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MONITORING AND SIMULATION OF MECHANICALLY VENTILATED UNDERGROUND CAR PARKS

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ABSTRACT

Rapid motorization in developed and developing countries demands more parking spaces in urban areas. Underground car parking space in multi story buildings offers viable solution. However, lack of natural ventilation accumulates the harmful emissions from cars, operating in underground car parks. Exposure to these hazardous pollutants causes health risk to the users. Therefore, proper mechanical ventilation system should be adopted for the removal of harmful pollutants. This paper discusses the usage of modeling and simulation tools in the design of the mechanical ventilation system. Two widely used modeling techniques, multi-zone modeling and CFD modeling were used to simulate the contaminant distribution in a mechanical ventilated environment. The former provides an approximate macroscopic solution of the carbon monoxide (CO) distribution, while the later provides precise distribution of CO contours. The two models were validated against field measurements made at Chennai, India. The model predictions were very close to the actual site measurements. The impact of garage height and CO generation rate on ventilation requirement has been analysed.

PRACTICAL IMPLICATION

In Indian construction industry, there is no standard design procedure available for the ventilation design of basement car park. The awareness on modeling techniques for simulation of vehicular emission behavior is minimal. The key objective of this paper is to present a brief portrait of modeling techniques, which will help the engineers in construction field to use modeling techniques to its potential. This paper will also help the planning engineers to develop and improve their modeling skills.

1. INTRODUCTION

Last few decades had witnessed rapid growth of the automobile population. This had created a huge demand for the parking space. Underground car parks were able to cater this demand and it has many unique advantages over the conventional parking, which includes space economy, aesthetics and safety. Because of poor natural ventilation and harmful emissions from operating cars, proper mechanical ventilation system is required. The mechanical ventilation system must be optimized during design, because over sizing of ventilation system will lead to high initial and operating cost, while under sizing will result in poor indoor air quality, which will have adverse effect on the inhabitance (Mohammed et al., 2014). Therefore, modeling tools can be employed in optimization of the ventilation system.

In recent years, many researchers had performed experimental (Li and Xiang, 2013; Chow et al., 1996) and numerical (Xue and Ho, 2000; Papakonstantinou et al., 2003) studies of underground car parks. These studies range widely, covering gaseous and particulate pollutants, energy consumption of the ventilation system, and impulse ventilation (Lu et al., 2011). Li and Xiang (2013) monitored PM_{10} and $PM_{2.5}$ concentrations at entry and exit of an underground car park, and analyzed the composition using the atomic absorption spectrometer. Mohammed et al. (2014) monitored SO_2 and NO_2 concentration in a multistory underground car park and found them to breach the Malaysian ambient air quality guidelines. Areselene et al. (2000) discussed about field studies on seven underground car parks at various locations in USA and provided the basic framework for carrying out a field study. Ho et al. (2004) presented the results of a field study that investigated the traffic patterns and carbon monoxide (CO) level in an underground car park. This study provided quantitative information needed for modeling. Duci et al. (2004) presented the mathematical formulation and application of a model, utilized in a general purpose CFD commercial code. The study was concerned with the CO dispersion, and suggested that, increasing outdoor airflow rate decreases the indoor air quality problems. Krarti and Areselene (2003) presented a study which simulated the CO concentration levels in an underground car park. The Reynolds averaged Navier Stokes (RANS) turbulence model was used. Emission rate was calculated as a function of number of cars in operation within the garage, average operating time of cars in garage and CO emission rate for a typical car.

This paper has focused on two of the modeling techniques namely multi-zone air flow network model and computation fluid dynamics (CFD) model. Commercial software packages were used to evaluate the performance of these modeling techniques. The performance evaluation was done by modeling a real world car park. The site taken for present work is a basement car park of a hospital building located in Chennai, India. The CO concentration was simulated using the models and the results were compared with the actual site measurement. Even though operating car emits number of harmful gases (Moncef and Areselene, 1999, Rakesh, 2009), only CO is considered in this study, because CO emission is of higher degree when the car is operating at lower speed, and control of CO will control all other contaminants effectively (Chan et al., 1997).

2. METHODOLOGY

This section gives a brief description about the site, the general testing procedure that was followed while carrying out field measurements, and the methodology used for modeling and simulation of air flow patterns and CO concentration levels. A brief description of the software packages used for modeling is also included in this section.

2.1 DESCRIPTION OF SITE

The site selected for carrying out field measurements is a hospital building in Chennai, India. It is a three level basement car park with floor area of 814 m^2 per floor and capacity of 30 cars per floor. The garage height of all the three basements was 3 m. The first basement was naturally ventilated, while the second and third basements were mechanically ventilated. Each of the mechanically ventilated floors has a constant volume supply with an exhaust fan capacity of 6.22 m^3/s. Fresh air was supplied by supply fans. The space was designed for 9 air changes per hour (HSE, 1994).

2.2 INDOOR AIR QUALITY MONITORING:

Controlling the quality of indoor air is essential to ensure healthy environment of the occupants. Elimination of all the airborne contaminants is unachievable; however the contaminants can be controlled within the prescribed exposure limit. One of the key elements in this study is to carry out field measurements. A general outline for performing the field monitoring is provided below:

i. *Walk - Through Survey*: In this survey, information about the physical layout of the facility and characteristics of the heating, ventilation and air-conditioning (HVAC) system design are collected. This is done through consultation with the service manger.

ii. *Vehicle usage pattern*: The numbers of vehicles entering and exiting the facility are collected on the day, when testing is to be performed. In addition, the type of vehicles, the time of motor operation, and the typical paths are obtained through discussion with the security officer of the facility and through direct observations.

iii. *Contaminant measurements*: The contaminant (CO) levels at eight locations (Fig.1) of the facility are measured at a height of 1.5 m (breathing level). The locations were chosen so as to depict the entire car park. GasProbe IAQ from BW technologies is used to monitor the contaminant level (www.cihequipment.com). The instrument uses electrochemical technique to measures CO in the range of 0-250 ppm with sensitivity of 1 ppm.

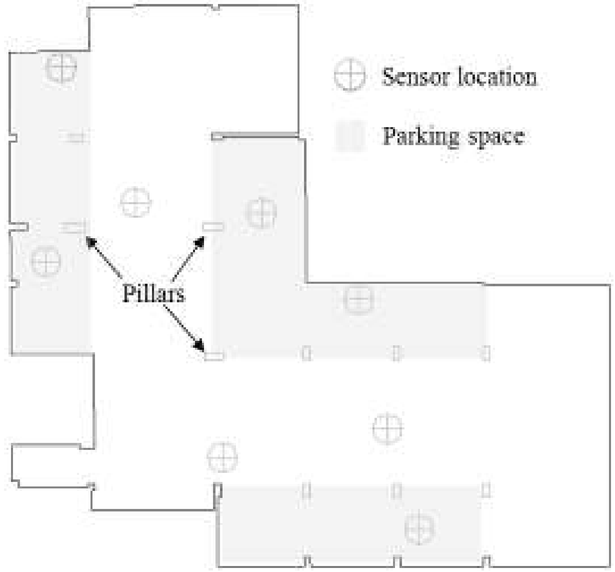

FIG.1 PLAN OF CAR PARKING WITH LOCATIONS OF SENSORS AND PARKING SPACE

2.3. SIMULATION:

This section gives a brief description of modeling tools, and the methodology used for modeling and simulation. The models were developed using CONTAM, a commercial multi-zone modeling software (Walton and Dols, 2008) and Fluent 6.3 a commercial CFD code, which utilise the random average k-ε model (Fluent, 2006).

2.3.1 MULTIZONE AIR FLOW MODEL:

Multi-zone air flow and contaminant dispersion model assumes perfect mixing within each zone. Each zone can represent an individual room or an entire level depending on the goal of modeling. CONTAM was used to simulate the CO concentration dispersion. CONTAM had been used in applications of smoke management, indoor air quality performance of building, ventilation design, etc.

Steps involved in multi-zone air flow modeling

Modeling and simulation using CONTAM involves the following five steps. The first step is building idealization. In this step, the building to be analyzed is represented as a set of zones. Depending on the problem of interest and building layout, the building can be idealized in various ways. Next step is sketch pad representation. In this, a sketch pad diagram of the idealized building is prepared. This diagram is translated by the software to a set of equations, which will be used for simulation (Axley, 1988). The third step is data entry. This involves input of numerical value of parameters associated with each building element. These values can be obtained from product literature, building-specific data and engineering handbook. The fourth step is simulation. In simulation, CONTAM solves the set of equations obtained from sketch pad representation, to generate the contaminant concentration. Depending on the nature of problem, the types of analysis can be chosen. The final step is recording the result and review of it. The software provides viewing of the various results and exporting of results to other data analysis program.

Model Assumptions

i. Each zone is treated as a single node with well-mixed conditions i.e. temperature, pressure, and contaminant concentrations are same at all point of a zone.

ii. The contaminant is assumed to be trace i.e. the contaminant concentration is low such that the concentration does not affect the density of air.

iii. Heat transfer is not accounted and temperature of the zone remains constant.

The above assumption did not have a dramatic influence on the problem under investigation.

2.3.2 CFD MODELLING:

CFD divides the solution domain into thousands or millions of nodes. The problem variables are stored at these nodes after computation using the numerical technique. The stored nodal values provide a 3D representation of fluid flow domain. CFD helps engineers to study various design options, to reduce the need for physical model studies and to reduce risk of major modifications in later stages of the design. FLUENT, which uses finite volume method, was used to simulate the air flow and contaminant dispersion contours of the problem in hand.

Steps involved in CFD modeling

The car park was created using AutoCAD and imported to Gambit for meshing. The volume was meshed using Hex-sub map resulting in regular structured mesh of 90,568 cells (Fig.2). The model was imported to FLUENT, and the setting and boundary conditions were specified. The eight supply inlets were specified as mass flow inlets. The entry and exit ramps were defined as pressure boundaries. The walls were specified as no-slip boundary. The driving lane was modeled as a volume with a height of (0.2 - 1.2) m from the ground and the CO source was assigned to this volume (Xue and Ho, 2000). A moving CO source was not considered in this model as the path of individual vehicle had not been recorded during field measurements, rather number of vehicle entering and leaving the parking space was only recorded. The driving lane was meshed finer as compared to other location, due to higher CO concentration gradient at this location. The appropriate physical model was chosen. The material properties were defined using material database. Grid independence study was done with 45284, 90568 and 213210 cells, and the CO concentration difference between the last two was found to be insignificant. The temperature of car park was set to be constant at 32°C with zero heat transfer in all boundaries.

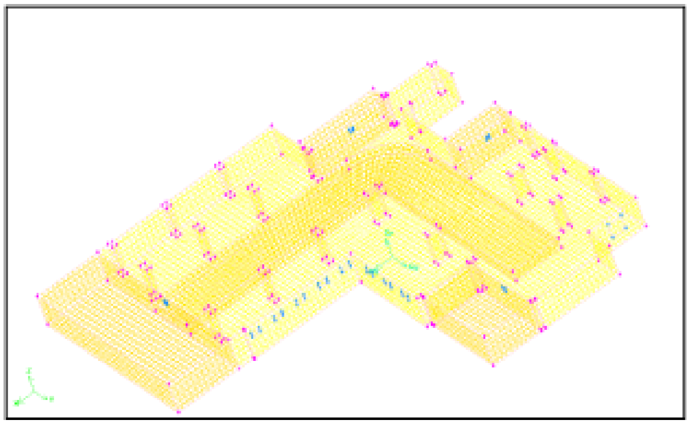

FIG.2: VOLUME MESHED USING HEX- SUB MAP (SIZE = 0.5)

A pressure based solver was selected. The implicit solution approach was followed. The SIMPLE algorithm for pressure velocity coupling was taken. Realizable k-ε model was used to close the set of equations. For numerical stability under-relaxation factors were used. Convergence criteria were set to be 10^{-3}. Species transport was enabled and CO was considered to be trace contaminant. Second order upwind scheme had been used for convective terms. The mass flow rate of supply inlet was specified as 7.48475 kg/s with turbulence intensity of 10 %. The pressure jump of exhaust fan used at experimental site was specified by the manufacturer and was given as:

$$P = -0.013V + 5.448 \qquad (1)$$

where, V - Local fluid velocity normal to the fan.

After the settings, the simulations were made to run with a time step of 600 seconds for 50 times steps. Surface monitors were placed at eight points on a plane z = 1.5 m to represent the eight sensor locations of the filed study. CO concentration at these points was monitored at the end of each time step. From the data obtained for field campaign, each half hour average CO concentration levels for eight points were taken for validation.

3. RESULTS AND DISCUSSION:

3.1 INDOOR AIR QUALITY ASSESSMENT:

Second basement was chosen for present study as it is mechanically ventilated and it was used to its maximum capacity. Eight locations within the parking space were selected to monitor contaminant level. The basement was monitored for a period of 8 hours. The CO concentration and car movement data collected during the field campaign are shown in Figure 3 and 4, respectively. Table 1 provides other miscellaneous data obtained during the field campaign.

3.2. MODEL PERFORMANCE:

3.2.1 AIR FLOW NETWORK – CONTAM 2.4

The average CO emission for 10 minute interval was simulated using car movement profile data obtained from field measurement. Each car engine source strength was considered as 1.89 and 3.66 g/minute for hot and cold emission, respectively (ASHRAE, 2007). CONTAM accepts this data as a time step curve of emission density, where 100 % emission density represents the maximum emission (Figure 5).

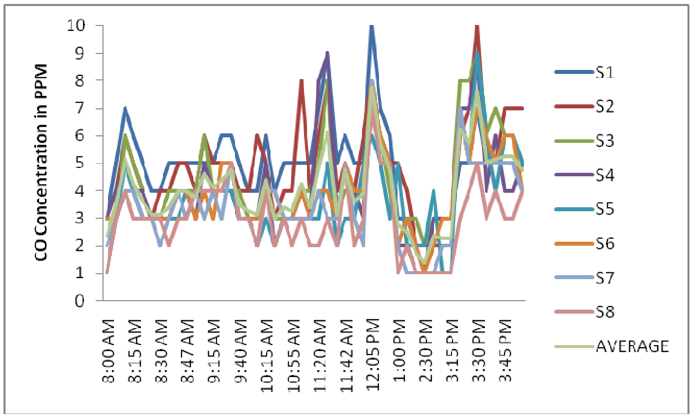

FIG.3: CO CONCENTRATION MEASURED AT EIGHT LOCATIONS

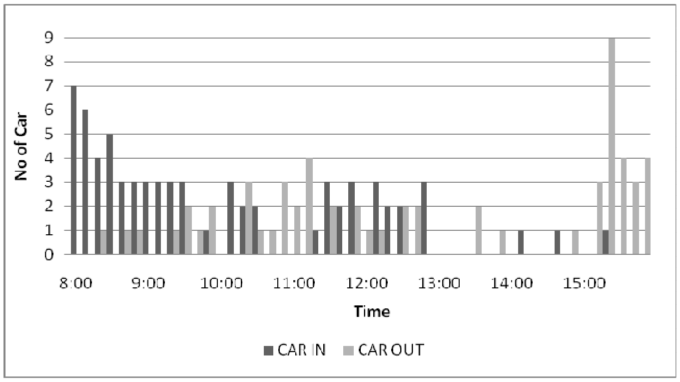

FIG.4: NO OF CAR ENTERING AND LEAVING THE CAR PARK IN 10 MINUTE INTERVAL

TABLE 1: MISCELLANEOUS DATA OBTAINED IN FIELD MEASUREMENT

S.NO.	DESCRIPTION	VALUE
1	Average Distance To Ramp	45 meters
2	Average Time To Ramp	20 seconds
3	Average Speed	8.05 km/hr
4	Date of Monitoring	15.10.2009
5	Average Temperature in Car Park	32^{0}C
6	Background CO Concentration	1 ppm

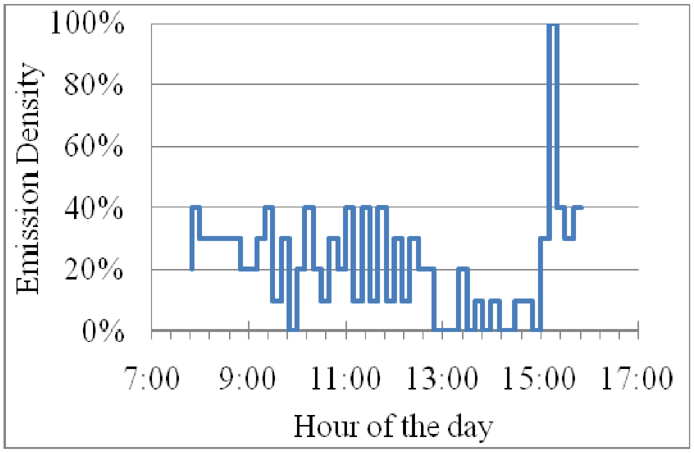

FIG.5: VARIATION OF SOURCE STRENGTH

The car park was taken as a single zone as shown in Fig.6. Two constant volume fans, one for supply and other for exhaust were considered. The mass flow rate of the fans was calculated to be 7.484 kg/s from the field data of 13,000 cfm of volume flow rate. The background CO concentration was taken as 1 ppm from the observation at site. It must be noted that the location of contaminant source, supply and exhaust fan did not impact the result as the car park was considered to be single well mixed zone.

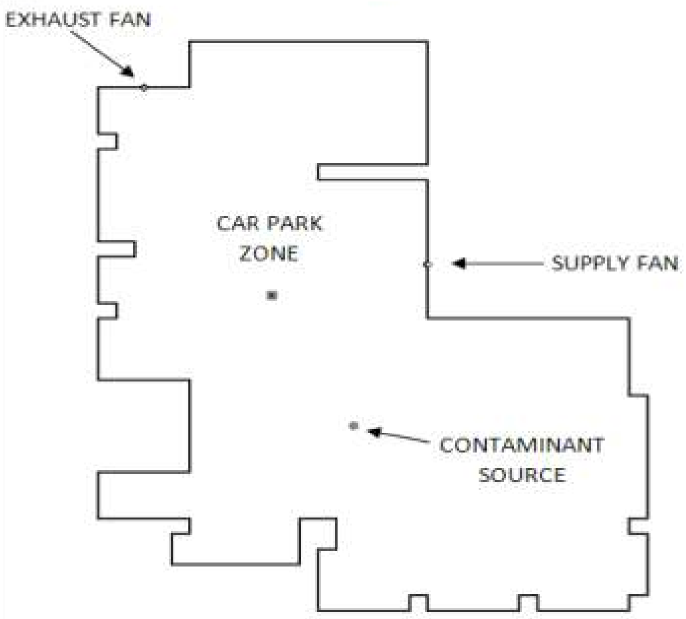

FIG.6: SKETCH PAD REPRESENTATION OF CAR PARK

Figure 7 presents the performance of CONTAM in predicting CO concentration in an underground car park. As seen in the figure, a good degree of agreement is observed between CONTAM CO prediction and field measurement.

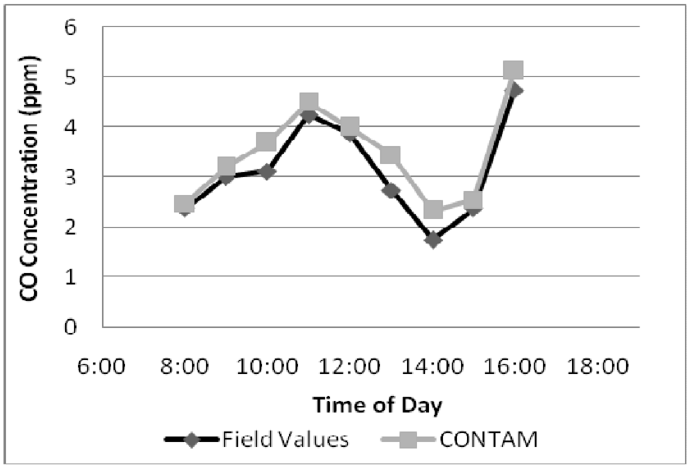

FIG.7: COMPARISON BETWEEN CONTAM PREDICTION AND FIELD MEASUREMENT

3.2.2 FLUENT:

The model has been validated with experimental data. Figure 8 compares fluent prediction of half hour average CO concentration and field measurement at eight sensor locations. The scatter plot shows good agreement between model prediction and field measurement. Figure 9 presents the error in percentage for the entire eight sensors at different time. Figure 10 presents the contour plot of CO concentration at breathing height of 1.5 m.

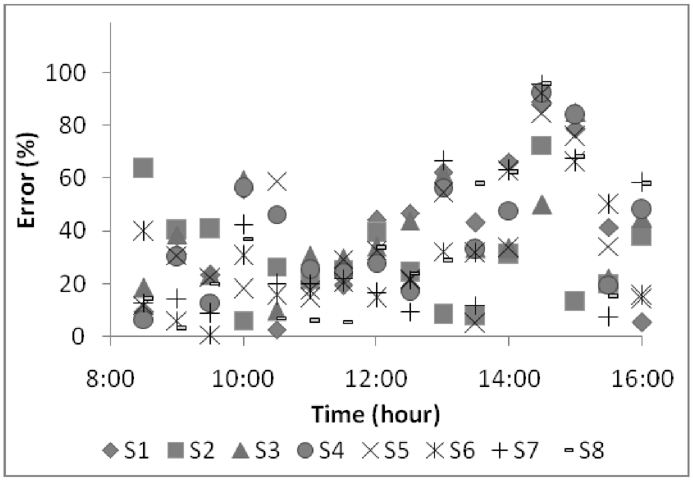

FIG.9 ERROR OF SIMULATION RESULTS AGAINST MONITORED VALUE AT DIFFERENT SENSOR LOCATION (S REPRESENT SENSOR)

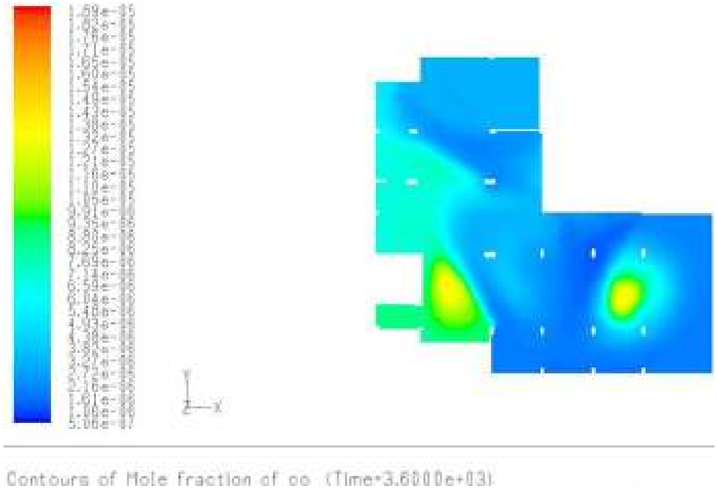

FIG.10: CO CONCENTRATION CONTOUR PLOT (Z=1.5M)

Parametric analysis

The validated model has been used for parametric analysis. Two parameters namely garage height and CO generation rate are analyzed.

Garage Height

Height of the car park is a critical factor while designing a ventilation system as the volume of the car park will vary. A height range of 2.5 to 3.5 m was considered in this study with step size of 0.25 m. The CO generation rate profile was the same as the one observed at site and it is used for validation of the CFD Model. However, the peak generation rate was increased to 1.56 x 10-7 kg/m^{2}s considering a worst case of all 30 cars operating in the car park for the 10 min interval. The ventilation rate required to maintain a one hour average of less than 30 ppm at 1.5 m from ground (breathing level) was obtained through simulations for each height step. Figure 11 shows the variation in ventilation rate required to keep CO

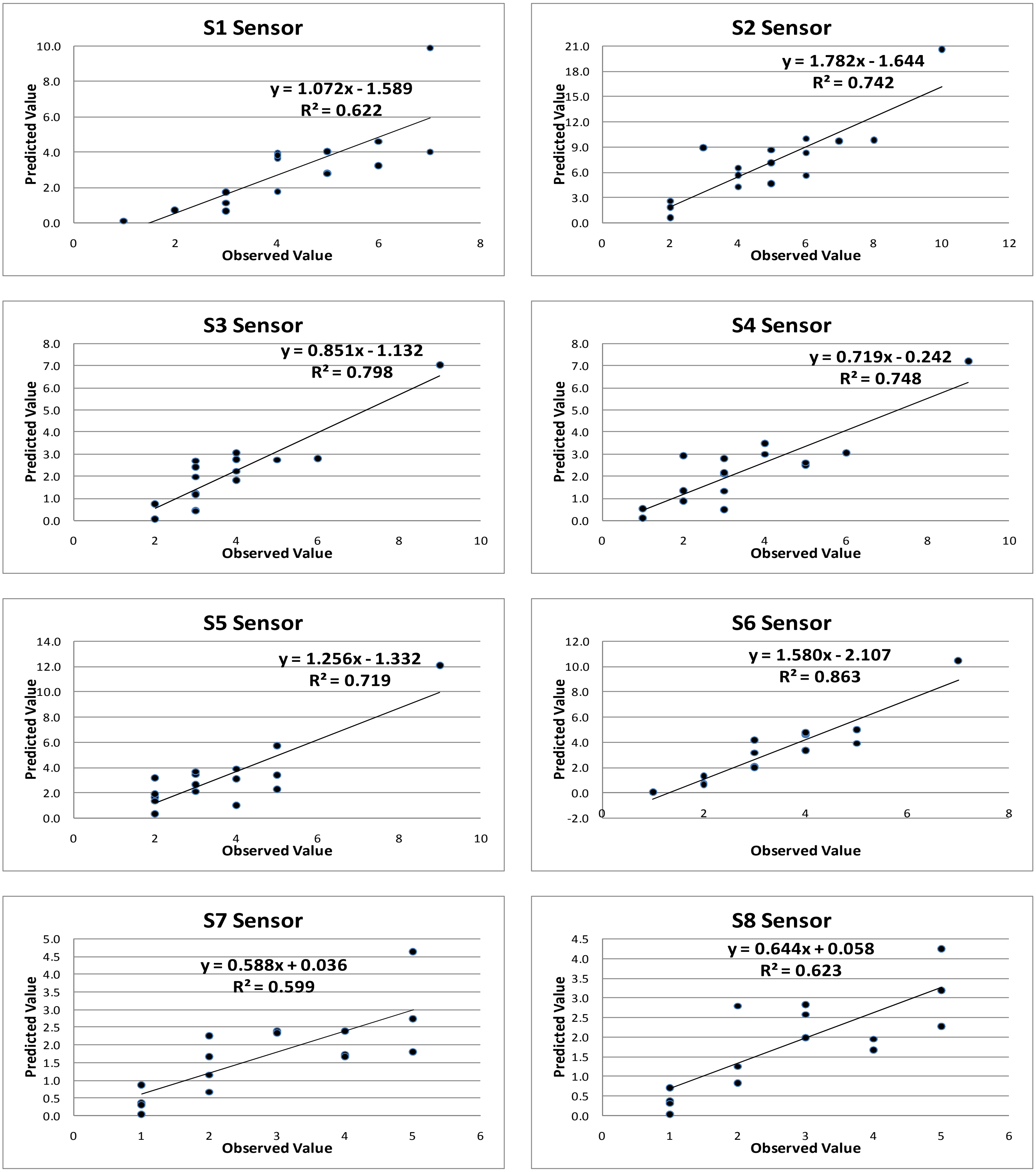

FIG.8: SCATTER PLOT OF SITE OBSERVED VALUE VS. MODEL PREDICTED VALUE AT VARIOUS SENSOR LOCATION

levels below 30 ppm (one hour average) with garage heights. It is clear that with an increase in garage height the ventilation rate required to keep CO level within the acceptable level also increases as the volume of car park increases. Therefore, considering 3 m as the reference height, an optimized ventilation rate can be easily calculated for any height from 2.5 to 3.5 m using the results obtained above as

$$v = v_{ref} \times (h/h_{ref})^3 \qquad (2)$$

where v is the required minimum ventilation rate for garage height of h when v_{ref} is the required minimum ventilation rate for reference garage height of h_{ref}.

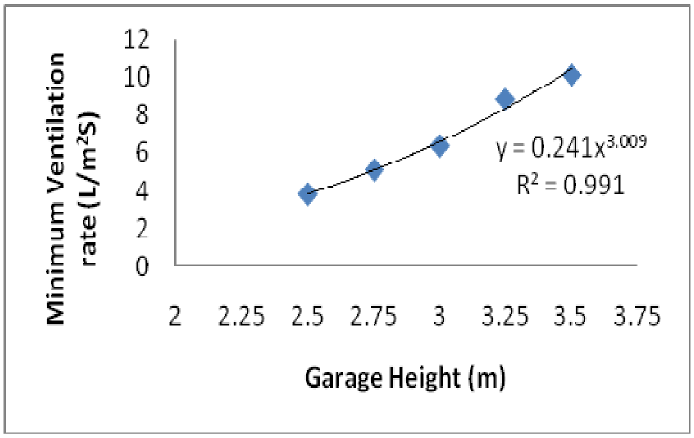

FIG.11 VARIATION OF MINIMUM VENTILATION RATE WITH GARAGE HEIGHT

CO Generation Rate

CO generation rate is a function of engine operating time, CO emission rate and number of cars in operation. For performing the analysis, this peak generation rate was varied such that its profile remained the same. However, its magnitude was increased and decreased. The worst generation rate of 1.56 × 10^{-7} kg/m^{2}s considering all 30 cars in operation was taken as reference peak 'Gr'. Figure 12 presents the peak CO level against ventilation rate for various CO generation rates. The equations of the curves in Fig.12 are presented in Table 2. The minimum ventilation rate required to keep the average CO level below 30 and 20 ppm for different generation rate are presented in Fig.13.

4. SUMMARY:

Multi-zone airflow network analysis and CFD technique were used to simulate the CO concentration in multi-story car park. Two commercially available software packages namely CONTAM and FLUENT were applied. Simulation result indicated that both the model predictions were close to the CO values of field measurements. Simulation using the former gave a macroscopic picture of the CO level while the latter predicted CO levels at various points in the car park. This study demonstrated that both CONTAM and FLUENT models can be effectively used in predicting vehicular emission in underground car parks. The validated model has been used to study the impact of garage height, CO generation rate on indoor CO levels and minimum ventilation rate required.

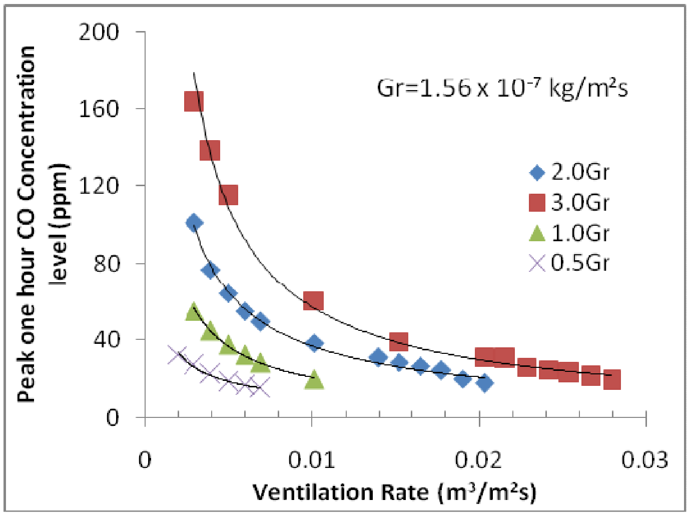

FIG.12: VARIATION OF PEAK CO LEVEL WITH VENTILATION RATE FOR DIFFERENT CO GENERATION RATES

TABLE 2: EQUATION AND R^2 VALUE OF CURVES DEPICTING VARIATION OF PEAK CO LEVEL WITH VENTILATION RATE FOR DIFFERENT GENERATION RATES

	Generation Rate	Equation	R^2 Value
0.5 x Gr	0.78 x 10-7 kg/m^{2}s	y = 0.612x-0.64	0.989
Gr	1.56 x 10-7 kg/m^{2}s	y = 0.442x-0.83	0.995
2 x Gr	3.12 x 10-7 kg/m^{2}s	y = 0.843x-0.82	0.981
3 x Gr	4.68 x 10-7 kg/m^{2}s	y = 0.710x-0.95	0.992

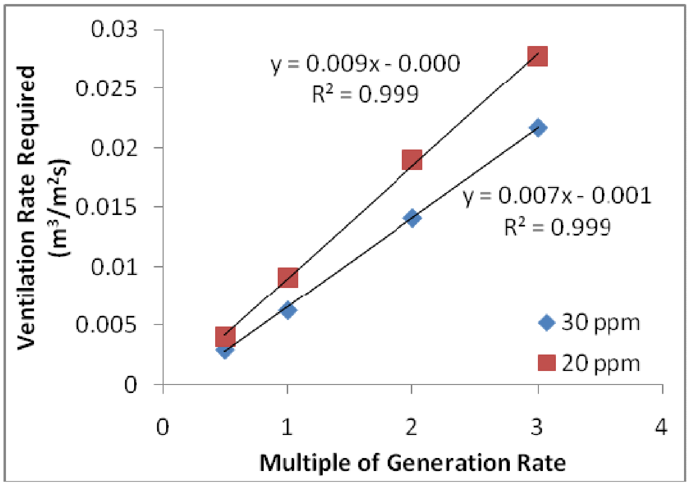

FIG.13 VARIATION OF MINIMUM VENTILATION REQUIRED WITH CO GENERATION RATE

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