Proceedings of the 8th World Congress on Mechanical, Chemical, and Material Engineering (MCM'22)
Prague, Czech Republic – July 31, 2022 - August 02, 2022
Paper No. HTFF 123
DOI: 10.11159/htff22.123

Underground Car Park Smoke Management System Design Validation Using CFD Simulation: Car Fire Products Yields Rates

Muhanad Hajjawi[1]
[1]Higher Colleges of Technology
University city, Sharjah, UAE
mhajjawi@hct.ac.ae

***Abstract* -** Smoke management systems design is very important as it affect saving human lives in case of fire. The majority of fire-related deaths are caused by smoke inhalation of toxic gases, only 30% of deaths are due to fire burns. Recently, a great attention has been given to smoke management systems design validation using CFD simulations to ensure its effectiveness and compliance with fire codes regulations. CFD smoke simulation usually conducted using the inert fire species transport model, in which the fire source values specified at the fire inlet are assumed to be equivalent to an actual car fire products generation rates. Nonetheless, with the lack of a comprehensive conclusion on actual car fire products generation rates in literature, fire codes usually specify a certain fuel to represent a car fire, such as polyurethane as per UAE fire code. Considering the aforementioned, this work reviews literature on both polyurethane and actual car fires products generation rates, in an effort to conclude a proper fire products generation rates for CFD smoke simulations. Furthermore, this study demonstrates the use of the concluded fire source values to validate an underground car park smoke management systems design of a residential tower in UAE. The design is validated in compliance with the UAE fire code regulations considering both fire products concentrations and visibility analysis. The simulation results shows considerable difference in smoke generation between actual car fire and polyurethane fire. Mainly due to polyurethane higher fire growth rate and soot generation rates. On the other hand, the results illustrate that the smoke management system design satisfies the fire code CO and CO2 concentrations limits, yet it failed to comply with the fire code visibility requirements when polyurethane was used as fire source.

***Keywords*:** Car fire products yields, underground car park smoke simulation, smoke visibility, polyurethane fire products yields

1. Introduction

Underground facilities such as, car parks, metro stations, and bus stations are increasingly used in the development and modernization of modern crowded cities. The design of proper ventilation and smoke management systems for such large and highly populated spaces is essential to guarantee healthy and safe environment. At present, the design and analysis of ventilation systems for underground facilities can be achieved by field measurements, scale model experiments, or numerical simulation using computational fluid dynamics (CFD) [28]. With the increase of computational power, grid generation capabilities, and the number of physical modeling, CFD simulations are gaining momentum in the area of fire simulation. This due to the fact that CFD simulations provides more flexibility over physical experiments when it comes to assessing full scale simulations. Many smoke control systems design validation studies have been published recently using CFD simulations. Santoso [13] studied the effect of horizontal ventilation system and its thrust direction on the spread of smoke, as well as, the impact of additional building structure on smoke flow pattern and extraction effectiveness. X. Deckers [1] study presented a full-scale fire and smoke CFD simulation and showed the effect of structural beams on the spread of smoke. Kmecová [7] studied the design of a fire ventilation system with impulse jet fans for an underground car park. B. Merci [11] concluded several full scales studies on underground car park fire smoke simulation and physical testing, taking account the effects of sprinklers and multiple cars fire scenario. Yet unfortunately, the fire source specifics and combustion parameters used in each simulation were not explicitly stated in the aforementioned works. Hence, in this study, the fire source parameters calculations and setup will be explicitly investigated in literature, to conclude a proposed car fire source parameters set to be used for smoke management simulations.

2. Fire smoke source for car park numerical simulations:

There are two fire numerical models that can be implemented for car fire smoke simulations, the combustion model and the inert species transport fire model. Inert species transport model with a fire source is usually used due to its lower computational demands and complexity comparing to the combustion model. Yet, this model requires defining the fire products mass flow rates at the fire source surface. The challenge in modeling a car fire, is to define a fire source parameters that reflects a realistic car fire characteristics and car fire products generation. The complexity of defining the same comes from the fact that car fires characteristics depend on many factors, such as, the car shape, size, material, and fire ignition initial location. Due to these factors, each car fire will provide somewhat different heat release curve and different fire products generation rates. The treatment of such complexity in CFD simulation could be challenging to achieve the required simulation accuracy.

In literature, different car fire source treatments were implemented for car fire smoke simulations. Santoso [13] set the fire source of 10MW steady state HRR with soot and CO yield of 0.01 and 0.1 respectively. Eimermann [2] recommends soot yield of 0.1 to 0.2 and He 20 to 40J /kg, which leads to soot production of minimum of 5.8kg to 68kg in 10 to 20 minutes. Kmecova [7] used Polyurethane foam GM27 fire source to represent a car fire with a soot and CO yields of 0.1 and 0.042 receptively. Tharimaa [23] used the combustion model with methane fire source yielding Soot and CO of 0.07 and 0.2 respectively. Deckers [1] used the combustion model with soot yield of 0.22. Vigne [26] simulated different fuels with a wide range of soot yield (from 0.001g/g fort Methanol to 0.178g/g for Toluene) and concluded that a cutoff value of 0.1 to be used for smoke management evaluation. Many others did not provide explicit details of fire source values such as [25][22]. On the other hand, fire codes set different requirements to represent a car fire source, for example, the UAE fire code set the car fire source as flaming polyurethane with 5MW steady HRR. Reference to the above presented studies, there is no conclusive agreement on the most realistic car fire source products yields to be used for single or multi car fire simulations. Nonetheless, several car fire tests studies were conducted to provide reference car fire product generation rates and heat release rates curves [5] [20] [9]. Accordingly, in an effort to conclude a proper fire source treatment for car fire smoke simulations, a proposed fire source products mass flow rates are presented in this study, based on the available data in literature.

2.1. Polyurethane fire products mass flow rates

Following the UAE fire code, polyurethane fire source to be used for underground car park simulations. Accordingly, species transport model requires specifying the mass flow rate (total of all fire products) and each fire product concentration percentage at the fire inlet surface. The below formula 1 is used to calculate the mass flow rate of fire products including carbon monoxide CO, Soot, CO2 and H2O. Other fire products are neglected in this study as its yield values are considered negligible.

$$m_x = Y_x Q / H_c \quad (1)$$

Yx is the yield of each fire product species, *Hc* is the heat of combustion *(kJ/kg)* and *Q* is the heat release (KW). Yields and *Hc* could be found in literature [8][12][3][10]. Yet, it was difficult to find all species fire products yields values resulting from flaming polyurethane. Several studies listed different products yields values for different types of polyurethane (density and shape) using different test setups and procedures [10][12]. With the absence of specified polyurethane fire products yields values in the fire code, the highest listed values for CO, CO2 and Soot are selected in this study for underground smoke simulations. This selection represents an upper Limit fire scenario with highest products release rates for smoke management system design validation.

Table 1 lists proposed polyurethane (rigid) fire products values, and the corresponding calculated species mass flow rates using formula 1. Note that CO yield and *He* values were selected from [12] which is in line with [8][3]. The mass flow rate for CO2 was calculated using CO2 yield from [12], and the H2O mass flow rate was calculated using the mean yield value from [10].

Table 1: Recommended polyurethane (rigid) fire products Yields for Species transport model smoke simulations.

$H_e = 17.9 Mj/kg$, $Q = 5MW$		
Species	Yi e l d (kg/kg)	Mass flow rate (kg/s)
CO	0 18	0 050
Soot	0 11	0 031
CO_2	1 71	0 478
H_2O	0 96	0 268
HC	0 014	0 004
O	0 011	-
HC	0 01	-
Total mass flow rate		0 831*

**NO and HCI neglected in this Study*

2.2. Car fire products mass flow rates

For a realistic car fire simulation using the species transport model, the challenge is to define the fire source parameters corresponding to a real car fire. Mainly, the challenge is to determine each car fire product mass flow rate at fire source boundary condition. For predefined material combustion, defining theses parameters is somewhat well studied in literature for most materials as presented in section 2.1 for polyurethane. Yet, knowing that a car fire involves he combustion of different material types, different car types and sizes, it is somewhat more complex to define the fire source parameters. Car fire products yield rates and compositions are still not fully studied nor defined in literature. Unfortunately, most of the conducted car fire tests did not focus on fire products yields recording, rather, many was conducted with emphasis on heat release rate curves generations for single and multi-car fires, or car fire classifications based on HRR, or the effect of car fire HRR on steel structure design applications[24] [21] [27] [5].

Table 2: Car fire products mass flow rates at Max. HRR as per General Motors (GM) car fire Tests

	GM [15]	GM [4]	GM [16]	GM [17]	GM [14]	GM [18]	GM [19]
CO (kg/s)	0.02	0.0018	0.0013	0.0024	0.002	0.00015	0.00025
Soot (kg/s)	0.004	0.15×10^{-5}	0.07×10^{-5}	0.1×10^{-5}	0.0075×10^{-5}	0.1×10^{-5}	0.13×10^{-5}
CO2 (kg/s)	0.25	0.087	0.09	0.1	0.032	0.06	0.085
Mass loss		3kg/300 sec	25kg/ 15min		5kg / 4 min	3kg/150 sec	20kg/27 min
HHR max (KW)	5000 kW	1200kw	1200kw	1350 KW	500kw	750kw	1200kw
Co2+Co+Soot (kg/s)	0.274	0.0888	0.0913	0.1024	0.0340	0.0602	0.0853

*GM: General Motors

Few car fire experiments in literature provided explicit data on fire product yields and mass loss rates curves (which equals to fire products mass flow rate) needed for species transport model CFD simulations. Table 2 provide a summary for car fire products data corresponding to several car fire tests conducted by General motors. But unfortunately, the mass loss rates curves were not provided and the conducted fire tests were not a full car burn tests (rear or front cars burnouts). Nonetheless, total mass loss was listed for each test corresponding to the test burning time, which gives an average mass loss flow rate value. Yet for smoke management system design validation, the system must be able to handle maximum smoke release rates conditions hence, the average mass loss rates are not adequate to be used for smoke management system design validations.

For maximum fire products mass flow rates, we reference to car fire experiments as per Joyeux 2002 [5]. This reference is selected in this study based on the fact that class 3 car fires provide the highest heat release rate and mass loss rate compared with other car classes [24]. From [5] a maximum flow rate of 0.47 kg/ is presented corresponding to a maximum HRR of 10MW. Note that, the mass loss rate curves are in line with the heat release rate curves when multiplying the mass loss rate by the mean heat of combustion of 22.8MJ. Yet, unfortunately the fire products concentrations and flow rates for each car fire product were not reported in these tests, although it was indicated that the CO, CO2 and H2O concentration were monitored during the tests.

With the absence of well-defined car fire source parameters based on car fire tests, hereafter we propose the same by combining all available car fire tests data in literature. Table 3 lists a proposed car fire source parameters to be used car fire smoke management system design simulations. Note that, H2O yield data was not available in the reviewed fire tests studies, hence it was calculated in relation to percentage of the Polyurethane H2O flow rates as an ultimate case.

Table 3: Recommended car fire products mass flow rates for Species models smoke simulations

Fire products	Mass flow rate(kg/s)	Calculated Car fire products (%)
CO	0.02[1]	4.3
Soot	0.004[1]	0.85
CO_2	0.25[1]	53. 2
H_2O	0.19[2]	41.1
HC	00.003[2]	0.06
Total fire products (mass loss)	0.47[3]	100

1 As per [16]

2 calculated in relation to Polyurethane (rigid)

H_2O and HCN flow rate ratios and total mass loss

3 As per [5]

3. The smoke management system design:

In this study, the smoke management system design for underground car park is assessed using the proposed car fire source parameters. The provided design uses purging system, which is a fire rated duct system connected to variable speed axial fans that extracts the smoke in case of fire. The system is also used as a ventilation system for the parking, by inducing fresh air and extracting car exhaust to keep oxygen level within the health and safety acceptable concentration. In case of fire, the extract fans will operate at max speed to achieve 10 air volume exchanges per hour as per AE fire code requirements. Accordingly, for a total parking volume of *19,691* m^3, *a 196,916* m^3/h air flow rate is required to be extracted to achieve 10 air changes per hour. With 67 extract outlets provided in the design, a flow rate of 820 l/s = 2952 m^3/h for each is set to comply with the air changes requirement. Make up air is assumed to be induced by the entrance ramp opening. The 3D model of the parking and ducts layout is shown in Figure 1.

As per fire codes regulations, the design should keep a smoke free layer below 1.8 height for pedestrian safe exit firemen entry. Furthermore, it should also keep the CO2 concentration level below 35,000 ppm (0.054kg/m3) for 10min exposure and CO concentration below the 6,000 ppm (0.0068kg/m3) for 5 min exposure. Note that, considering the car park size and fire exit locations, five minutes will be enough for pedestrian to reach the fire exists locations in case of fire. On the other hand, the system should also be able to keep a clear visibility of at least 5 meters under 1.8m height, at any given time during the fire first 20 minutes as per the code.

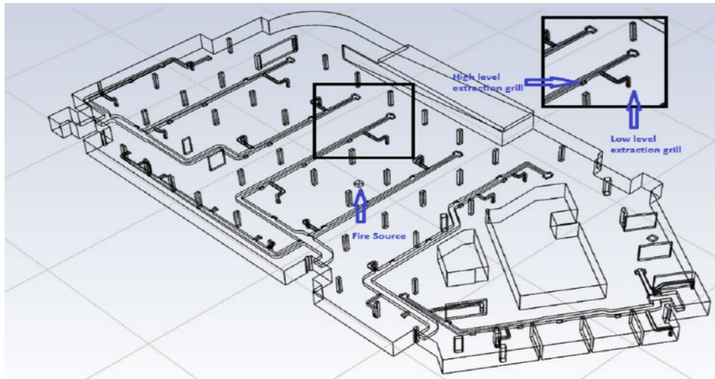

Fig. 1: underground parking smoke ducts layout 3D CAD model

.

4. Mesh and simulation setup

800K Polyhedral cell mesh with element sizes from 0.11 to 0.5m is generated using the ANSYS Fluent meshing [2]. The viscous layer first cell height spacing is set to 0.01m corresponding to *Yplus* of 200, which is within the recommend limit for the use of the wall function. The selected viscous layer spacing is good enough to provide an accurate simulation results, knowing that resolving the forces at the walls is not the interest of this study simulations.

ANSYS Fluent solver is used in this study. The Realizable k-epsilon turbulence model with enhanced wall treatment set along with the Species transport combustion model. For the boundary conditions, a mass flow fire inlet as per tables 3 and 5 are defined at the fire surface. A pressure outlet at the parking ramp entrance are set with ambient temperature of 300K, and finally, a mass flow outlet set at the smoke extract outlets with mass flow rate of 0.9kg/sec

5. Design validation:

Two fire simulations are conducted for the validation of the provided smoke management system design using the proposed fire source treatment parameters:

5.1. Flaming polyurethane fire source

This simulation is set following the UAE code requirements for enclosed parking smoke simulations. As per UAE fire code, CFD simulation is a requirement for car parks with jet fan smoke exaction systems or purging extraction system. Yet, to validate the purging system design using CFD simulation in this he code simulation parameters set for jet fan smoke system CFD simulation are followed, as both systems achieve the same life and safety measures. Accordingly, flaming polyurethane fire source of a steady 5MW HRR at t = 0(no gradual increase in fire HRR with time) is set as per table 3. Minimum simulation time of 20min is required by code and an extraction rate of 10 air changes per hour.

5.2. Actual car fire source

For more accurate car fire simulation, the car fire products flow rates should be specified based on a test experimental data, hence, a car fire source and the corresponding proposed car fire products release rates presented in section3 at maximum HRR are considered in this simulation. Nonetheless, in a real car fire, it takes 20 to 40 min until the fire reach its maximum HHR. To account for the same, the HRR profile shown in figure 2 is adopted, and the corresponding fire products release rates are calculated and set at the fire inlet surface. On the other hand, in a real fire scenario, the extraction fans will not start until the fire alarm system detects the fire and send a signal to initiate the extraction via the fire control panel. Depending on the type of smoke and heat sensors used in the design, the reaction time may vary, usually the process will take between 30 − 200 sec in a car park fire, considering the low smoke and heat generation rates at the initial stage of a car fire. In this scenario, the extraction is set to start after 100 sec.

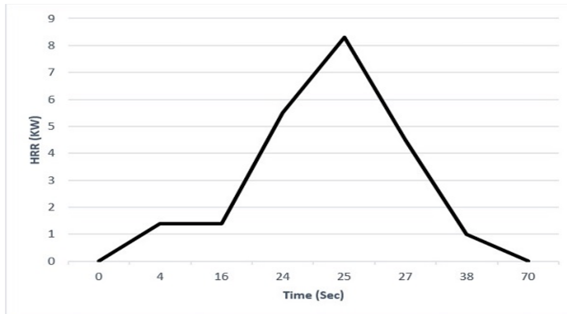

Fig. 2 Heat release rates for class 3 single car fire [5]

Finally this study consider only one car fire scenario, which believed to be adequate for smoke management deigns evaluation, knowing that 95% of underground car fires involve one car only. Yet for multiple car fire scenario, the same proposed parameters in table 3 could be used by implementing the same on multi fire inlet surfaces corresponding to multiple car fires. A delay time should be set between fires products release start time, to account for fire mitigation time between cars parked next to each other.

8. Simulations Results:

8.1 Flaming polyurethane fire source results:

Following the UAE code simulation requirements, this case was set as described in section 5.1 and Table 1. Figure 3 present CO2 and CO concentrations (kg/m3) contours at t=1200 sec. Values for CO2 and CO are clipped at critical values of 0.054 and 0.0068 kg/m^3 respectively. The results show that pedestrian will have minimal risk of intoxication after 20min. On the other hand, Figure 4 present the visibility after 20min, it shows some areas with *S* values less than 5 meters. Figure 11 presents visibility counters at 1.8m plan, the area weighted average of *S* at this plan equaled to 4 meters. Knowing that the UAE fire code requires a visibility of 5 meters after 20min, the design needs to be adjusted to achieve the same by increasing the extraction rate. At t=510 the total CO and CO2 mass accumulation equaled to 15.6kg and 149.6kg respectively, the CO2 extraction rate equaled to 0.387kg/sec comparing to CO2 generation rate of 0.477 kg/sec, hence the extraction effectiveness of 81% is achieved at 510 sec. At t=1200 sec, the total CO2 extraction rate increased to 0.457kg/sec, hence corresponding extraction effectiveness of 96% is achieved. The extraction increased as the smoke accumulated and spread to reaches all extraction outlets.

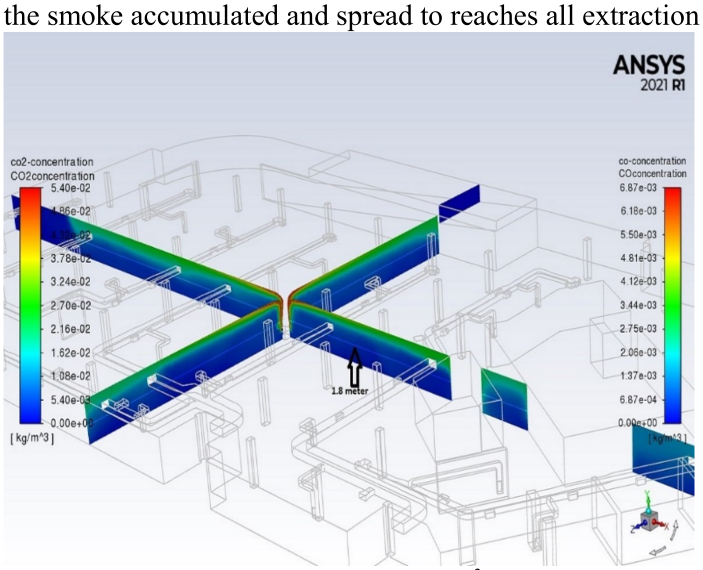

Fig. 3 CO and CO2 concentration (kg/m^3) at time 1200sec

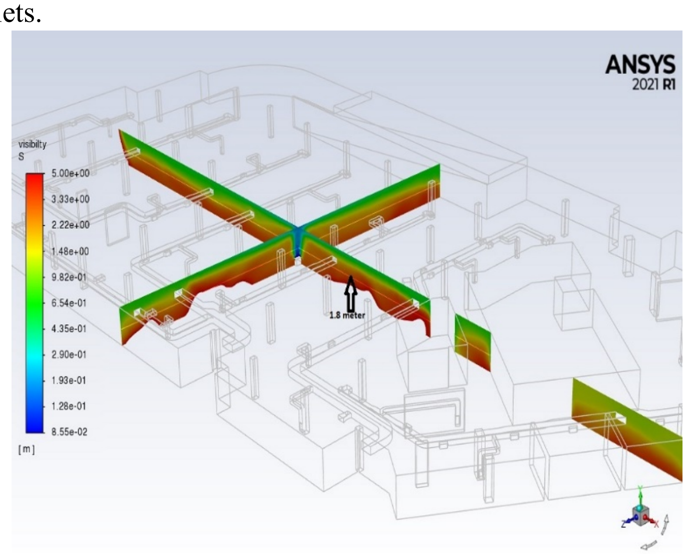

Fig. 4 Visibility *S* (meter) at 1200sec,

8.2 Actual car fire source results:

This simulation was set to represent a more realistic car fire scenario as described in section 5.2 and table 3. Figure 5 shows CO2 and CO concentrations (kg/m3) contours at t=20min. Values for CO2 and CO are clipped at 0.054 and 0.0068 kg/m^3 respectively. The simulation results shows that the concentration levels are lower than the critical values. The visibility results shown in Figure 6 indicates visibility of 5 meters is available after 20min. On the other hand, the total CO and CO2 mass accumulations after 20min equaled to 4.5 kg and 60.3 kg respectively. The results shows that gradual fire profile will have a big effect on smoke accumulation and extraction effectiveness.

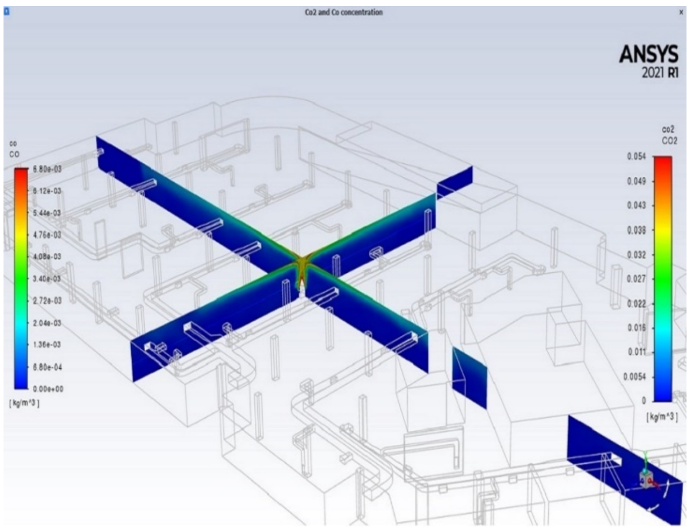

Fig.5 CO and CO2 concentration (kg/m3) at time 1200sec

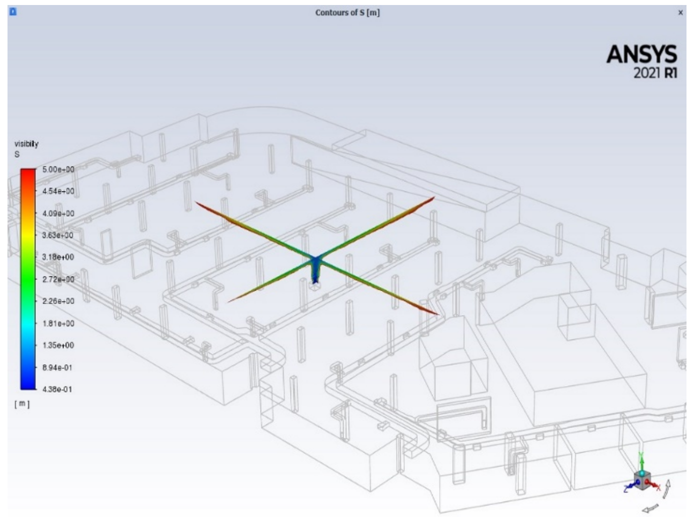

Fig. 6 Visibility S (meter) at 1200sec

8.3 Results accuracy

With the absence of experimental data to validate our underground parking smoke simulation results, a simulation result for smoke layer thickness is compared with theoretical smoke generation relationships as an indication of accuracy. For an axisymmetric plume where $z_1 = 0.035Q_p^{2/3} \,/\, \left(ds + 0.74\, Q_P^{2/5}\right)^{2/3}, z > z_1,\ and\ Q_p^{2/5} < 14d_s$, the time at which the smoke layer is at height z can be calculate by solving the below equations [8].

$$\frac{dZ}{d\tau} + \frac{M}{\rho_0 (gh)^{1/2} h^2} + Q^* = 0 \tag{2}$$

$$Z = \frac{z}{h} \tag{3}$$

$$Q^* = \frac{Q}{1100 h^{5/2}} \tag{4}$$

$$\tau = 3.13 t h^{3/2} / A_f \tag{5}$$

$$\tau = \int_Z^1 \frac{dZ}{0.195\,(Q^*)^{1/3} Z^{5/3} + Q^*} \tag{6}$$

Where;

$z = height\ above\ base\ of\ fire\ (inside\ fire\ room)$
$z_1 = intermittent\ flames\ limmiting\ height\ (m)$
$Q_p = convective\ portion\ of\ the\ heat\ relase\ rate\ kW$
$\rho_0 = density\ of\ ambient\ air\ kg/m^3$
$c_p = specific\ heat\ capacity\ of\ air \frac{kJ}{kg} K$
$A_f = Parking\ floor\ area\ (m2)$
$d_s = diameter\ of\ fire\ source\ or\ longer\ side\ of\ rectanguler\ source\ (m)$
$M = mass\ flow\ rate\ by\ entrainment\ kg/s$

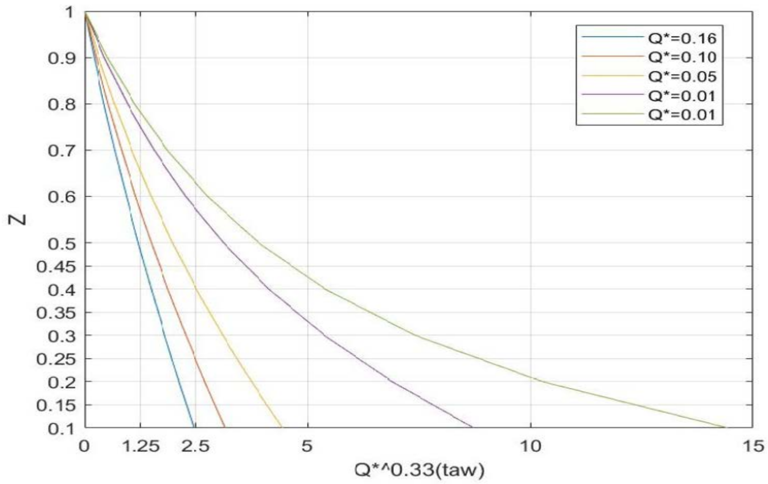

Fig.7 Smoke layer thickness theoretical solution.

Solving the above equation we generates Figure 7 for values of the accumulated smoke layer thickness, note that, in these equations a steady state values of heat release rates are assumed. As per the provided formulas for z = 1.8m, Z = 0.47 and Q* = 0.16, a steady state fire of 5MW will take 510 sec for the smoke layer to reach 1.8m height assuming no smoke extraction. The simulation results shown in Figure 8 are in close agreement with the theoretical smoke layer estimation. The figure shows that the smoke products are concentrated at 1.8m height at time 510 sec.

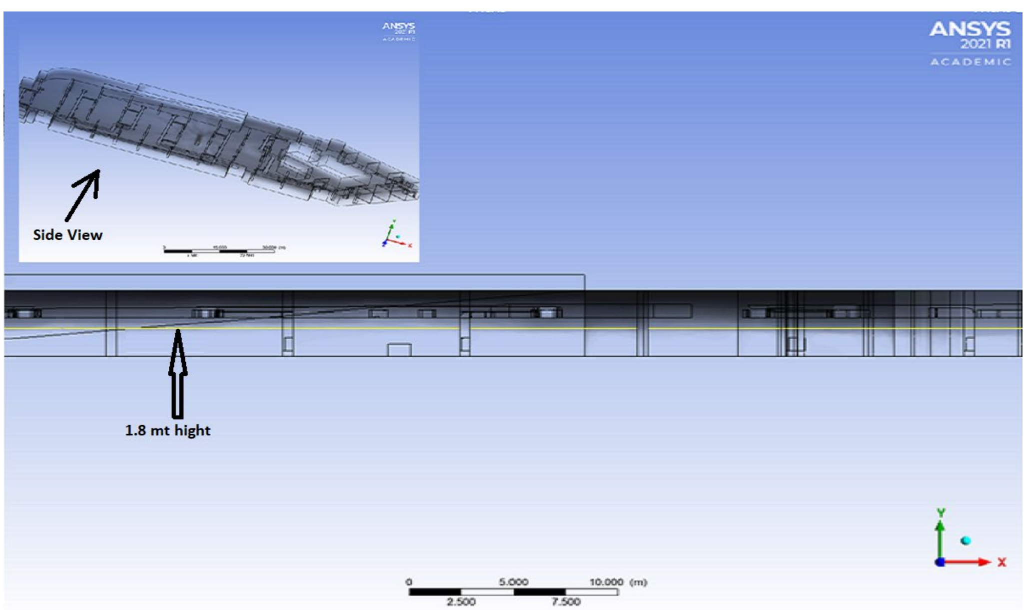

Fig.8 Smoke accumulation after 510sec with no extract.

9. Conclusion:

For car fire simulations using the species transport model, the fire products flow rates specified at the fire source must be equivalent to an actual car burnout. Yet, with the lack of a comprehensive conclusion on car fire products generation rates in literature, fire codes and researchers tends to specify a fuel type to imitate a car fire (such as polyurethane as per UAE fire code). Accordingly, this study presents a literature overview on car fire simulations, and concludes a recommended fire products yields for both, polyurethane and an actual single car fire burnouts. The proposed fire source yields values are used to investigate an underground car park smoke management system design of a residential tower in UAE. Two fire simulations case studies are conducted, one with polyurethane as a fire source, while the other with actual car burnout fire source. The results shows that the provided design satisfies the CO and CO2 concentrations and kept it under the critical levels in both cases. Nonetheless, the results indicate that the design fails to achieve the visibility fire code requirement when polyurethane is set to represent a car fire. On the other hand, considering a real car fire scenario using the proposed fire source parameters, along with taking into consideration the car fire heat realse rate curve, the simulations results shows that the design is capable of satisfying the fire code visibility requirements. This study demonstrate that using polyurethane or any other fuel to represent a car fire burnout could lead to an overdesigned smoke extraction system particularly to comply with the visibility requirements. Yet, keeping in mind that smoke visibility calculations and its graphical representations are still under research investigation, the simulation results of the same should be carefully analyzed to withdraw a reliable conclusion. Hence, further actual car fire burnouts tests are needed to investigate visibility and fire products yields values.

References

[1] Deckers, X., Haga, S., Tilley, N., Merci, B., 2013. Smoke control in case of fire in a large car park: CFD simulations of full-scale configurations. Fire Safety Journal 57, 22–34.

[2] Eimermann, M., 2007. Defining the governing parameters for reliable numerical simulation of smoke evacuation in underground parking garages, in: Proceedings of Clima 2007 Well Being Indoors.

[3] Hertzberg, T., Blomqvist, P., Dalene, M., Skarping, G., 2003. Particles and isocyanates from fires. http://www.diva-portal.org/smash/get/diva2:962229/FULLTEXT01.pdf.

[4] Jensen, L., Santrock, J., 2002. Evaluation of motor vehicle fire initiation and propagation 6: Propagation of an underbody gasoline pool fire in a 1997 rear wheel drive passenger car, (June 2002) docket nhtsa-1998-3588-158, general motors corporation. (1997 Camaro, rear impact, underbody pool fire). https://www.mvfri.org/Library/b-03.html.

[5] Joyeux, D., Kruppa, J., Cajot, L., Schleich, J., Luer, P., Twilt, L., 2002. Demonstration of real fire tests in car parks and high buildings. https://op.europa.eu/en/publication-detail/-/publication/74d025be-8e5f-4c03-917a-d168f5516aa5/language-en/format-PDF/source-219861764.

[6] KAI, K., 2015. Modeling smoke visibility in CFD. https://iafss.org/publications/fss/8/1265/view/fss_8-1265.pdf.

[7] Kmecová, M., Krajík, M., Straková, Z., 2019. Designing jet fan ventilation for an underground car park by cfd simulations. Periodica Polytechnica Mechanical Engineering 63, 39–43.

[8] Law, M., 1995. Technical memoranda tm19:1995 relationships for smoke control calculations. https://www.cibse.org/knowledge/knowledge-items-(1)/knowledge-archive.

[9] Lonnermark, A., Blomqvist, P., 2006. Emissions from an automobile fire. Chemosphere 62, 1043–1056.

[10] Lucas, V., Thomas, R., Eric, G., Guillermo, R., Jose, T., 2009. Analysis of principal gas products during combustion of polyether polyurethane foam at different irradiance levels. Fire Safety Journal 44, 933–940.

[11] Merci, B., Shipp, M., 2013. Smoke and heat control for fires in large car parks: Lessons learnt from research. Fire Safety Journal 57, 3–10.

[12] Raghu, T., Kotresh, M., Indushekar, R., Murugesh, B., 2014. Fire behaviors of polyurethane foams. Indian Journal of Advances in Chemical Science 3, 109–112.

[13] Santoso, M., Zilvan, B., Yulianto, N., 2015. CFD study on the ventilation system and shape configuration of underground car park in case office. Applied Mechanics and Materials 758, 143–151.

[14] Santrock, J., 2002a. Evaluation of motor vehicle fire initiation and propagation part 10: Propagation of a mid-underbody gasoline pool fire in a 1998 sport utility vehicle, (May 2002) docket nhtsa-1998-3588-189, general motors corporation. (1998 explorer, frontal crash, mid-body pool fire). https://www.mvfri.org/Library/b-03.html.

[15] Santrock, J., 2002b. Evaluation of motor vehicle fire initiation and propagation part 4: Propagation of an underbody gasoline pool fire in a 1996 passenger van, (January 2002) docket # nhtsa-1998-3588-143, general motors corporation. (1996 plymouth voyager, rear impact, underbody pool fire). https://www.mvfri.org/Library/b-03.html.

[16] Santrock, J., 2002c. Evaluation of motor vehicle fire initiation and propagation part 7: Propagation of an engine compartment fire in a 1997 rear wheel drive passenger car, (august 2002) docket #nhtsa-1998-3588-178, general motors corporation. (1997 camaro, frontal pole crash, engine compartment fire). https://www.mvfri.org/Library/b-03.html.
[17] Santrock, J., 2002d. Evaluation of motor vehicle fire initiation and propagation part 9: Propagation of a rear-underbody gasoline pool fire in a 1998 sport utility vehicle, (May 2002) docket nhtsa-1998-3588-188, general motors corporation. (1998 explorer, rear impact, rear pool fire). https://www.mvfri.org/Library/b-03.html.
[18] Santrock, J., 2003a. Evaluation of motor vehicle fire initiation and propagation part 12: Propagation of an underbody gasoline pool fire in a 1998 front-wheel drive passenger vehicle, (November 2003) docket nhtsa-1998-3588-201, general motors corporation. (1998 accord, rear impact, rear fire). https://www.mvfri.org/Library/b-03.html.
[19] Santrock, J., 2003b. Evaluation of motor vehicle fire initiation and propagation part 13: Propagation of an engine compartment fire in a 1998 front-wheel drive passenger vehicle, (November 2003), docket nhtsa-1998-3588-203, general motors corporation. (1998 accord, frontal impact, engine compartment fire). https://www.mvfri.org/Library/b-03.html.
[20] Shintani, Y., Kakae, N., Harada, K., Masuda, H., Takahashi,W., 2004. Experimental investigation of burning behavior of automobiles, in: 6th Asia-Oceania Symposium on Fire Science and Technology.
[21] Shippetal, M., 2010. Fire spread in car parks. https://webarchive.nationalarchives.gov.uk/ukgwa/20120919204054/http:/www.communities.gov.uk/documents/planningandbuilding/pdf/1795610.pdf.
[22] Splijar, S., Schnedier, D., Drakulic, M., 2018. Analysis of smoke stratification and smoke layer thickness in underground car park. Thermal science 22, 1963–1972.
[23] Tharima, A., Rahmanb, M., Yusoffb, M., Kuehc, A., 2019. Multi-objective optimization of underground car park design for tenability under fire-induced smoke. Smoke Tunneling and Underground Space Technology 85, 220–230.
[24] Tohir, M., 2015. Multiple vehicle design fire cases in car parking buildings. https://ir.canterbury.ac.nz/handle/10092/11411.
[25] Viegas, J., 2010. The use of impulse ventilation for smoke control in underground car parks. Tunneling and Underground Space Technology 25, 42–53.
[26] Vigne, G., W¦grzy«ski, W., 2016. Experimental and numerical analysis of the influence of the soot yield when conducting cfd analysis for the estimation of the available safe evacuation time, in: Interflam Conf.
[27] Zahirasri, M., Spearpoint, M., 2013. Distribution analysis of the fire severity characteristics of single passenger road vehicles using heat release rate data. Fire Science reviews 2.
[28] Zhao, R., Ling, Z., Jinsheng, M., 2018. Cfd design of ventilation system for large underground bus terminal in Macau barrier gate. , Journal of Wind Engineering and Industrial Aerodynamics 179, 1–13.