A Response Surface Methodology for Mitigating Hot Gasses in Enclosed Car Park

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Abstract A hot gas rise towards ceiling due to fire buoyancy will cause severe damage to the building structure. The temperature rises need to be controlled as among the elements of compliance in performance-based design. The channel flow between beams has used in this study to mitigate hot gases out of the enclosure by mean of response surface methodology. Fire Dynamic Simulator was employed as a simulation tool while the result was statistically examined using analysis of variance via Minitab application. It was found that the result was linear with predicted R² (93.25%) and within the permissible R² (98.13%). The ceiling height has been identified not affect in controlling hot gases while four control parameters which are beam spacing, transversal beam, extraction rate and longitudinal beam with p-values of 0.00, 0.000, 0.023 and 0.000 respectively, have been found to have the significant effect on the smoke temperature control. This study contributes a good input to the fire safety community in providing the initial design of enclosed car park with better condition.

1 Introduction

The temperatures rise need to be controlled as among the elements of compliance in performance-based design as well as in perceptive code. A hot gas rise towards ceiling due to fire buoyancy will reduce oxygen concentration eventually create harmful to an occupants [1] and cause severe damage to the building structure such as enclosed car park [2], subway station [3] corridor-like structures [4], tunnel-like corridor [5] and underground shelter [6] as well as others buildings.

The fire temperatures measurement is essential to predict ignition of the object, the onset of flashover and structure damage [7]. Apart of that, it is also beneficial for predict smoke layer descent towards the floor [8] and arranges for a smoke detection [9–11] as well as sprinkler activation [12]. Following that, previous researchers had developed various ratio from experimental and numerical simulation such as beam depth to the ceiling height [13–15], radial distance to the ceiling height [16], beam spacing to ceiling clearance [15]. Most of it is to investigate the effect of the ceiling beam against flow visualization, temperature and velocity profile. In addition, it also can identify subcritical flow or density jump before and after ceiling jet intersect the ceiling beam.

However, according to the literature [11–15], most studies were conducted by means of trial and error based. These arrangements have not yet statistically proofed and which parameters show the significant effect of the temperature. In addition, the parameters that were investigated such as heat...
release rate (HRR) and the wind were categorized as non-control factors. Indeed, a few research papers related to the hot smoke control with the presence of the beam has been reported by [13–15,19,22–27] but still lacking regarding cost operational reducing (i.e in term of horizontal ventilation numbers and volume flow rate). Therefore, this study aims to channel the hot gasses by means statistical analysis based on established control parameters and resulting in the optimum operational cost of the ventilation fan.

2 Method
The research procedures were designed in the following steps [29]:
(a) identify the significant controllable factors
(b) performing the Design of Experiment (DOE)
(c) performing Computational Fluid Dynamics (CFD) simulation
(d) conducting the reliability test of DOE
(e) performing statistical analysis

2.1 Controllable Factors
The key factors that influence the temperature was identified which are ceiling height, beam span length, transversal beam depth, longitudinal beam depth and extraction fan rate [13–16]. The range of these factors is reported in Table 1. According to a general rule of Reynolds number, the ceiling height range from the literature review was changed to 0.3m due to the smallest height that supports turbulent flow is 0.3m [30,31]. The other amendment made within this range is beam span length; 0.556m to 0.57m in accordance to actual geometry size in Simulator Building at Fire and Rescue Malaysia Academy.

| Parameters       | Name                        | Coded Factor | Lower  | Upper   |
|------------------|-----------------------------|--------------|--------|---------|
| Factors          | Ceiling Height,             | X            | 0.3m   | 0.442m  |
|                  | Beam Span Length,           | $X_1$        | 0.213m | 0.57m   |
|                  | Transversal Beam Depth,     | $X_2$        | 0.02m  | 0.06m   |
|                  | Extraction Fan Rate         | $X_3$        | 0.18m$^3$/s | 0.31m$^3$/s |
|                  | Longitudinal Beam Depth     | $X_4$        | 0.02m  | 0.061m  |
| Response         | Temperature                 | Y            |        |         |

2.2 Design of Experiment
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 2.
2.3 CFD Simulation
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. Table 3 shows the numerical settings of the simulation.

Table 2. Numerical simulation design and results

| Run | Factors | Temperature |
|-----|---------|-------------|
| 1   | 0.442   | 0.213       | 0.31 | 0.061 | 315.97       |
| 2   | 0.371   | 0.3915      | 0.04 | 0.245 | 0.02 | 185.51       |
| 3   | 0.3     | 0.57        | 0.06 | 0.18  | 0.061| 163.45       |
| 4   | 0.3     | 0.57        | 0.06 | 0.31  | 0.02 | 115.67       |
| 5   | 0.3     | 0.213       | 0.02 | 0.31  | 0.02 | 253.63       |
| 6   | 0.371   | 0.3915      | 0.04 | 0.245 | 0.0405| 215.69       |
| 7   | 0.371   | 0.3915      | 0.04 | 0.245 | 0.0405| 203.70       |
| 8   | 0.3     | 0.57        | 0.02 | 0.18  | 0.02 | 181.76       |
| 9   | 0.442   | 0.213       | 0.06 | 0.18  | 0.061| 216.17       |
| 10  | 0.371   | 0.3915      | 0.04 | 0.18  | 0.0405| 212.89       |
| 11  | 0.371   | 0.213       | 0.04 | 0.245 | 0.0405| 231.64       |
| 12  | 0.371   | 0.3915      | 0.04 | 0.245 | 0.061| 225.11       |
| 13  | 0.442   | 0.57        | 0.06 | 0.18  | 0.02 | 162.44       |
| 14  | 0.3     | 0.3915      | 0.04 | 0.245 | 0.0405| 215.46       |
| 15  | 0.371   | 0.3915      | 0.04 | 0.245 | 0.0405| 215.61       |
| 16  | 0.371   | 0.3915      | 0.04 | 0.31  | 0.0405| 201.17       |
| 17  | 0.442   | 0.213       | 0.02 | 0.18  | 0.02 | 223.52       |
| 18  | 0.371   | 0.57        | 0.04 | 0.245 | 0.0405| 179.82       |
| 19  | 0.371   | 0.3915      | 0.02 | 0.245 | 0.0405| 262.6        |
| 20  | 0.3     | 0.213       | 0.06 | 0.31  | 0.061| 265.12       |
| 21  | 0.3     | 0.213       | 0.02 | 0.18  | 0.061| 398.07       |
| 22  | 0.371   | 0.3915      | 0.04 | 0.245 | 0.0405| 197.79       |
| 23  | 0.371   | 0.3915      | 0.04 | 0.245 | 0.0405| 211.11       |
| 24  | 0.442   | 0.213       | 0.06 | 0.31  | 0.02 | 181.86       |
| 25  | 0.442   | 0.57        | 0.06 | 0.31  | 0.061| 185.51       |
| 26  | 0.3     | 0.213       | 0.06 | 0.18  | 0.02 | 125.71       |
| 27  | 0.442   | 0.57        | 0.02 | 0.31  | 0.02 | 206.29       |
| 28  | 0.371   | 0.3915      | 0.04 | 0.245 | 0.0405| 205.38       |
| 29  | 0.442   | 0.57        | 0.02 | 0.18  | 0.061| 223.92       |
| 30  | 0.371   | 0.3915      | 0.06 | 0.245 | 0.0405| 193.45       |
| 31  | 0.3     | 0.57        | 0.02 | 0.31  | 0.061| 278.27       |
| 32  | 0.442   | 0.3915      | 0.04 | 0.245 | 0.0405| 209.38       |
| Parameter                      | Description of Car Park                  |
|-------------------------------|-----------------------------------------|
| Geometry dimension           | 4m x 1.6m x 0.3m                         |
| Mesh size                    | 0.0094m                                 |
| HRRPUA                       | 2842.7kW/m²                             |
| Fuel                         | Propane (C₃H₈)                           |
| CO yield                     | 0.005                                   |
| Soot yield                   | 0.024                                   |
| Fire source area             | 0.11684m x 0.0762m                      |

2.3.1 Boundary conditions
- The ceiling, floor and side walls were prescribed as inert boundaries.
- The surrounding environment was not modelled. The ambient temperature was simply prescribed as 30°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.

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

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = \dot{m}'''
\]

\[
\frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) + \nabla p = \rho \mathbf{g} + \mathbf{f}_b + \nabla \cdot \mathbf{\tau}_{ij}
\]

\[
\frac{\partial}{\partial t} (\rho h) + \nabla \cdot (\rho h \mathbf{u}) = \frac{Dp}{Dt} + q''' - q''_b - \nabla \cdot q'''
\]

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

2.4 Reliability of DOE
The reliability of the DOE model was performed using the replication procedure which requires six models. As shown in Table 4, the results are ranging from 0.52% to 4.44%, indicating that the model is reliable.
Table 4. Replication of an enclosed car park model

| Factors                              | Response          | Error |
|--------------------------------------|-------------------|-------|
| Ceiling Height                       | 0.371             |       |
| Beam Span Length                     | 0.3915            | 0.3915|
| Transversal Beam Depth               | 0.04              | 0.04  |
| Extraction Rate                      | 0.245             | 0.245 |
| Longitudinal Beam Depth              | 0.0405            | 0.0405|
| Temperature                          | 205.11            | 203.7 |
| Error                                | 0.65              | 1.33  |
|                                      | 205.38            | 4.19  |
|                                      | 197.79            | 4.44  |
|                                      | 211.11            | 2.26  |
|                                      | 215.61            | 4.26  |
|                                      | 203.7             | 0.52  |

2.5 Statistical Analysis

The form of mathematical model is as follows:

\[ y = \alpha_0 + \sum_{i=1}^{3} \alpha_i x_i + \sum_{i=1}^{3} \alpha_{ii} x_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \alpha_{ij} x_i x_j \]  

(4)

Where \( y \) is the predicted response (hot gases temperature); \( x_i \) and \( x_j \) are the uncoded independent variables and \( \alpha_0, \alpha_i, \alpha_{ii} \) and \( \alpha_{ij} \) are intercept, linear, quadratic and interaction constant coefficient respectively. Minitab was used for regression analysis and analysis of variance (ANOVA).

3 Results

3.1 Mesh independence Test and Geometry Validation

This model has been verified using a grid independence test and validated using a relative error percentage [32]. The grid independence study showed the finer mesh count was sufficient to conduct a further simulation. Moreover, the finest mesh was resulting in the lowest error with only 4.33%. The readers are referred to [33] for a complete description of the numerical experiment. Besides, a geometric validation also was performed between an enclosed car park and corridor-like structures experimented by Ji et al., (2015). According to Figure 1, it shows a similar pattern and indicating the enclosed car park design is good agreement with corridor-like structures simulation.
3.2 Regression model

The relationship between temperature and five controllable factors (namely ceiling height $X_1$, beam span length $X_2$, transversal beam depth $X_3$, longitudinal beam depth $X_4$ and extraction rate $X_5$) was studied. The simulation result based on CCD model has developed a full quadratic equation as follows:

$$y = 360.9 - 265X - 365.0X_1 - 8401X_2 + 81.7X_3 + 8032X_4 + 31285X_2^2 + 710XX_1$$

$$+ 9598XX_2 - 11194XX_4 + 2436X_1X_2 - 3584X_1X_4 - 16229X_2X_4$$

(5)

Based on statistical analysis, the result was linear with predicted $R^2$ (93.25%) and within the permissible $R^2$ (98.13%). It was found that the result was linear and good agreement can be seen between actual and predicted values.

3.3 ANOVA

Table 5 shows the linear, interaction and quadratic variables for the coded coefficient. In ANOVA analysis, the terms that found statistically significant only will be included in the model. Each variable with P-value less than 0.01 is considered highly significant, and between 0.01 and 0.05 is significant. The variable with P-value more than 0.05 is considered non-significant [34]. In the present work, it is observed that most of the variables have a highly significant on the linear effect, interaction and second order form. Only the ceiling height term in the linear effect was not significant. This illustrates the importance of employing the significant variables in design lower temperature in the enclosed car park.

![Figure 1. HRR for corridor-like structures fire and car park](image-url)
The influence hot gasses temperature is investigated with identified factors such as ceiling height, beam span length, transversal and longitudinal beam depth, as well as extraction rate. For that purposes, the Response Surface Methodology (RSM) and Fire Dynamic Simulator (FDS) were used as a tool. The reliability result showed RSM can be used to investigate the controllable probability factors that influenced the response. In accordance to that, four factors have confirmed effect temperature in an enclosed car park. With only important parameters were included in this study, it is considered novelty in yielding lower temperature for the overall of car park geometry. The engineers afterwards could only have considered the high significant factors mentioned above in their design as compared to others factors studied in the previous study.

4 Conclusion

In this research, the influence hot gasses temperature is investigated with identified factors such as ceiling height, beam span length, transversal and longitudinal beam depth, as well as extraction rate. For that purposes, the Response Surface Methodology (RSM) and Fire Dynamic Simulator (FDS) were used as a tool. The reliability result showed RSM can be used to investigate the controllable probability factors that influenced the response. In accordance to that, four factors have confirmed effect temperature in an enclosed car park. With only important parameters were included in this study, it is considered novelty in yielding lower temperature for the overall of car park geometry. The engineers afterwards could only have considered the high significant factors mentioned above in their design as compared to others factors studied in the previous study.

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Finally, based on P-value discussed above and significant effect, only the ceiling height term in the linear effect was not significant and should be removed. Thus, the model can be summarized as the following equation:

\[ y = 360.9 - 365.0X_1 - 8401X_2 + 81.7X_3 + 8032X_4 + 31285X_2^2 + 710XX_1 + 9598XX_2 - 11194XX_4 + 2436X_1X_2 - 3584X_1X_4 - 16229X_2X_4 \]

### Table 5. Coded Coefficients for Transformed Response

| Coded Factor | Effect | Coef | SE Coef | T-Value | P-Value | Degree of Importance |
|--------------|--------|------|---------|---------|---------|----------------------|
| X            | -8.01  | -4.00| 2.15    | -1.87   | 0.078   | Non- significant      |
| X_1          | -57.17 | -28.59| 2.15    | -13.32  | 0.000   | High significant     |
| X_2          | -81.63 | -40.81| 2.15    | -19.01  | 0.000   | High significant     |
| X_3          | 10.62  | 5.31 | 2.15    | 4.97    | 0.000   | High significant     |
| X_4          | 70.58  | 35.29| 2.15    | 16.44   | 0.000   | High significant     |
| X_2^2        | 25.03  | 12.51| 3.25    | 7.86    | 0.001   | Significant          |
| XX_1         | 18.00  | 9.00 | 2.28    | 8.00    | 0.000   | High significant     |
| XX_2         | 27.26  | 13.63| 2.28    | 12.51   | 0.000   | High significant     |
| XX_4         | 32.58  | -16.29| 2.28  | -7.16   | 0.000   | High significant     |
| X_1X_2       | 17.40  | 8.70 | 2.28    | 3.82    | 0.001   | High significant     |
| X_1X_4       | -28.20 | -14.10| 2.28   | -6.19   | 0.000   | High significant     |
| X_2X_4       | -13.31 | -6.65| 2.28    | -2.92   | 0.009   | High significant     |
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