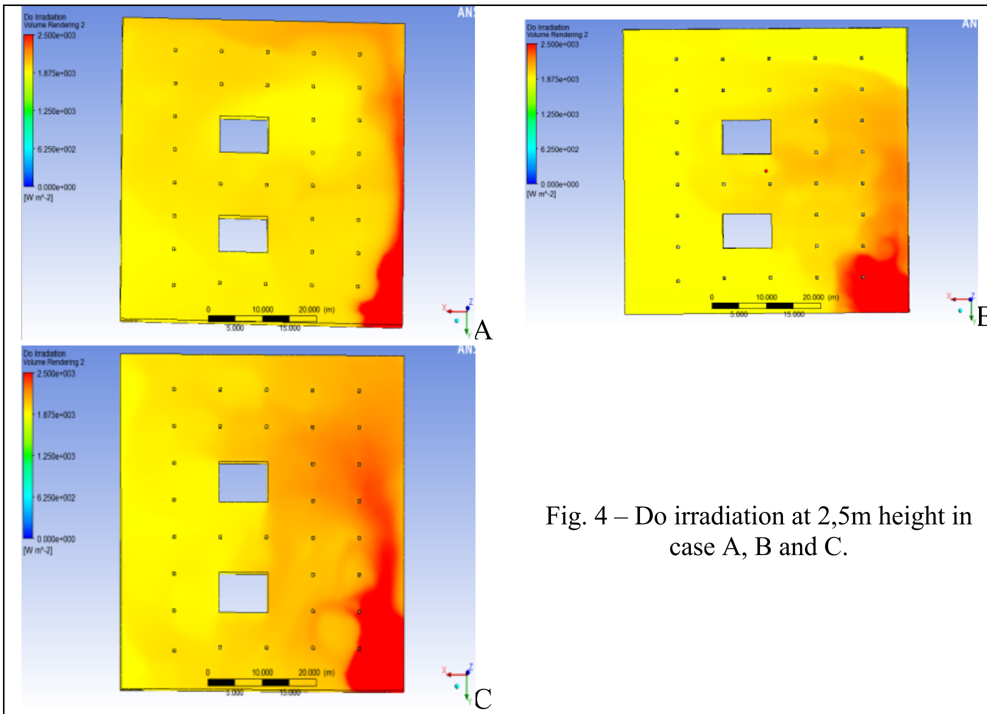


Fig. 4 – Do irradiation at 2,5m height in case A, B and C.

In parallel, following the simulations performed in the case of equipping the underground car park with 5 jet pulse fans arranged according to the figure above, differences were highlighted compared to the cases detailed above. Thus, in these circumstances the superior results were obtained in case F in which the only supply of fresh air was achieved by means of specially provided gaps, as opposed to the situation in which no impulse jet fans were used at all.

In the other two cases studied, respectively D and E, the results obtained were relatively similar, an aspect highlighted including by studying the pressure regime, as well as the thermal radiation in the parking lot. Thus, contrary to the aspects resulting from the first set of 3 simulations, it is relevant that although in the first two cases the pressure regime is negative in the area of the smoke and hot gas evacuation device, which would normally favor the evacuation of smoke and heat, as in the previous set of simulations, by using impulse jet fans was significantly improved case F, which highlights the existence of a constant pressure throughout the underground parking.

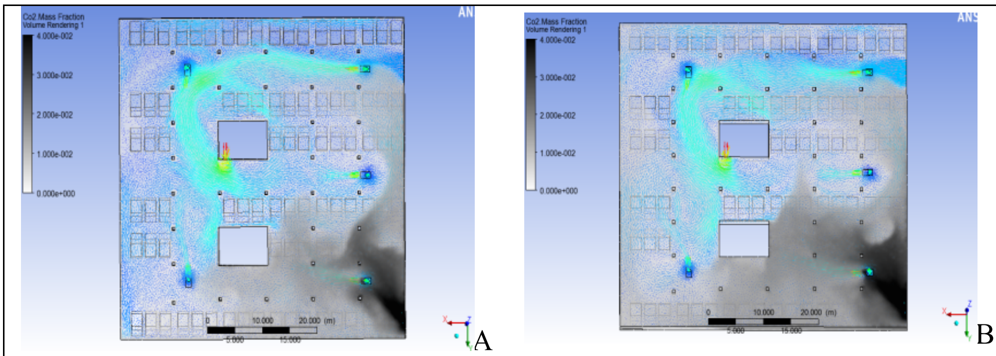
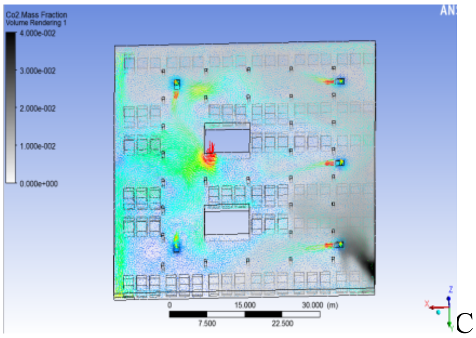



Fig. 5 – CO_2 mass fraction combine with velocity vectors in case D, E and F.

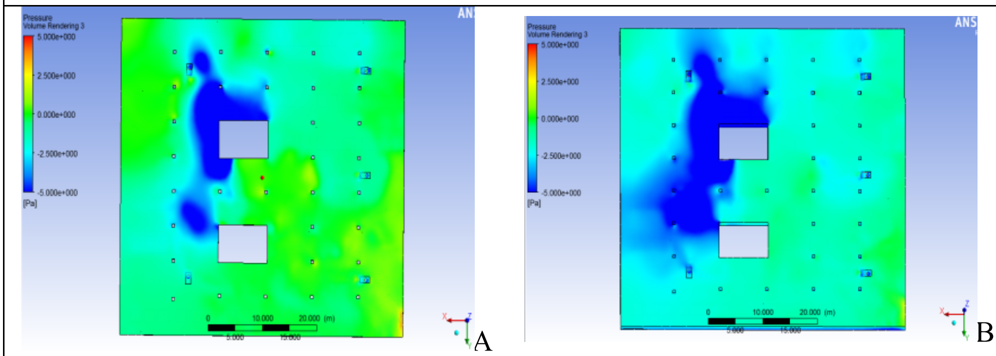
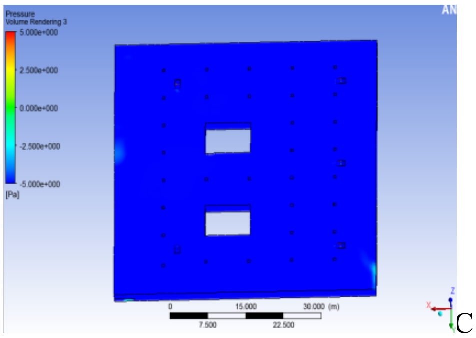



Fig. 6 – Pressure regime in case D, E and F.

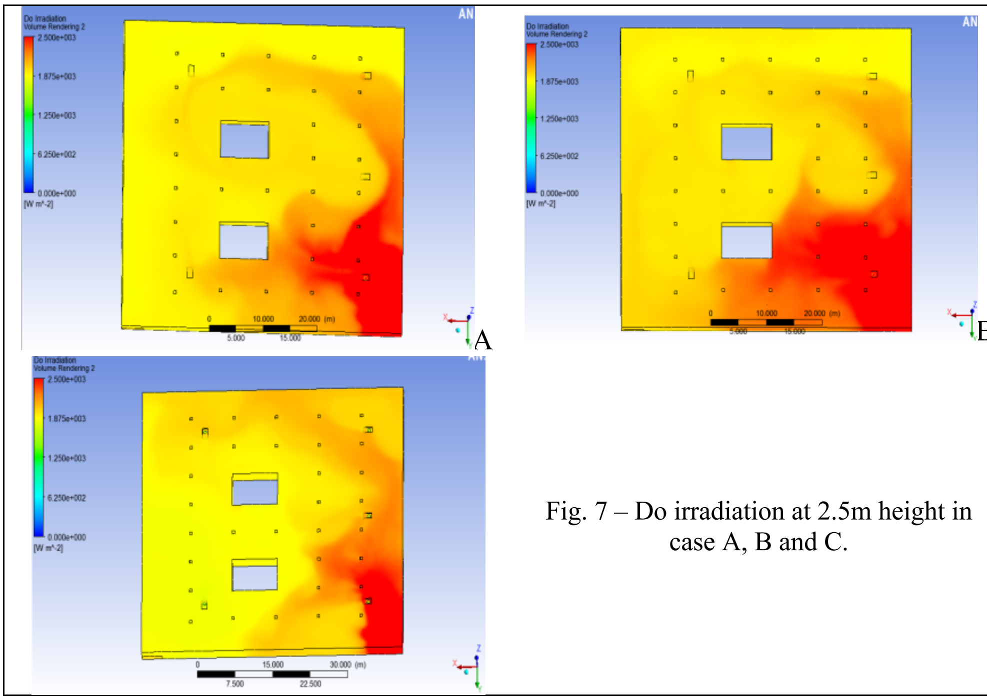
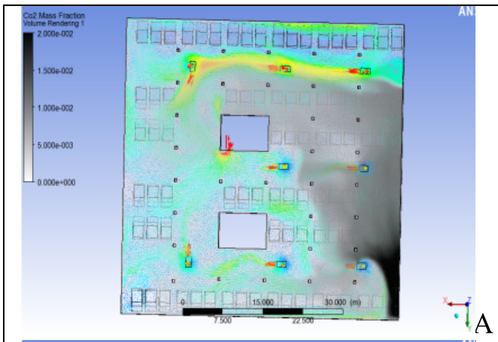


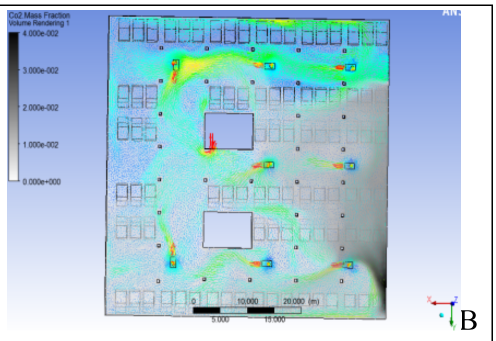
Fig. 7 – Do irradiation at 2.5m height in case A, B and C.

Also, by increasing the number of impulse jet fans to 8, relevant aspects of novelty were highlighted, but first of all it is noteworthy that an increase in the amount of carbon dioxide in the entire car park was reported in all three cases. Moreover, in these circumstances it was highlighted that by keeping open all three gaps for fresh air supply can be determined the existence of problematic solutions in terms of compliance with performance criteria to protect users, generating flows of atypical type in case G. Therefore, according to Fig. 11, due to the supplementation with three more jet impulse fans, through one of the gaps designed for fresh air supply is forced the evacuation to the outside of a significant quantity of combustion products, aspect not allowed by the specific standards.

In the other two cases, respectively H and I, we notice that the area in which the radiation level at height of 2.5 meters exceeds 2.5 kW/m^2, limit value established by the European standards, occupies approximately ¼ of the surface of the entire underground car park, which does not indicate the existence of superior results from the perspective of fire safety of the enclosure

Similarly, it should be noted that in case I, which requires the supply of fresh air to be achieved exclusively through the two gaps specially designed for this purpose, the pressure remains constant throughout the car park, and the overall results remain acceptable.





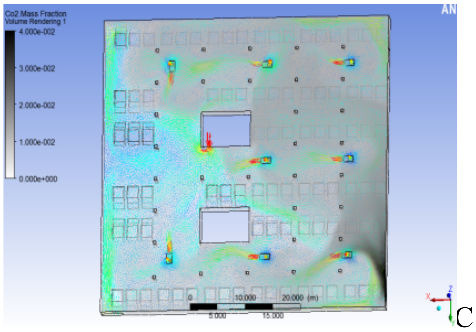
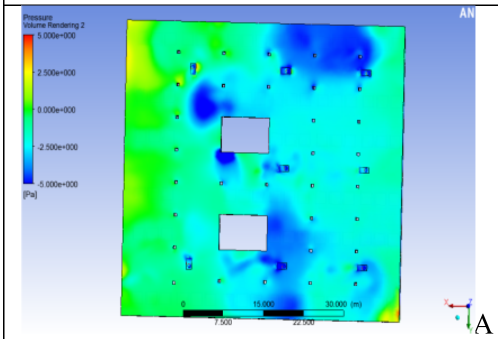
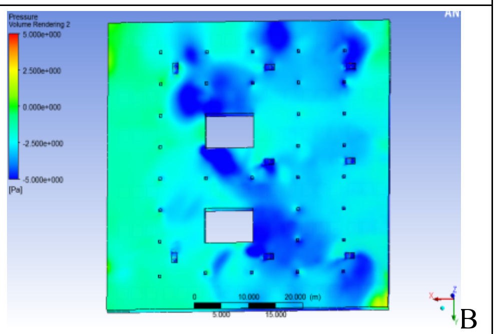


Fig. 8 – CO_2 mass fraction combine with velocity vectors in case G, H and I.





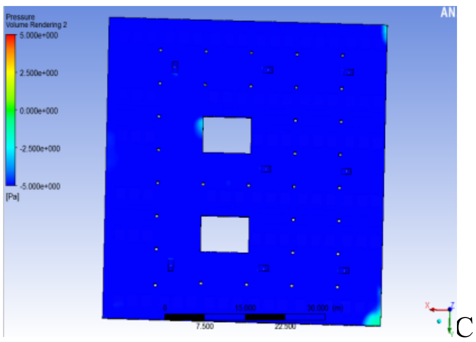


Fig. 9 – Pressure regime in case G, H and I.

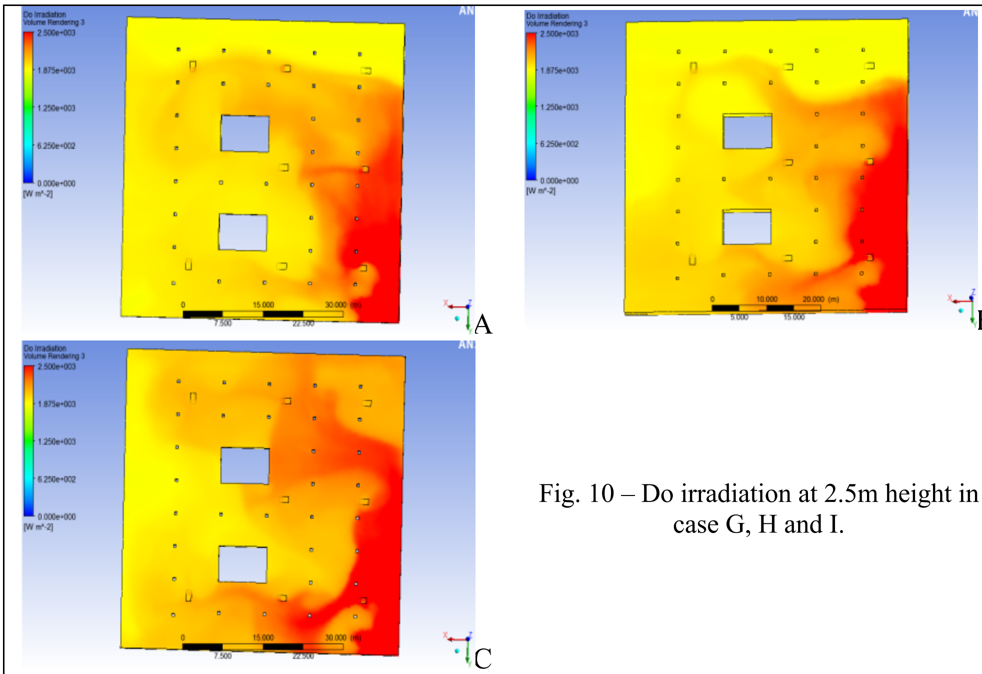


Fig. 10 – Do irradiation at 2.5m height in case G, H and I.

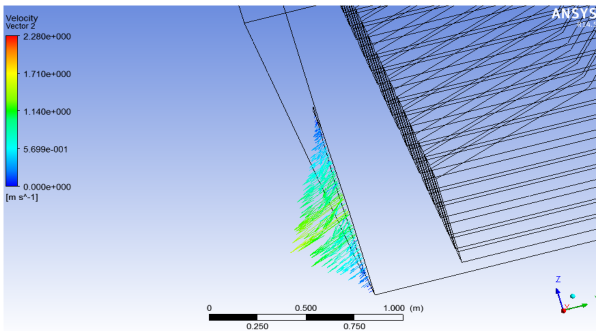
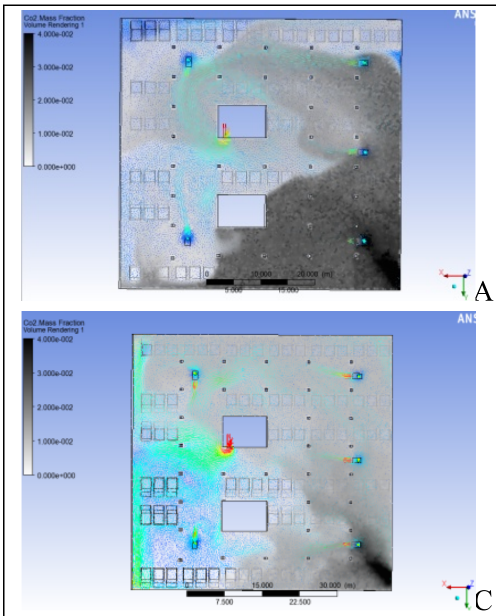


Fig. 11 – Velocity vectors at fresh air inlet in case G.

Also, in cases J, K and L it is proposed to analyze the flow of the smoke and hot gases, if 5 impulse jet fans are used, but with the modification of their dimensioning criteria to the value of 80 N/m.

Thus, in cases J and K the results are significantly more unfavorable from the perspective of the amount of combustion products remaining in the parking lot, compared to the similar case when impulse jet fans where sized at 100 N/m. Implicitly from the perspective of the thermal radiation level at the parking lot we find the existence of an area consisting of ½ of the total area of the parking lot where the thermal radiation level at the height of 2.5 meters exceeds the value of 2.5 kW/m^2, aspect not allowed by specific standards.

However, in the case L where the air intake is achieved exclusively through the gaps for fresh air supply, the results remained relatively constant compared to previous similar cases, thus reiterating the opportunity to use this model.



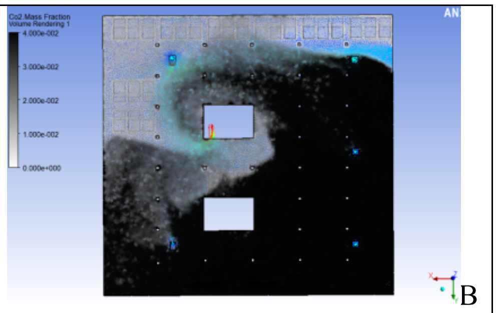
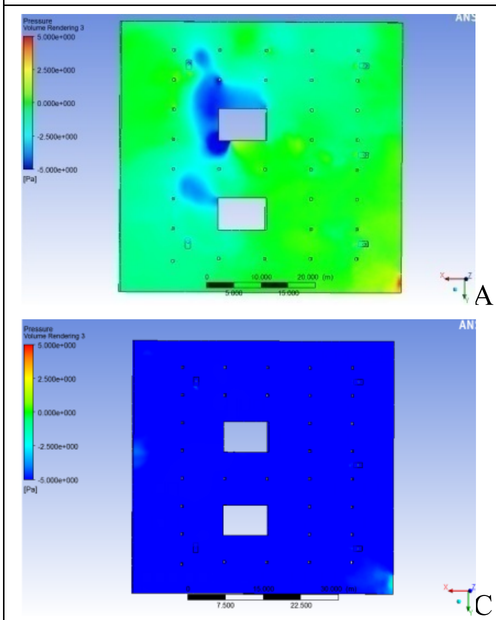


Fig. 12 – CO_2 mass fraction combine with velocity vectors in case J, K and L.



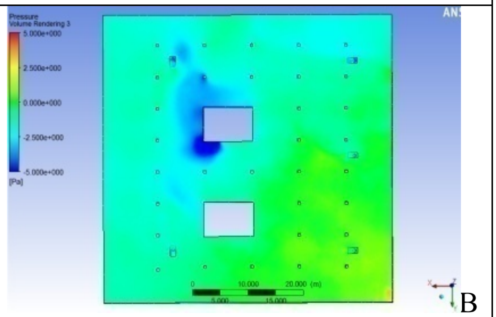
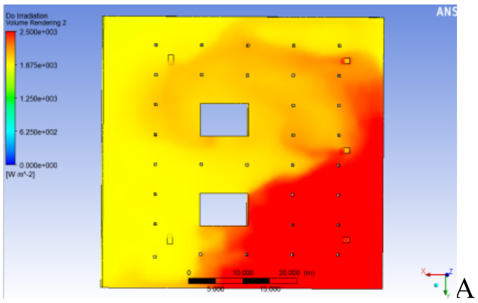
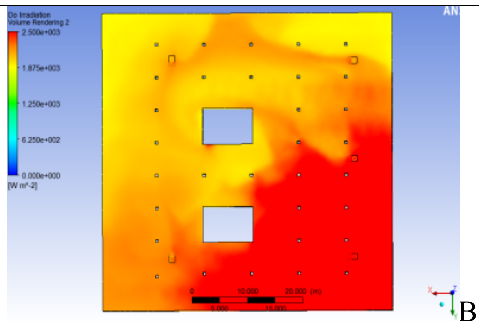


Fig. 13 – Pressure regime in case J, K and L.





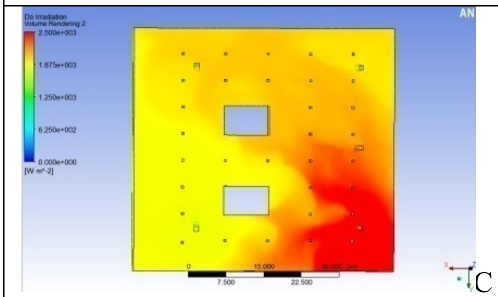
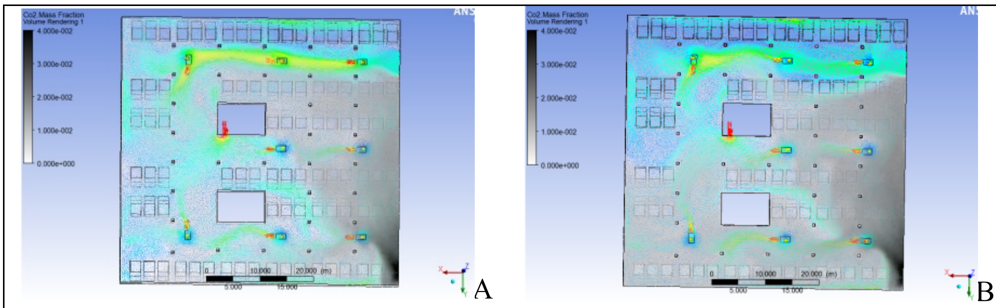


Fig. 14 – Do irradiation at 2.5m height in case J, K and L.

At the same time, in order to verify the validity of the previously presented theses, a new set of 3 simulations was performed, in which it was decided to use 8 impulse jet fans whose dimensioning was set at the value of 80 N/m.

From the perspective of the phenomenon of atypical flow of smoke and heat towards the outside of the car park through one of the gaps provided in fact for the supply of fresh air, this phenomenon was kept constant similarly in case M like in case G, but it was established the existence of a 50% reduction in fluid flow through that gap, aspect according to fig. 18.

Also, regarding to the aspects resulting in cases N and O, they remain relatively constant compared to similar cases D and E, in which fans where sized at 100 N/m.



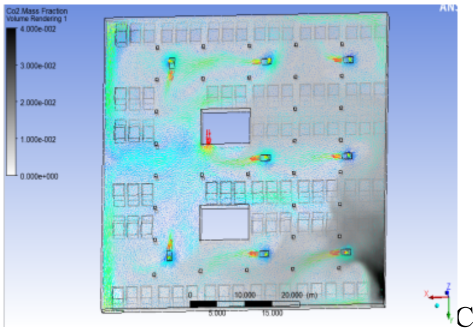
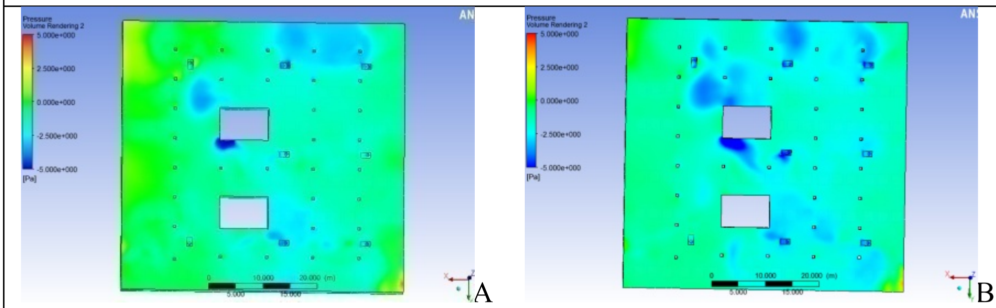


Fig. 15 – CO_2 mass fraction combine with velocity vectors in case M, N and O.



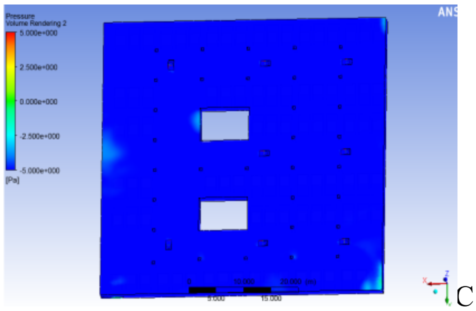


Fig. 16 – Pressure regime in case M, N and O.

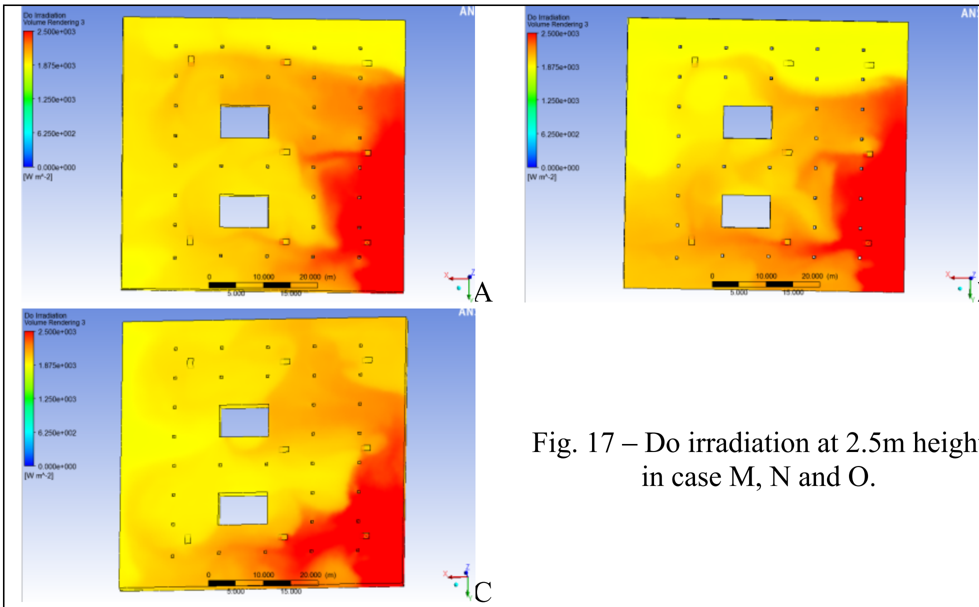


Fig. 17 – Do irradiation at 2.5m height in case M, N and O.

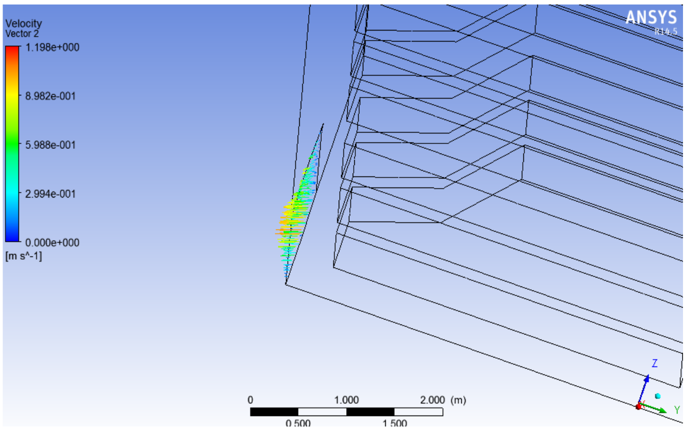


Fig. 18 – Velocity vectors at fresh air inlet in case M.

At the same time, by reducing the size of the impulse jet fans to the value of 60 N/m, in the case of the use of 5 such equipment, better results were identified in case P, which assumes that all the gaps provided for fresh air intake are closed, by comparison with cases J and D, in which jet impulse fans were used dimensioned at the values of 80 N/m, respectively 100 N/m.

On the other hand, in the R case, where the fresh air supply was carried out exclusively through the ramp for access to the parking lot, the results obtained remained approximately constant compared to the K case, in which jet impulse fans sized at value of 80 N/m.

However, an interesting aspect was highlighted in the case of S, in which the undersizing of the jet impulse fan generated the circumstances that the smoke and hot gases resulting from the fire could not be transported to the area of the device provided for their evacuation. Thus, in the context of the short distance between the gaps provided for the intake of fresh air and the device for the evacuation of smoke and hot gases, the conditions were generated for a significant amount of smoke and hot gases to remain inside the underground parking lot, all the specific performance criteria being violated, unlike the similar F and L cases.

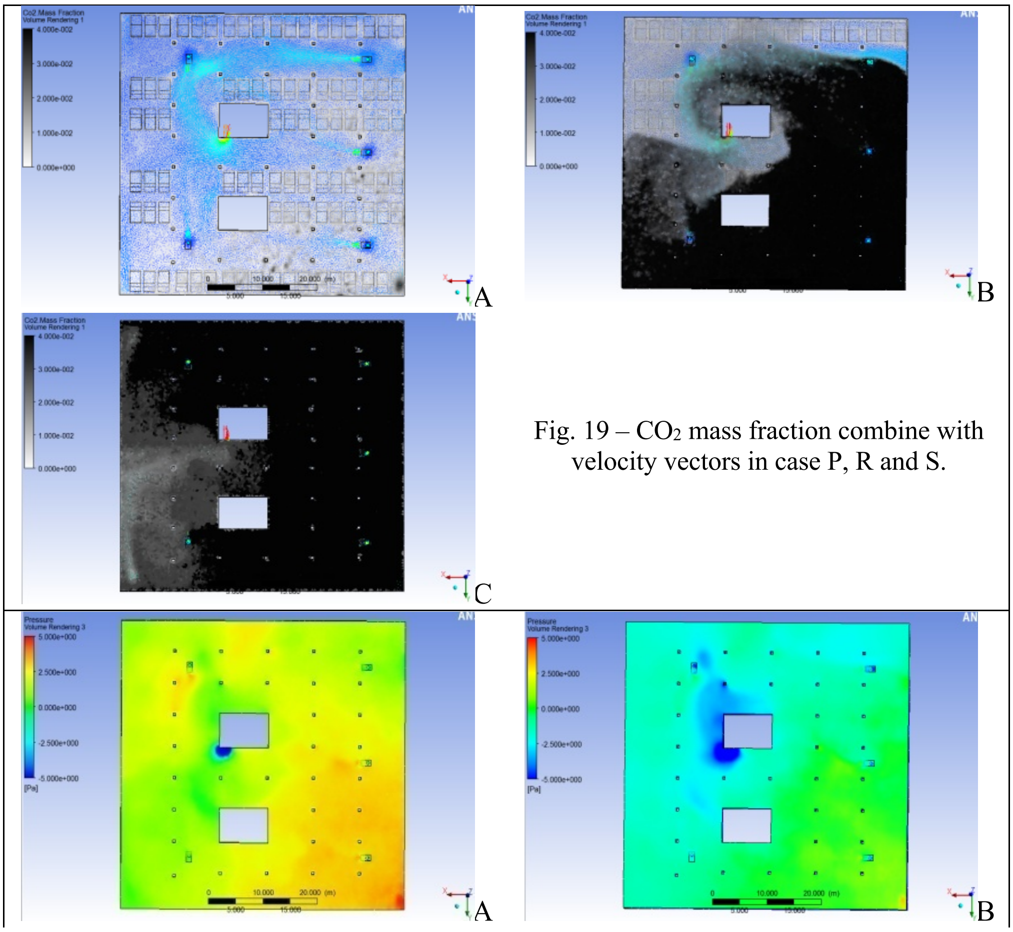


Fig. 19 – CO_2 mass fraction combine with velocity vectors in case P, R and S.

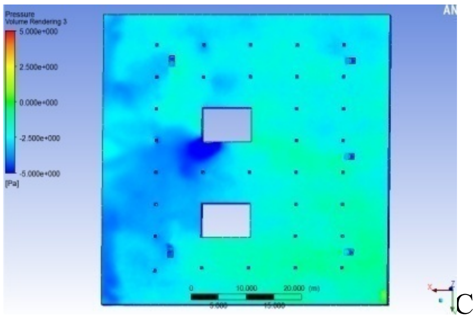
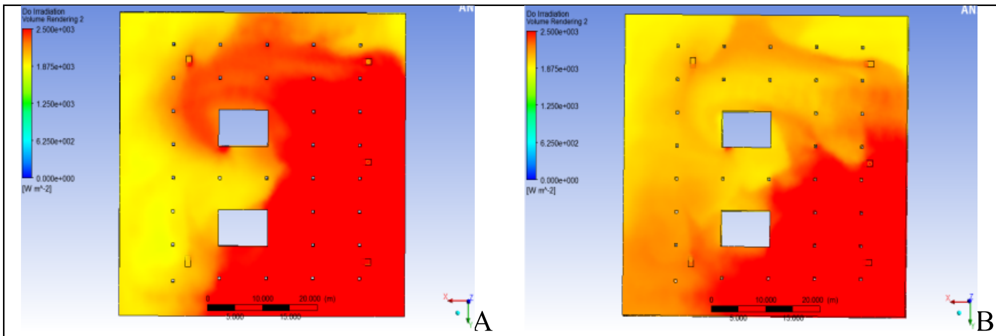


Fig. 20 – Pressure regime in case P, R and S.



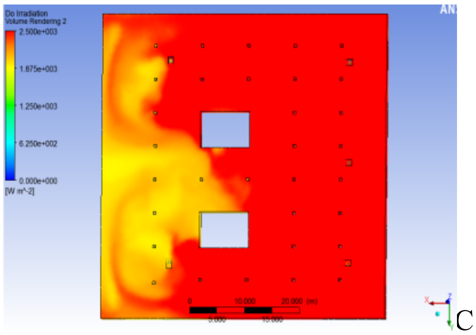


Fig. 21 – Do irradiation at 2.5m height in case P, R and S.

Also, in the last set of simulations carried out, cases T, U and V were analyzed, which assume the use of 8 impulse jet fans sized at the value of 60 N/m.

Thus, in the case T, the results obtained regarding the amount of carbon dioxide existing in the parking lot, as well as the level of thermal radiation in the parking lot, are improved by comparison with the similar cases M and G, in which jet impulse fans were used sized at values of 80 N/m, respectively 100 N/m. Also, by reducing the size of the jet impulse fans, it is also observed that the phenomenon of the outward flow of the fluid from the parking lot through one of the gaps provided exclusively for fresh air intake has decreased in intensity, in figure 25 it can be observed how the fluid flows in both directions, by comparison with figures 18 and 11. Thus, a potential further reduction in the size of the impulse jet fans to a value lower than 60 N/m could completely remedy the conditions for the appearance of this phenomenon and would lead to obtaining some positive results on all levels.

In parallel, by reducing the size of the jet impulse fans, in case U, which involves closing the gaps provided for fresh air intake, much worse results were obtained, compared to similar cases N and H, this solution not being viable from the perspective of the required performance criteria to be respected.

However, a positive aspect was highlighted in case V, because by supplementing it with three jet impulse fans, the results obtained are clearly superior compared to case S, practically through this addition, the premises for the circulation of smoke and hot gases are generated in the vicinity of the device provided for their evacuation and under these conditions the amount of carbon dioxide in the parking lot was significantly reduced. Even so, by comparison with similar cases O and I, the results obtained in case V are weaker, especially from the perspective of the level of thermal radiation that exceeds the value of 2.5 kW/m^2 on an area of more than ¾ of the underground parking lot.

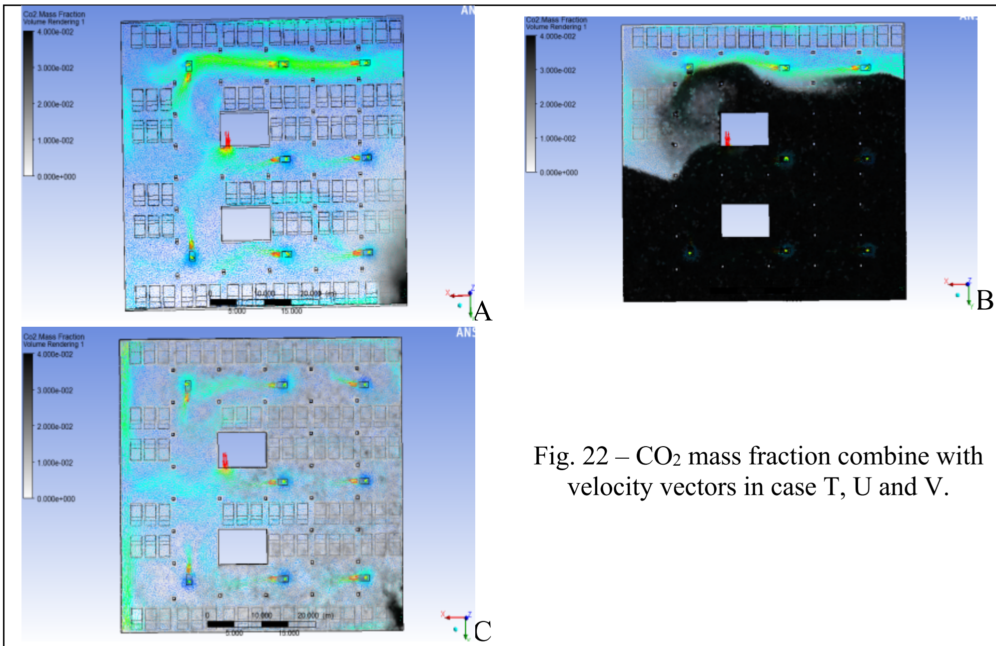
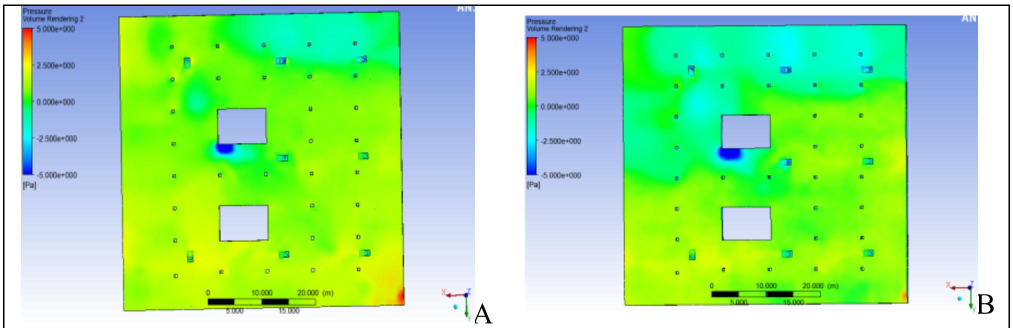


Fig. 22 – CO_2 mass fraction combine with velocity vectors in case T, U and V.



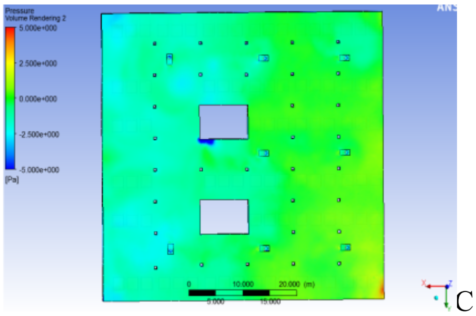
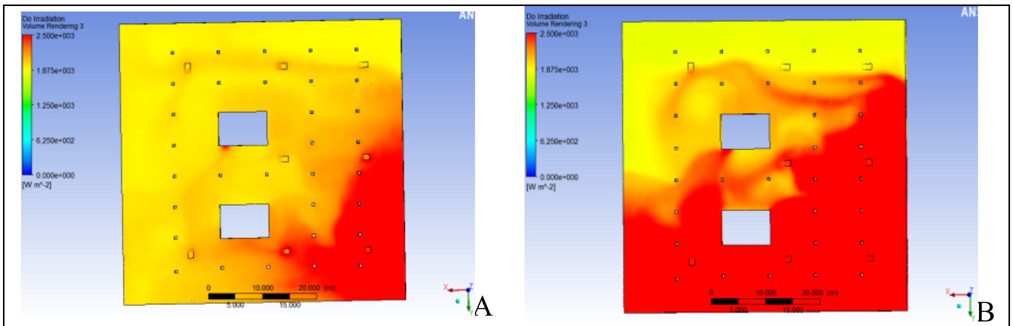


Fig. 23 – Pressure regime in case T, U and V.



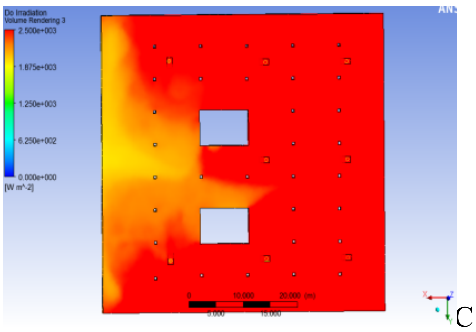


Fig. 24 – Do irradiation at 2.5m height in case T, U and V.

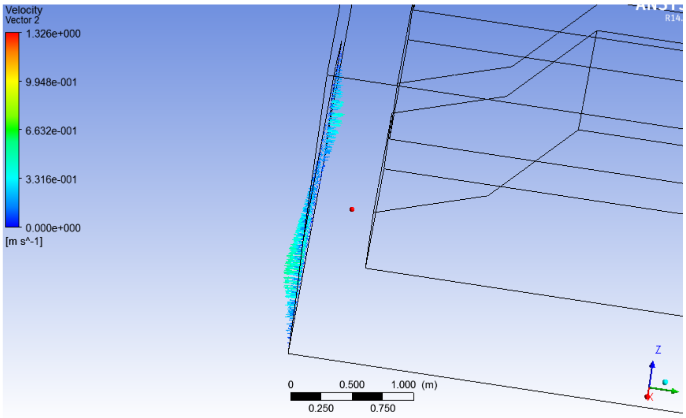


Fig. 25 – Do irradiation at 2.5m height in case T, U and V.

Considering the exposed aspects, the comparison of the obtained results creates the premises of establishing an interdependence between the number of jet-impulse fans used and their technical performances related to the size of the parking lot, respectively to the location of the gaps for smoke evacuation and fresh air supply.

4. Discussions

In view of the elements detailed above, some relevant aspects are outlined from the perspective of the design and sizing of smoke and heat ventilations systems in closed underground car parks.

Thus, in relation to the dimensioning and location of the gaps for fresh air supply, it resulted that in the event of the use of jet impulse fans it is not appropriate to keep open other gaps for fresh air supply except those expressly designed and dimensioned according to applicable standards. Capitalizing on the positive contribution of this equipment in order to facilitate the flow of combustion products to the smoke and heat exhaust device, it is appropriate to ensure a constant level of pressure throughout the underground car park. The previously concluded aspects are of great relevance in the context in which most underground car parks in operation are provided with permanently open access ramps or provided with grids through which fluids can flow, which can cause a malfunction of the system according to the aspects shown above.

Relatedly, it has been established that the exclusive use of the parking access gap as a source of fresh air is not necessarily likely to adversely affect the functionality of the smoke and heat exhaust ventilation systems, especially if the car parks are no longer provided with other gaps that cause negative interference from the perspective of fluid flow. However, the experimental simulations performed revealed that in the case of using these ramps as the only source of fresh air, at the same time with the use of impulse jet fans, situations may arise with negative results from the perspective of ensuring optimal fire safety conditions in the parking lot.

It was also observed that in the event of the use of conventional systems, without impulse jet fans, the results were better if they were used simultaneously the both sources of fresh air supply, because the negative pressure existing in the immediate vicinity of the smoke and heat exhaust device generated the premises for an efficient evacuation of the combustion products from the car park. In case of no use of jet impulse fans the results remained relatively constant positive even if the both fresh air supply sources were alternatively closed, unlike in cases where impulse fans were used.

At the same time, the experimental analysis revealed the existence of a link between the number of jet impulse fans used and their sizing, as well as the existence of negative consequences in the operation of the smoke and heat exhaust ventilation systems, generated on the one hand by oversizing, and on the other hand by undersizing the number or the performance of the impulse jet fans, aspects that should be analyzed in detail during another scientific paper.

Therefore, the experimental study performed revealed that for situations where CFD simulations are not performed in the design activity to demonstrate the validity of the proposed technical solution, especially in cases of use of jet impulse fans, it is strongly recommended to close all other possible fresh air sources except expressly provided for in this regard.

5. Conclusions

The lack of predictability of the design criteria from national and international standards, as well as the diversity of design solutions identified in practice, in terms of the arrangement and sizing of both impulse jet fans and gaps for natural fresh air supply, related to smoke and heat exhaust ventilation systems from underground car parks, have generated the circumstances of implementing solutions that can provide negative results in the event of fires, with the risk of affecting the safety of users, intervention forces and construction stability.

The conclusions drawn from the previous analysis generate the premises for adapting the design of these installations by reference to the arrangement of sources for fresh air supply, in order to eliminate possible cases where the systems with which the buildings are equipped are inefficient, but also to improve from a technical-economic point of view these indispensable systems from the perspective of ensuring the fire safety of the constructions.

REFERENCES

Viegas J.C., *The use of impulse ventilation to control pollution in underground car parks*, International journal of ventilation, 57-74 (2003).

Viegas J.C., *The use of impulse ventilation for smoke control in underground car parks*, Tunelling and Underground Space Technology, 2010 (page 42-53)

Teodosiu C.I., Ilie V., Radu G.D., Teodosiu R.S., Assessment of ventilation efficiency for emergency situations in subway systems by CFD modeling, 2015;

*** EN 12101 – 5, NP 127:2009 – Romanian fire safety regulations for underground car parks.

Lu S., Wang Y.H., Zhang R.F., Zhang H.P., Numericul study on Impulse Ventilation for Smoke Control in an Underground Car Park, Procedia Engineering 11/2011, (page 369-378).

Chan M.Y., Chow W.K., Car park ventilation systems: performance evaluation. Building Enviroment 2004 (page 635-643).

Chan M.Y., Chow W.K., On safety systems for underground car park. Tunnelling and Underground Space Technology 1998 (page 281-287).

Zhang X.G., Guo Y.C., Chan C.K., Lin W.Y. Numerical Simulations on fire spread and smoke movement in an underground car park, Building Enviroment 2007 (page 3466-3475).

EVALUAREA PERFORMANŢEI SISTEMELOR MECANICE DE EVACUARE A FUMULUI ŞI A GAZELOR FIERBINŢI PENTRU PARCĂRILE SUBTERANE CU SURSE NATURALE DE AER PROASPĂT, UTILIZÂND METODA CFD

Un rol deosebit de important în proiectarea sistemelor de ventilaţie mecanică pentru evacuarea fumului şi a gazelor fierbinţi din parcările subterane este dimensionarea şi amplasarea surselor naturale de aer proaspăt. Astfel, studiile efectuate au fost relevante în sensul că există premise pentru îmbunătăţirea funcţionalităţii acestor instalaţii atât din punct de vedere tehnic, cât şi economic, prin dimensionarea şi aranjarea deschiderilor destinate aportului de aer proaspăt, corelate cu decizia de a utiliza sau nu ventilatoare cu jet de impuls.