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Application of response surface methodology for optimizing evacuation time in enclosed car park

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Abstract. Smoke fills the car park area due to smoke back layering occurred during a fire. The presence of the beam which leads to the smoke back layering phenomena is investigated to remain smoke layer longer at the upper level with fewer occurrences of backflow. In the current study, a combination of Design of Experiment (DOE); Central Composite Design, (CCD) and statistical tools Response Surface Methodology, (RSM) were utilised to evaluate an optimal design for longer smoke residing time. The Fire Dynamic Simulator (FDS), a CFD model for the fire-driven fluid flow, was employed as a flow simulation tool. The result of six replication model produced by DOE, the error that ranged from 0.48% to 1.77% indicating that the model is reliable. It was also found that the polynomial regression result was linear with predicted R^2 of 97.64%, which was within the actual R^2 (99.45%). The effects of five control parameters such as ceiling height, beam spacing, transversal beam, extraction rate and longitudinal beam on the smoke descend time has been found to be significant. In the optimal design, the smoke remained longer at the upper level with the percentage of improvement 217.95%. The contribution of the study is the time measured in this analysis is adequate within the beam span only. Interestingly, it effects to the overall geometry with having a lengthier time of smoke to descend. The polynomial model should be used for future engineering design in an enclosed car park.

1. Introduction

A car park is constructed either at above or underground of a building. In term of fire severity, enclosed car park presents the most significant impact to the nearest property, produces more structural damage and releases larger amount of toxic gases. Due to limited air supply, the fire will be fully developed, thus generating a large amount of heat which is detrimental to the environment. In contrast, for open car park fire, the fuel-burning is localised as long as the fuel is still available. The fire might propagate to the nearest vehicles due to heat radiation or convection [1]. Smoke fills the car park area due to smoke back layering occurred during a fire. Ceiling barriers such as beam joists, miters and surface mounted light fixtures have been identified as the main components in causing ceiling jet blockage [2-3] smoke back layering, recirculation as well as stagnant smoke flow.

The effects of beam configuration on the obstruction of unconfined ceiling jet were investigated extensively by [2, 4-5]. Besides of gas temperatures, results such as smoke layer height, room pressure, oxygen concentration, flame height, smoke layer temperatures and smoke-layer depth in compartment have been reported. Johansson [6] have conducted numerical experiments to evaluate the previous correlations of ceiling jet temperature (average, maximum & maximum excess temperature) and velocities (average and maximum).

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Besides that, Siang [3] has estimated the fire temperature and smoke concentration below multiple beams (19 bays and 0.54 m beam depth) by using salt-water modelling. A similar study has been conducted by Delichatsios [7]. The author has revealed the behaviours of ceiling jet flow along the unobstructed beam with no smoke leakage to the adjacent beam. However, the results were limited to square beam configuration. In contrast, Merci and Shipp [8] have devised the new research direction of car park geometry. The Fire Protection Research Foundation's Detection and Alarm Research Council has conducted a research to determine the performance of smoke detection between different ceiling structures (waffle construction) such as smooth ceiling, ceiling with deep beam and deep beam pocket [9]. Another full-scale experiment and CFD simulation in a large car park have been carried out by [10-11] in order to investigate the significances of heat release rate, extraction flow rate, opening of incoming air and transversal beam (beam which perpendicular to the longitudinal beam). Apart from affecting the smoke propagation and the flow pattern, the use of ceiling beam could affect the sprinkler activation time as well. Accordingly, the sprinkler activation times in compartments employing beamed, sloped and sloped-beamed ceilings have been measured by [12]. Apart from that, the channelling effect has been reviewed separately by [13-15]. Moreover, sidewall fire experiment was carried out by [16] in order to investigate the effect of channel width on the burning rate and the ceiling temperature distribution.

In order to ensure proper smoke propagation, mechanical and extraction fans should be used. Many studies related to mechanical fan efficiency have been carried out. Santaso et al. [17] have performed a simulation to investigate the efficiency of horizontal ventilation system. The effects of CO contribution and additional building structures have been discussed. [18-19] have utilized ventilation fans such as extraction and jet fans and investigated the temperature profiles by using the buoyant plume. A very similar smoke control approach has been adopted in an underground car park separately by [20-21]. Their studies focused on parameters such as number of jet fan, jet fan velocity, extraction rate and fire location. Similarly, Meroney et al. [22] redesigned a ventilation system in an underground military firing range tunnel due to unwanted separation, reverse flow, stagnate, dead zone and recirculation at specific point spotted in the previous design.

To the best of our knowledge, studies related to the smoke control in presence of the beam are rather limited. Correspondingly most of researchers were not investigate on how ceiling jet or smoke flow by the presence of beam allow smoke remain longer at the upper level without or fewer occurrences of backflow. For this purpose, the actual underground car park of Simulator Building at Fire and Rescue Academy of Malaysia has been chosen to examine the current problem.

2. Method

The computational fluid dynamics (CFD) simulation was performed by using FDS software, which is specialized software in modelling fire-driven fluid flow. Flow turbulence was modelled via Large Eddy Simulation. The wind effects were not taken into consideration. Figure 1 and Table 1 show the boundary conditions and the numerical settings, respectively.

Table 1. Numerical setting for the simulation.

Parameter	Description of Car Park
Geometry dimension	4m x 1.6m x 0.3m
Mesh size	0.0094m
HRRPUA	2842.7kW/m^2
Fuel	Propane (C_3H_8)
CO yield	0.005
Soot yield	0.024
Fire source area	0.11684m x 0.0762m

2.1. Boundary conditions

- The ceiling, floor and side walls were prescribed as inert boundaries.

- The surrounding environment was not modeled. The ambient temperature was simply prescribed as 28.95°C.
- The wind effects were not considered.
- Two longitudinal beams placed at the center of car park were supported by transversal beams and columns of different sizes.
- The smoke extraction rate was specified at the downstream opening which was positioned below the transversal beam depth.
- The size of fuel source area was 0.11684m x 0.0762m with height of 0.02667 m.

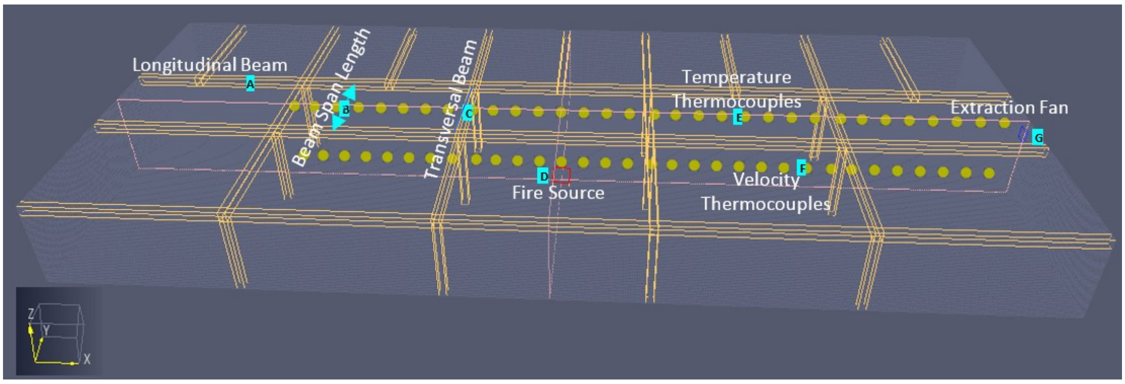

Figure 1. Boundary conditions.

The mass (1) momentum (2) and energy (3) conservation equations can be written as:

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \mathrm{u} = \dot{\mathrm{m}}_{\mathrm{b}}''' \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \mathrm{u}) + \nabla \cdot \rho \mathrm{uu} + \nabla p = \rho g + \mathrm{f_b} + \nabla \cdot \tau_{\mathrm{ij}} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \mathrm{h}) + \nabla \cdot \rho \mathrm{hu} = \frac{\mathrm{Dp}}{\mathrm{Dt}} + \dot{\mathrm{q}}''' - \dot{\mathrm{q}}_{\mathrm{b}}''' - \nabla \cdot \mathrm{q}''' \tag{3}$$

In these equations, ρ is density, t is time, **u** is velocity vector, $\dot{\mathrm{m}}_{\mathrm{b}}'''$ is net heat flux from thermal conduction and radiation, p is pressure, $\boldsymbol{g}$ is gravity vector, $\mathbf{f}_{\mathrm{b}}$ is external force vector, τ_{ij} is viscous stress tensor, $\dot{\mathrm{q}}'''$ is heat release rate per unit volume from a chemical reaction, $\dot{\mathrm{q}}_{\mathrm{b}}'''$ is energy transferred to the evaporating droplets, $\dot{\mathbf{q}}''$ is conductive and radiative heat flux and ε is dissipation rate.

2.2. Statistical Process

The research procedures involved are:

- obtaining the important controllable factors
- performing the Design of Experiment (DOE)
- performing CFD Simulation
- conducting the reliability test of DOE
- performing RSM and analysis of variance (ANOVA)
- Optimization

2.3. Factors Identification

In the current work, the key factors that influence the smoke descends time are ceiling height, beam span length, transversal beam depth, longitudinal beam depth and extraction fan rate. The constraints of these factors were reported in Table 2.

Table 2. Factor and response parameters.

Parameters	Name	Coded Factor	Lower	Upper
Factors	Ceiling Height (m)	X	0.3	0.442
	Beam Span Length (m)	X_1	0.213	0.57
	Transversal Beam Depth (m)	X_2	0.02	0.06
	Extraction Fan Rate (m^3/s)	X_3	0.18	0.31
	Longitudinal Beam Depth	X_4	0.02	0.061
Response	Smoke descend time (s)	Y		

2.4. Design of Experiment and Statistical Analysis

The selected DOE was Central Composite Design (CCD) because it incorporates better design points. Correspondingly, the Face Central Design was employed to obtain the 32 design points. In order to maintain a hierarchical model at each step, terms were added during the process by using the stepwise procedure. The design points and their corresponding results are reported in Table 3.

Table 3. Numerical simulation design and results

Run	Factors					Time
	X	X_1	X_2	X_3	X_4	Y
1	0.442	0.213	0.02	0.31	0.061	25.00
2	0.371	0.3915	0.04	0.245	0.02	15.30
3	0.3	0.57	0.06	0.18	0.061	9.48
4	0.3	0.57	0.06	0.31	0.02	9.27
5	0.3	0.213	0.02	0.31	0.02	10.64
6	0.371	0.3915	0.04	0.245	0.0405	12.36
7	0.371	0.3915	0.04	0.245	0.0405	12.36
8	0.3	0.57	0.02	0.18	0.02	10.52
9	0.442	0.213	0.06	0.18	0.061	22.28
10	0.371	0.3915	0.04	0.18	0.0405	12.16
11	0.371	0.213	0.04	0.245	0.0405	12.08
12	0.371	0.3915	0.04	0.245	0.061	13.40
13	0.442	0.57	0.06	0.18	0.02	25.84
14	0.3	0.3915	0.04	0.245	0.0405	7.48
15	0.371	0.3915	0.04	0.245	0.0405	12.36
16	0.371	0.3915	0.04	0.31	0.0405	13.28
17	0.442	0.213	0.02	0.18	0.02	27.64
18	0.371	0.57	0.04	0.245	0.0405	13.50
19	0.371	0.3915	0.02	0.245	0.0405	12.00
20	0.3	0.213	0.06	0.31	0.061	8.70
21	0.3	0.213	0.02	0.18	0.061	7.25
22	0.371	0.3915	0.04	0.245	0.0405	12.60
23	0.371	0.3915	0.04	0.245	0.0405	12.63
24	0.442	0.213	0.06	0.31	0.02	29.70
25	0.442	0.57	0.06	0.31	0.061	25.14
26	0.3	0.213	0.06	0.18	0.02	6.68
27	0.442	0.57	0.02	0.31	0.02	28.90
28	0.371	0.3915	0.04	0.245	0.0405	12.20
29	0.442	0.57	0.02	0.18	0.061	26.10
30	0.371	0.3915	0.06	0.245	0.0405	13.55
31	0.3	0.57	0.02	0.31	0.061	11.40
32	0.442	0.3915	0.04	0.245	0.0405	24.05

2.5. Froude Scaling

The car park model was scaled down 10 times from the actual model. As shown in Table 4, other parameters such as fire size, time, extraction flow rate, velocity, extraction fan size, fuel mass and fire source tray were scaled in accordance with the Froude scaling correlation [23-25]. However, the ceiling height was set to 3.0m in order to ensure that the flow is turbulent [26].

Table 4. List of scaling correlation for enclosed car park model. [7, 11]

Type of unit	Scaling Model
Geometric position	$X_m = X_f\left(\frac{l_m}{l_f}\right)$
Heat Release Rate, Q (kW)	$Q_m = Q_f\left(\frac{l_m}{l_f}\right)^{5/2}$
Time, t (s)	$t_m = t_f\left(\frac{l_m}{l_f}\right)^{1/2}$
Volume Flow (m^3/s)	$V_m = V_f\left(\frac{l_m}{l_f}\right)^{5/2}$
Velocity, u (m/s)	$u_m = u_f\left(\frac{l_m}{l_f}\right)^{1/2}$
Temperature (K)	$T_m = T_f$

3. Results and Discussion

3.1. Mesh Independence Test and Geometry Validation

The results of mesh independence test are presented in this Section. Three models employing different grid sizes such as 3.57 cm, 1.47 cm, and 0.94 cm were simulated. As reported in Table 5, the simulated maximum heat release rate is coming closer to the experimental value as the grid is refined. As observed, the error was reduced from 19% (coarse grid) to merely 4.33% (fine grid). The time histories of temperature are shown in Figure 2, showing the effectiveness of using fine grid in this model. Therefore, fine grid was employed in the subsequent simulations.

Table 5. Relative error.

Mesh	Mesh size (cm)	Number of cells	Time step	Total Time (hour)	Maximum temperature		Relative error
					Experiment	FDS	
Coarse	3.57	32,928	51766	4.4		166.33	19.01%
Moderate	1.47	471,648	166,467	107.85	205.38	189.95	7.51%
Fine	0.94	1,797,760	275,700	403.7		196.48	4.33%

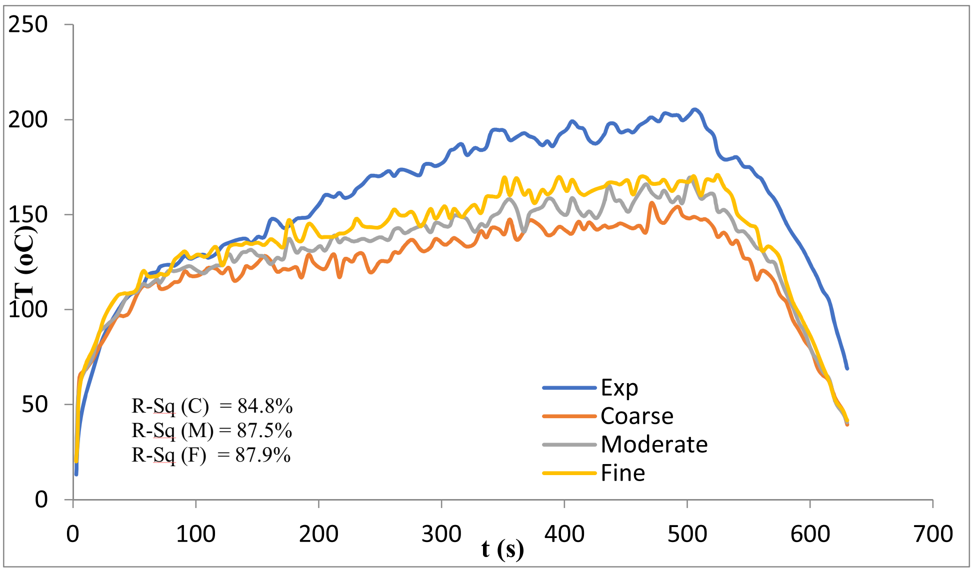

Figure 2. Temperatures at thermocouple tree A with 0.01 below the ceiling.

Apart from conducting the mesh independence test, geometric validation of the FDS model was also performed by comparing the results of an enclosed car park and a corridor-like structure as experimented by [27]. From Figure 3, it seems that HRRs of car park and corridor-like structure are comparable.

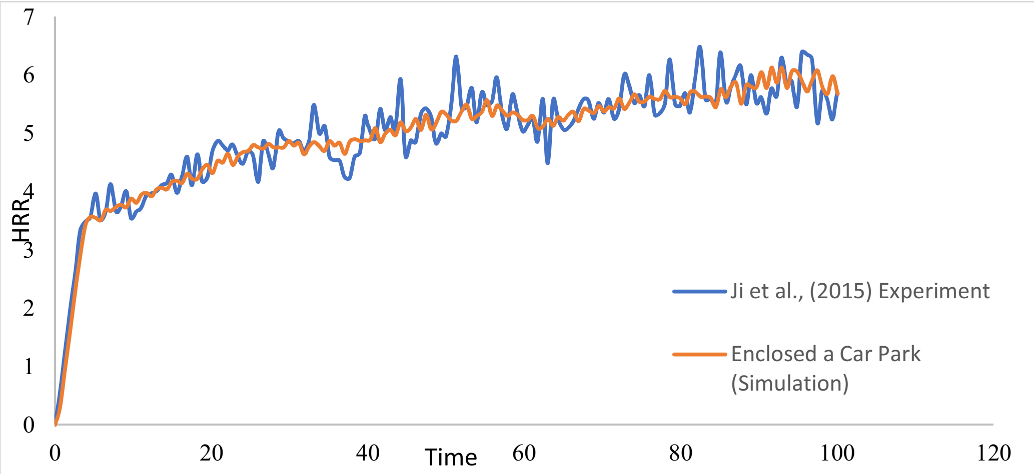

Figure 3. Validation between experiment and CFD simulation.

3.2. Reliability of Design of Experiment

The reliability test of the DOE model was performed using the replication procedure which involves six models. As shown in Table 6, the results are ranging from 0.48% to 1.77%, indicating that the experimental design for this model is reliable.

Table 6. Replication of an enclosed car park model.

Factors					Response	
Ceiling Height	Beam Span Length	Transversal Beam Depth	Extraction Rate	Longitudinal Beam Depth	Smoke Descend Time	Error
0.371	0.3915	0.04	0.245	0.0405	12.36	0.48
0.371	0.3915	0.04	0.245	0.0405	12.36	0.48
0.371	0.3915	0.04	0.245	0.0405	12.36	0.48
0.371	0.3915	0.04	0.245	0.0405	12.60	1.45
0.371	0.3915	0.04	0.245	0.0405	12.63	1.69
0.371	0.3915	0.04	0.245	0.0405	12.2	1.77

3.3. Polynomial Regression Model

Based on the CCD model, a full quadratic equation can be written as:

$$y = 1.1117 - 0.27X + 0.2892X_1 - 1.372X_2 + 0.558X_3 - 3.300X_4 + 2.26X^2 + 41.74X4^2 - 0.477XX_1 + 2.108XX_2 - 0.693\,XX_3 - 2.980XX_4 - 0.475X_1X_3 + 1.093X_1X_4 + 8.72X_2X_4 \quad (4)$$

From the statistical analysis, the result was linear with predicted R^2 of 97.64%, which was within the actual R^2 of 99.45%. Therefore, good agreement can be seen between actual and predicted values. Based on the P-value obtained from ANOVA, the degree of importance for main, interaction and quadratic factors can be determined (i.e. highly significant if $P < 0.001$; significant if $0.001 < P < 0.05$; insignificant if $P > 0.05$). As shown in Table 7, the P-value is less than 0.001 (with F-value 221.57), indicating that the model is highly significant and reliable. The coded coefficients for linear, interaction and quadratic variables are shown in Table 8. As seen, most variables are either highly significant or significant.

Table 7. Analysis of variance for response surface quadratic model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	0.099424	0.007102	221.57	0.000
Linear	5	0.091557	0.018311	571.30	0.000
Height	1	0.088743	0.088743	2768.71	0.000
Span	1	0.000934	0.000934	29.15	0.000
Tranv	1	0.000404	0.000404	12.59	0.002
Extrac	1	0.001013	0.001013	31.62	0.000
Longi	1	0.000463	0.000463	14.44	0.001
Square	2	0.005729	0.002864	89.37	0.000
Height*Height	1	0.000440	0.000440	13.72	0.002
Longi*Longi	1	0.001075	0.001075	33.53	0.000
2-Way Interaction	7	0.002138	0.000305	9.53	0.000
Height*Span	1	0.000584	0.000584	18.21	0.001
Height*Tranv	1	0.000143	0.000143	4.47	0.050
Height*Extrac	1	0.000164	0.000164	5.11	0.037
Height*Longi	1	0.000301	0.000301	9.39	0.007
Span*Extrac	1	0.000485	0.000485	15.14	0.001
Span*Longi	1	0.000256	0.000256	7.99	0.012
Tranv*Longi	1	0.000204	0.000204	6.38	0.022
Error	17	0.000545	0.000032		
Lack-of-Fit	12	0.000530	0.000044	15.21	0.004
Pure Error	5	0.000015	0.000003		
Total	31	0.099969			

Table 8. Coded Coefficients for Transformed Response.

Coded Factor	Effect	Coef	SE Coef	T-Value	P-Value	Degree of Importance
X	0.14043	0.07022	0.00133	52.62	0.000	High Significant
X_1	0.01441	0.00720	0.00133	5.40	0.000	High Significant
X_2	-0.00947	-0.00474	0.00133	-3.55	0.002	High Significant
X_3	0.01501	0.00750	0.00133	5.62	0.000	High Significant
X_4	-0.01014	-0.00507	0.00133	-3.80	0.001	High Significant
X^2	0.02245	0.01122	0.00303	3.70	0.002	High Significant
X_4^2	0.03509	0.01754	0.00303	5.79	0.000	High Significant
XX_1	-0.01208	-0.00604	0.00142	-4.27	0.001	High Significant
XX_2	0.00599	0.00299	0.00142	2.11	0.050	Significant
XX_3	-0.00640	-0.00320	0.00142	-2.26	0.037	Significant
XX_4	-0.00867	-0.00434	0.00142	-3.06	0.007	High Significant
X_1X_3	-0.01101	-0.00551	0.00142	-3.89	0.001	High Significant
X_1X_4	0.00800	0.00400	0.00142	2.83	0.012	High Significant
X_2X_4	0.00715	0.00357	0.00142	2.53	0.022	High Significant

From the P-values shown in Table 8, Equation 4 should be used to relate the smoke descend time and the design parameters. Figure 4 compares the CFD results and those predicted by using Equation 4. The agreement is promising.

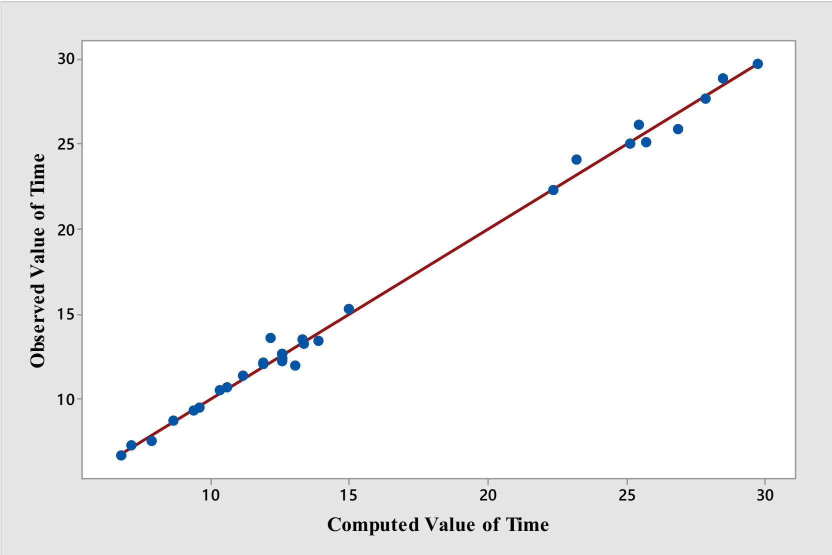

Figure 4. Scatterplot for time of smoke descending.

3.4 Optimization

The most critical things during a fire are evacuation process. The longer time for the smoke to descend, an occupant in the building can evacuate safely. To optimize, the possible factors from the literature review [2, 4-5, 7, 10, 13-14, 28-29] have been picked up and arranged as max-min parameters in Table 9. The objective function of the study is to maximize the smoke residing time at upper level for beam span that ranges between 0.4m and 0.57m. To get an ideal space, this range is applied in accordance to the preservation of Reynolds number to support the turbulent flow rule [26] With these input data, the statistical analysis has proposed an optimal design. The optimal design then simulated via FDS using the same value proposed by statistical analysis.

Table 9. Comparison between actual and optimal design.

Factors	Actual Design	Max – Min Parameters		Optimal Design	
		Lower	Upper	Statistical	FDS
Ceiling Height (m)	0.3	0.3	0.442	0.442	0.442
Beam Span (m)	0.57	0.213	0.57	0.4	0.4
Transvers (m)	0.04	0.02	0.06	0.02	0.02
Extraction (m^3/s)	0.18	0.18	0.31	0.31	0.31
Longitudinal (m)	0.04	0.02	0.061	0.02	0.02
Respond					
Smoke Descend Time (s)	9.75			30.12	31.00
Error (%)				2.93	
Improvement (%)				217.95	

Table 9 shows the design parameters of two geometrical car park designs (before and after optimization). In the optimized design, the smoke will remain longer at the upper level, which is favorable. The time predicted by Equation (4) agrees considerably well with the simulation result. It is interesting to note that the percentage of improvement is 217.95% (Figure 5). The contribution of the study is the time measured in this analysis is adequate within the beam span only. Interestingly, it effects to the overall geometry with having a lengthier time of smoke to descend as illustrated in Figure 6.

According to the parameters between actual design and optimal design as shown in Table 9, by increasing the ceiling height and extraction rate, the smoke descend time is increased. However, the effects of beam depth and beam span length on smoke descend time are not significant. It can be seen on the effect both beam depth and beam span length seems to be similar between an actual and optimal design.

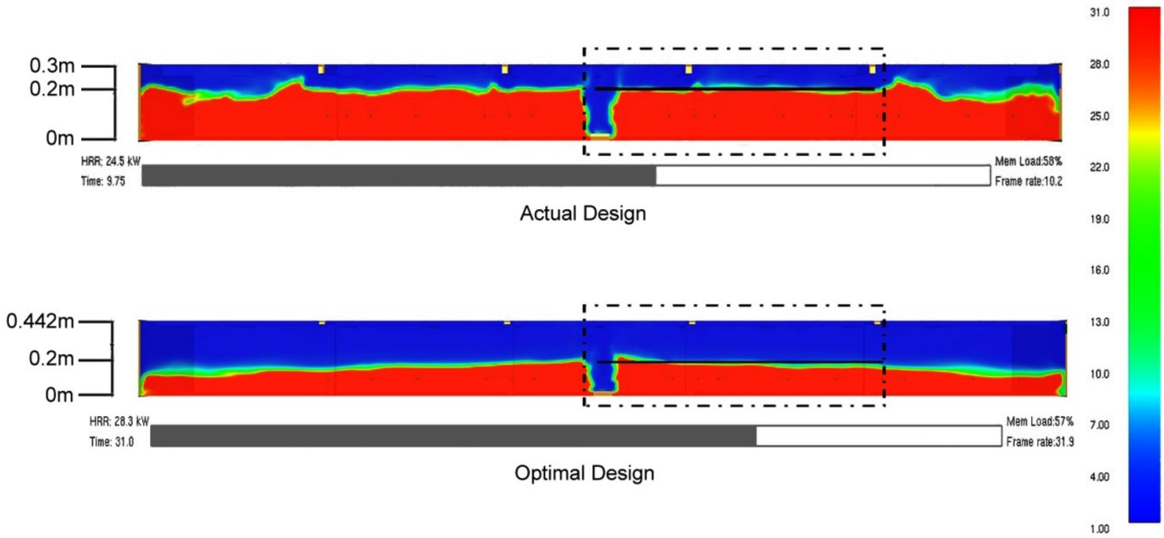

Figure 5. The different of smoke layer between actual and optimal design for enclosed car park.

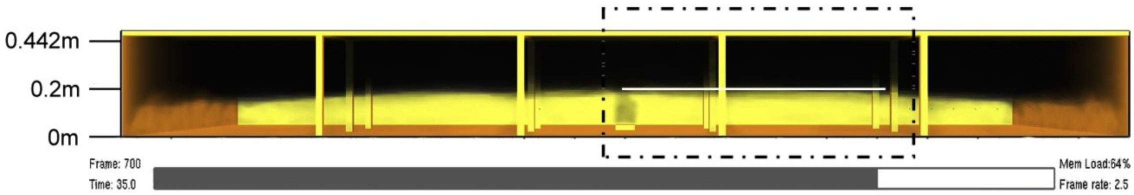

Figure 6. Overall smoke layer for optimal design of enclosed car park.

4. Conclusions

In this research, the effects of significant factors such as ceiling height, beam span length, transversal and longitudinal beam depths as well as extraction rate on the smoke descend time have been analysed by using Response Surface Methodology (RSM). The commercial software, i.e. Fire Dynamic Simulator (FDS) has been used for flow analysis. From the reliability test, it seems that RSM is able to generate a reliable model. The polynomial equation should be used to relate the smoke descend time with the design factors. In addition, these five significant factors have been optimized in order to maximize the smoke descend time, which yields 217.95% improvement as compared to the previous design. According to optimization model, the effects of beam depth and beam span length on smoke descend time are not significant but increasing the ceiling height and extraction rate was proved to be significant to the increment of smoke descend time. Therefore, engineers should focus on these five significant factors in the design stage. The research of treating temperature and smoke back layering distance as other response variables is currently underway.

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