Fire Simulation of a Car Park to Optimize Fire Ventilation Systems

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Abstract:- Fires in underground car parks are dangerous for they are isolated with confined quarters. Smoke, Fumes and Carbon Monoxide generated are dangerous and toxic to human life. Their evacuation via jet fans is an important safety requirement. This has the added benefit for ease of evacuation for fire fighters to tackle the situation safely. A Computational Fluid Dynamics (CFD) simulation was duly made, to represent this scenario for designing the ventilation system, using FDS v6.7. The car park is modelled as a bunker sized 40.125 x 24 x 3.75m, parked cars measuring 4 x 2 x 1.25m. The flow rate for venting from jet fans is set to 1m^3 s^{-1}. The effect of the smoke and heat control system (SHC) on the smoke movement in fire conditions is examined. A comparison between smoke extraction rate and smoke recirculation region was made for various cases. Computational models emphasize that proper location of elements of the ventilation system is crucial to attain high efficiency of fire ventilation. Consequently, evacuation plans can be made by proper estimation of smoke direction and density. Also, temperature rise is analyzed as it has a potential effect on safety of structures.

Keywords:- *Fire Dynamics; Smoke Propagation; Computational Method; Unsteady Solution; Evacuation Plan; Ventilation System.*

I. INTRODUCTION

Underground parking spaces are available in a number of layouts. They can be fully or partially enclosed, partly or entirely underground, have one or more storeys, and vary in motor capacity, volume, and size.

Although only a few partially closed garages are obligated to equip an electromechanical Smoke Control and Alarm System, it a requisite for fully enclosed garages to install these safety systems.

Underground garages are distinct in that they have a low clearance elevation of 220 to 300 centimeters (including wiring and vent sections) and are a vast compartmentalized area with no barriers or different fire zones. Furthermore, the adoption of fire-resistant walls and doors is uncommon.

1.1 The Major Challenges Faced by Designers.

When designing an underground garage, SCV system designers, alongside fire protection engineers, face three major challenges: Maintaining optimum conditions on routes for evacuation during a fire; maintaining a level of tenable Air-quality for daily use; designing an integrated, all-in-one solution, for both emergency and daily use demands.

II. AIR QUALITY

Since underground garage facilities are not naturally ventilated, system designers and engineers are required to take in account several air quality issues of which the most problematic is the high levels of Carbon monoxide (CO) gases emitted by vehicles entering, existing and traveling through the domain.

Other issues to be taken under consideration are the presence of oil, gasoline fumes, nitrogen oxides (NOx), Co_2 from diesel engines. Furthermore, in the near future, adaptation to new energy carriers due to global warming issues must be taken under consideration in both ventilation aspects and risk assessments for emergency scenarios. Designers need to take consideration of the emission of different range of gasses that are still under study. These gases and are not yet addressed in current regulations.

The regulations addressing the issue of Air-quality level and the system's requirements to maintain Tenable conditions for normal operation of underground garages vary on international, national and local level. Part of the regulation codes address the PPM threshold for CO exposure while others only address the number of air changes (ACH) per hour, state a sufficient extraction of air according to gross floor area.

To demonstrate this inconsistency:

NFPA 88A states the fixed ventilation of 5 L/s-M^2 of floor area is the minimum required.

NFPA 502 states CO exposure PPM threshold to be only for fire emergency.

ANSI/ASHRAE Standards 62-1989 state that a fixed ventilation of 7.62 L/s-M^2 of floor area is the minimum required while including a PPM threshold exposure time of 8 hours for 9 PPM and 1 Hour for 35 PPM.

III. SMOKE CONTROL SYSTEM CRITERIA

The regulations addressing the issue of smoke control and smoke management for underground parking garages is almost non-existent in terms of building usage for human occupancy. These structures are at times addressed as a storage occupancy areas or vast space areas.

NFPA 204 is at times used as a guide for smoke and heat venting in underground parking garages. This code addresses the smoke layer boundary height and temperature for building spaces with ceiling heights that permit the fire plume and smoke layer to develop.

The smoke management system should also provide suitable conditions for emergency services to enter the building, assist with the evacuation, rescue occupants and initiate fire-fighting strategies. Smoke layer Criteria is usually regarded as the threshold of smoke layer height ranging between 1.8m-2.5m.

IV. INTEGRATING AN ALL-IN-ONE COST-EFFECTIVE SYSTEM

When presented with such integrated requirements of both normal operation ventilation system and emergency ventilation system, designers tend almost automatically to design a system that is based on Vents, Jet Fans and Air ducts, resulting in a complex cost-ineffective system that is high on installation costs, energy consumption and rarely aesthetic to the eye.

4.1 Governing equations and LES simulations:

The Fire dynamics simulator (FDS) is a computational tool used for the simulation of the spread of fire and smoke inside a building. The results post simulation depends on the geometric layout of the building and the materials being implemented to build it. The governing equations of combustion during a fire is the basis for code used in Fire Dynamics Simulator. Certain cases of instability like turbulence are treated by means of the Smagorinsky form of Large Eddy Simulation (*LES*). There are a large number of investigations done to validate the code and results given by *FDS*. Based on these results from these investigations, it can be inferred that the results of *FDS* can be trusted for all fire simulation scenarios.

4.1.1 Flow Governing Equations

Fire Dynamics Simulator numerically solves a form of the Navier-Stokes equations appropriate for low-speed; thermally-driven flow with an emphasis on smoke and heat transport from fires. The Navier-Stokes equations are as follows:

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla.\rho\, u_i = 0 \qquad (1)$$

The conservation equation for momentum is given as:

$$\frac{\partial}{\partial t}(\rho\, u_i) + \nabla.\rho\, u_i\, u_j + \nabla p = \rho\, f + \nabla.\tau_{ij} \qquad (2)$$

The thermal energy equation is used. The thermal energy equation is given by,

$$\frac{\partial}{\partial t}(\rho\, h) + \nabla.\rho\, h\, u_i = \frac{Dp}{Dt} + \dot{q}''' - \nabla.q \; + \Phi \qquad (3)$$

Equation of state foe a perfect gas:

$$p = \rho\, R\, T \qquad (4)$$

In terms of the mass fractioins of the individual gaseous species, the mass conservation equation can be written as:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla.\rho\, Y_i\, u = \nabla.\rho\, D_i\, \nabla Y_i + \dot{m}_i''' \qquad (5)$$

Where, u_i is velocity in *i*-direction, i =1, 2, 3, ρ is fluid density, f is summation of external forces, τ_{ij} is shear stresses, p is pressure, h is enthalpy, q''' is heat release rate per unit volume, q is the heat transfer, Φ is any heat source, and T is the temperature. Y_i is the mass fraction.

4.1.2 Large Eddy Simulations (LES) and Sub-Grid Scale Models

The Large eddy simulation is used to resolve and model both small and large scales of the flow field solution in cases of turbulence. It provides accurate results and is preferred over other approaches to solving the problem.

For incompressible flow, the continuity-equation and Navier-Stokes equations are filtered, resulting in the following continuity equation:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \qquad (6)$$

And the filtered Navier- Stokes equation,

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u_i}\; \overline{u_j}) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + v\frac{\partial^2 \partial \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\tau_{ij} \qquad (7)$$

Where, $\underline{p}$ is the filtered pressure field and $\Gamma_{ij} = \overline{u_i u_j} - \underline{u_i}\,\underline{u_j}$ is the subgrid-scale stress tensor. $\Gamma_{ij}$is calculated by an eddy viscosity representation for small scales:

$$\tau_{ij} = \frac{1}{3}\tau_{kk}\,\delta_{ij} = -2\,\upsilon_T\,\overline{S_{ij}} \qquad (8)$$

Where, δ_{ij} is the Kronecker's delta. To calculate Γ_{ij}, the Smaronginsky-Lily SGS model is implemented.

The eddy viscosity is modelled as:

$$\nu_T = (C_s \Delta_g)^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}} = (C_s \Delta_g)^2 |\bar{S}| \qquad (9)$$

Where Δ_g is the filter width that is calculated as:

$$\Delta_g = (\Delta_x \Delta_y \Delta_z)^{1/3} \qquad (10)$$

Δ_x, Δ_y and Δ_z are the grid sizes in the three Cartesian coordinates x, y and z, respectively. C is a constant that is problem-dependent. The large-scale strain rate tensor magnitude is given by:

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) \qquad (11)$$

4.1.3 Combustion Model and Radiation Transport

Fire Dynamics Simulator uses the mixture fraction model as the default combustion model. The mixture fraction model is a conserved scalar quantity. It is defined as the fraction of a gas at a given point in the flow field that originated as fuel, as follows:

$$Z = \frac{sY_F - (Y_{O2} - Y_{O_2}^{\infty})}{sY_F^I + Y_{O_2}^{\infty}} \; ; \; s = \frac{\nu_{O_2} W_{O_2}}{\nu_F W_F} \; ; \; \nu_F = 1 \qquad (12)$$

Where, Y is the mass fraction. Subscripts F and O_2 refer to fuel and oxygen, respectively. Y_F^I is the fuel mass fraction in fuel stream. Superscript ∞ refers to "far away from the fire". ν is the stoichiometric coefficient. W is the molecular weight of gas. By design, mixture fraction varies from Z=1 in a region containing only fuel to Z=0 in regions (typically far away from the fire) where only ambient air with un-depleted oxygen is present.

Radiative heat transfer is accounted for in the model using the radiation transport equation for non-scattering grey gas. The equation is solved using a method similar to the finite-volume methods for convective transport.

RESULTS AND DISCUSSIONS

The smoke propagation and the various parameters such as Heat Release Rates and temperatures at various positions in the car park have been studied through simulations using FDS. The setup includes a room of size sized 40.125 x 24 x 3.75m with a ramp exit of dimensions 8 x 2.5m and a fire exit of 4 x 3.5m. The car park consists of six cars measuring 4 x 2 x 1.25m. The source of the fire in all the simulations is the car parked at the center of the room. The car park also consists of 6 jet fans that is used to direct the smoke towards the exhausts and vents.

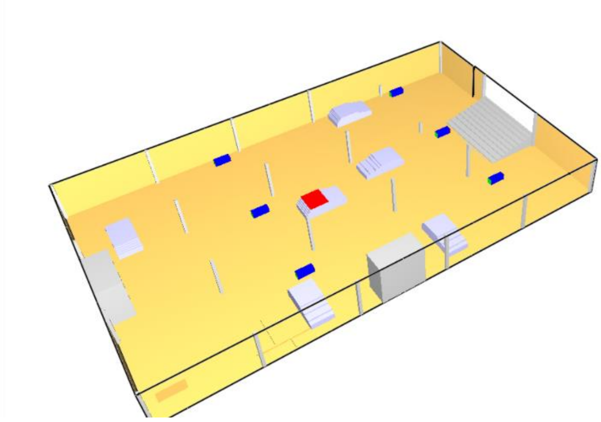

Figure-1: Car park layout

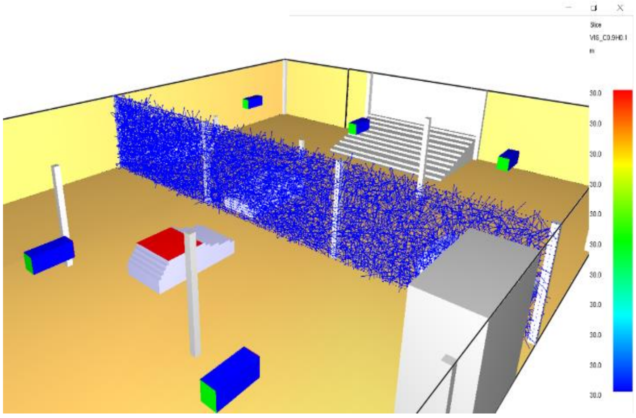

Figure-2: Soot yield distribution

The simulation was done for a total of 4 cases by varying the positions and orientations of the jet fans, number and size of vents. The simulation for each of the cases was run for 300 seconds. The various parameters such as heat release rates and Heat transfer from the walls are obtained and studied.

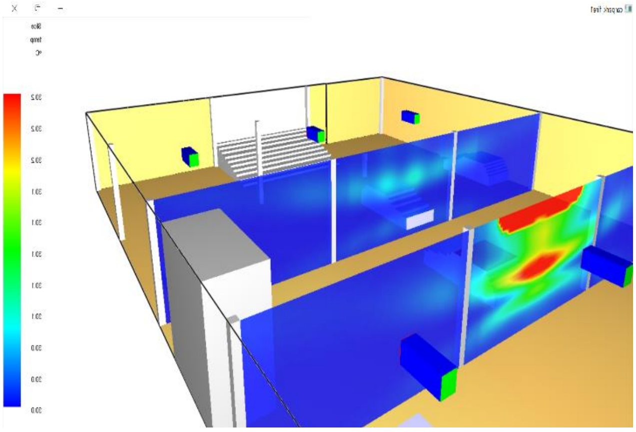

Figure-3: Temperature Distribution

The above images represent the soot yield and temperature distribution at various parts of the car park after 10 seconds of simulation. The various cases are explained below;

CASE 1: 2 exhaust vents

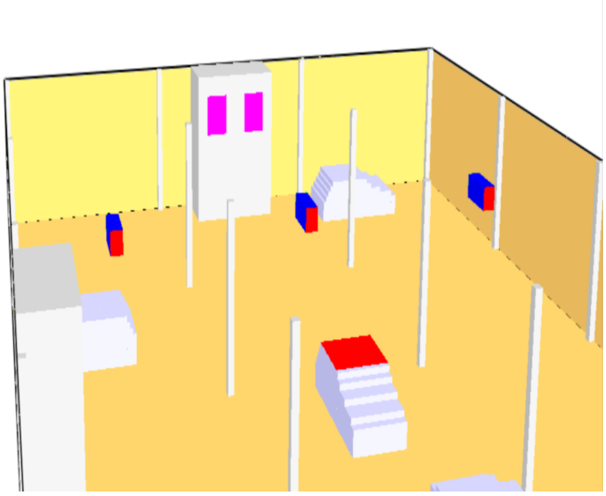

Figure-4

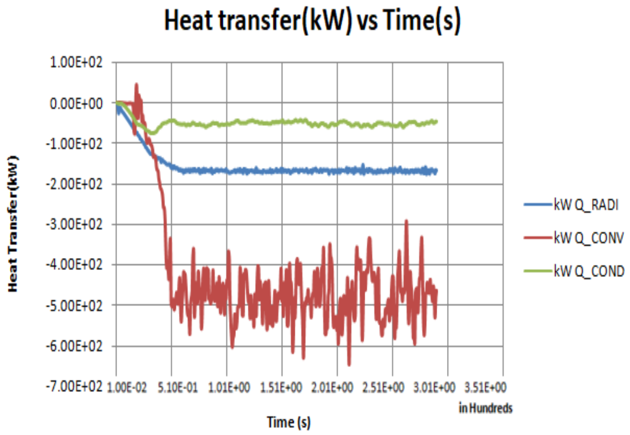

Chart-1: Heat transfer(kW) vs Time(s)

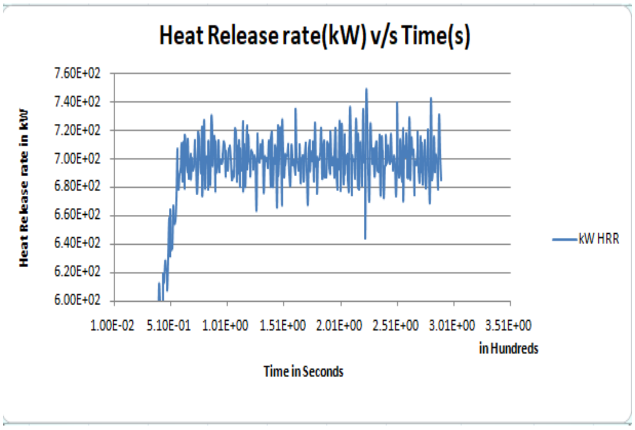

Chart-2: Heat Release rate (kW) v/s Time(s)

CASE 2: 2 additional inert vents are provided on the walls next to the exhaust vents.

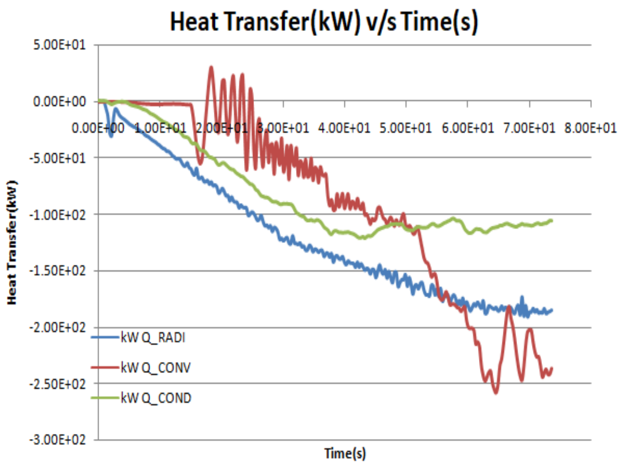

Chart-3: Heat transfer(kW) v/s Time(s)

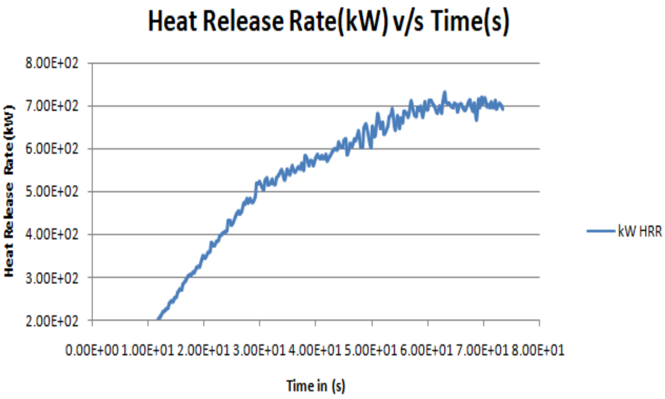

Chart-4: Heat release rate (kW) v/s Time(s)

Maximum heat release is achieved at 70 seconds.

CASE 3: 4 additional inert vents on the side walls along with the jet fans rotated to the side

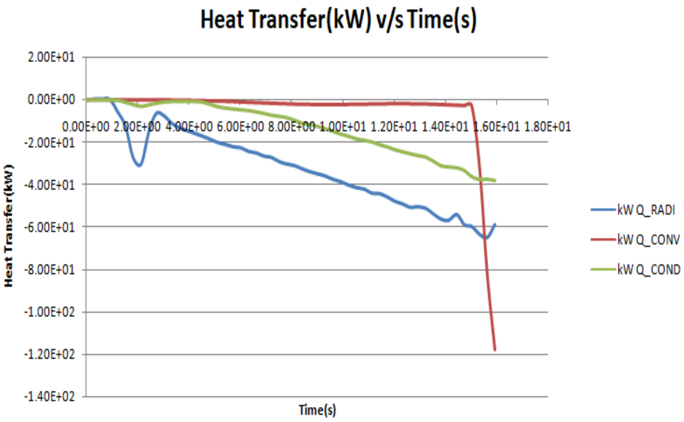

Chart-5: Heat transfer(kW) v/s Time(s)

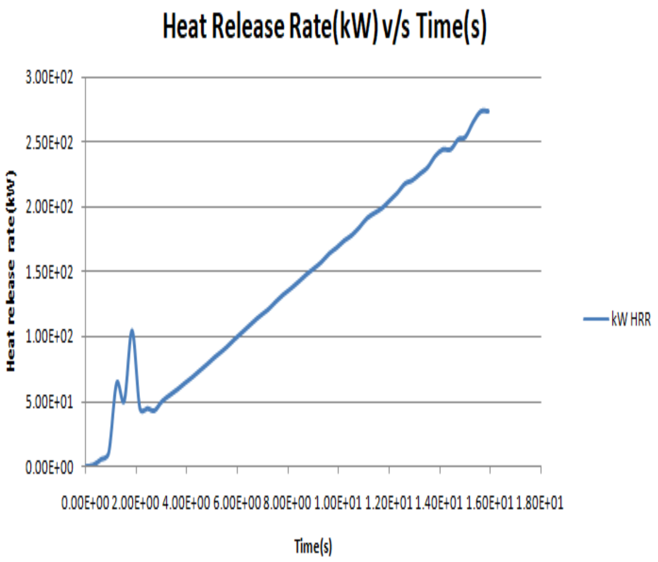

Chart-6: Heat release rate(kW) v/s Time(s)

CONCLUSIONS

A CFD model of a car park has been implemented and used for investigating the parameters that play a role in the smoke propagation from one part to another. The outcomes of the investigations show that the smoke spread is influenced by the geometrical layout. Specifically, the positioning of the jet fans and the vents play a very important role in the behavior of smoke propagation. The direction of the jet fans influences the temperatures of the various zones in the car park. This is important since this helps us place the jet fans in an optimum position so as to keep the temperatures next to the outlets as low as possible. The vents supplement the jet fans in reducing the smoke concentration.

Declaration of competing interest

There is not any conflict of interest for all authors of this manuscript.

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Nomenclature

C_s = modeling constant.
F = summation of external forces.
H = enthalpy.
Q = heat transfer.
$\dot{q}'''$ = heat release rate per unit volume (*HRRPUV*).
P = pressure.
$\overline{p}$ = filtered pressure field.
$\overline{S_{ij}}$ = magnitude of the large-scale strain rate tensor.
T = temperature.
u_i = velocity in i-direction, i =1, 2, 3.
$\overline{u_i u_j}$ = nonlinear filtered advection term.
W = molecular weight of gas.
Y = mass fraction.
Y_F^I = fuel mass fraction in fuel stream.
Z = mixture fraction.

Greek

δ_{ij} = Kronecker's delta.
Δ_g = filter width.
Δ_x, Δ_y and Δ_z = grid sizes in the Cartesian coordinates x, y and z, respectively.
Φ = any heat source.
ν = stoichiometric coefficient.
ν_T = Turbulent eddy viscosity.
ρ = fluid density.
τ_{ij} = subgrid-scale stress tensor.

Superscripts and Subscripts

∞ = refers to "far away from the fire".
F = refers to "fuel".
O_2 = refers to "oxygen".

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