THE AERO-THERMO-CHEMICAL FLOW FIELD IN LARGE SCALE ENCLOSED POOL FIRES WITH DIFFERENT ENCLOSURE HEIGHTS AND CENTRAL ROOF

C. S. Bhaskar Dixit, H. S. Mukunda
Centre for Disaster Mitigation
Jain University
Bangalore - Kanakapura Road
Jakkasandra 562 112
E mail: bhaskar.dixit@gmail.com

ABSTRACT

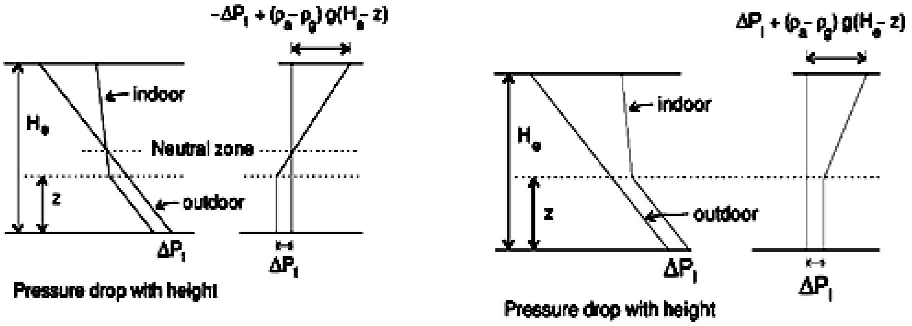
Fire test enclosures of 18 m × 12 m with heights 7.2 m, 11 m and 13 m are considered for analysis using Fire Dynamics Simulator, an LES/DNS based CFD tool. The objective of these calculations is to determine the total flow rate that would need to be handled and the smoke behaviour inside the enclosure. Calculations indicate that mass throughput required to maintain a positive pressure in the room is a strong function of enclosure height with mass flow rates varying from 47 kg/s to 70 kg/s for room heights between 7.2 m and 13 m. Steady Smoke zone is restricted to 5 m below roof for 11 m high room with 47 kg/s mass throughput. 13 m high enclosure with curved roof is found to have steady smoke region of just 1 m below roof and therefore appears a better arrangement for fire testing enclosure.

INTRODUCTION

Evaluation of effectiveness of fire extinguishers is an important prerequisite in their commercial deployment. Their effectiveness is evaluated by using them to extinguish fires of specified sizes using procedure outlined in various standards. Fires created within the enclosure could be ignited wood cribs or liquid fuel pools. Pool fire of size 20 B (UL-711, [**1**]), implying n-heptane liquid pool fire of size 2.16 *m* × 2.16 *m* (50 *square feet*) is the largest fire that is recommended for in-door operation. Indian standard IS 15683:2006 [**2**] also outlines procedures for performance of portable fire extinguishers which are similar to UL 711. Here too, the largest indoor fire is limited to the equivalent of UL-711:20 B. The duration of this fire is about 3 minutes. The smoke levels and ambient temperatures within the enclosure are a strong function of size and height of the enclosure. The standards also specify that indoor fires must be well ventilated. The height of enclosure, roof and exhaust configuration must not affect the pool fire. Determination of aero-thermo-chemical flow field within such enclosures through simulations will allow a simpler preview of proper ventilation scheme.

LITERATURE REVIEW

Fires in enclosures are studied in detail in literature [**3**]. One of the important criteria for design of vent configurations for enclosures with constant fire source inside is the height of smoke layer from the ground. CFD based calculations are inevitable for enclosures with fire source with time varying power. However, smoke filling process in large enclosures with a constant power fire is analyzed from the thermodynamic point of view in [**3**]. Smoke control measures by means of natural ceiling ventilation, mechanical ventilation from upper smoke layer and pressurization of lower layer by mechanical ventilation are discussed. Based on mass and energy balances within the enclosure, expressions for pressure differences across bottom inlet and ceiling vent in terms of ceiling height and air properties are presented and calculation procedure for evaluating smoke layer height for a given room & fire size and inlet & exit areas is outlined. Plume mass flow rates are computed using McCaffrey correlation.



a. Natural/active ceiling exhaust

b. Pressurization of lower layer

Fig. 1 Pressure variation along the height for enclosed pool fires [3]

The importance of providing ample inlet area in case of enclosures with natural ventilation is highlighted. A slight decrease in inlet area beyond a threshold value would result in a drastic increase in exit area requirement to maintain a given smoke layer height in the room. Fig.1 shows vertical pressure profiles in enclosures with mechanical ventilation. It is seen that in the case of ceiling exhaust, mechanical ventilation pressure in the lower layer is below ambient while in the case of lower layer pressurization, room pressure is higher than ambient. Z represents the smoke layer height.

Validation of the formulation for calculation of smoke layer height is based on experiments in large enclosures of size 18900 m^3 (720 m^2 × 26.3 m high) with a fire power of 1.3 MW leading to an enclosure power density of 0.068 kW/m^3. Steady state layer height is computed for durations beyond 10 min. However, the enclosures used for fire extinguisher testing have peak power densities two orders of magnitude higher at 6.2 kW/m^3 with fire lasting for about 3 min. Therefore ventilation requirement calculations even for the case of constant fire power in such enclosures may require an approach involving CFD simulation to ensure regions closer to ground are not compromised during the test.

CFD STUDIES

A hypothetical enclosure of 18 *m* × 12 *m* is considered for analysis. The aero-thermo-chemical flow field within this enclosure with central roof exhaust is *simulated* to determine appropriate air inlet configuration, room height and the need for smoke abatement. One of the crucial requirements is to ensure air enters at low velocity to prevent disturbance to the flame. Mass throughput is governed by amount of air entrained by combustion products. Enclosure height decides the amount of entrained air. Therefore sufficient inlet area must be provided to supply required amount of at low velocities to maintain the mass balance. If not, the pressure in the enclosure will go much below the ambient leading to undesirable conditions for the combustion process.

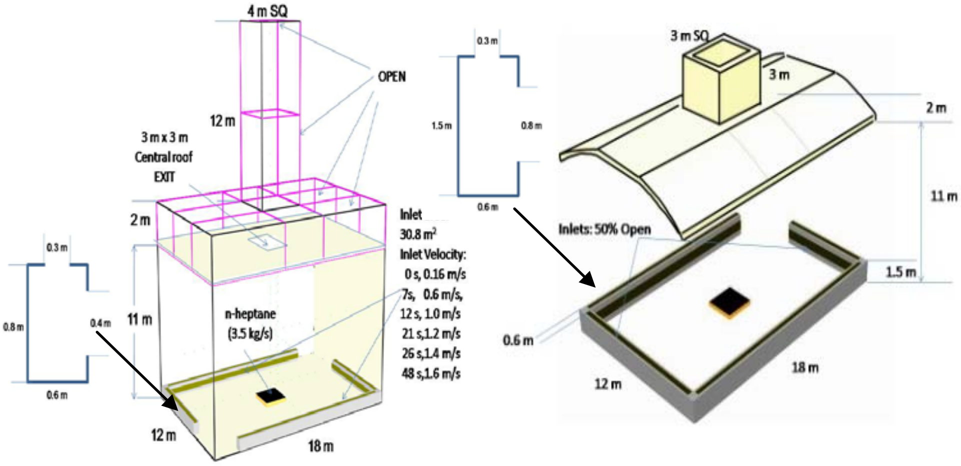
Fire Dynamics Simulator (FDS, Version 5.5), an LES/DNS based CFD tool [**4**] for computation of unsteady flows, available from NIST web site, is used to carry out these *simulations*. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. FDS uses a second-order accurate finite-difference approximation to the governing equations on a series of connected rectilinear meshes. The flow variables are updated in time using an explicit second-order Runge-Kutta scheme. Gray gas model is used to solve radiation transport equation with 104 angles in the present set of simulations. Also, radiation solver is updated every 3 time steps with 5 angles skipped every update. Mixture fraction model is used for combustion. Fuel release is modeled using the parameter Heat Release Rate Per Unit Area (HRRPUA) calculated to be 3.2 MW/m^2 from asymptotic fuel flux of 75 g/m^2s and heptane energy content of 46.1 MJ/kg. The default value of initial time step DT is $5(dxdydz)^{1/3} / (gH)^{1/2}$ s, where dx, dy, and dz are the dimensions of the smallest mesh cell, H is the height of the computational domain, and g is the acceleration of gravity. During calculations time step is normally set automatically by dividing the size of a mesh cell by the characteristic velocity of the flow.

Simulated Configurations

Flat roof geometry with an enclosure size 18 *m* × 12 *m* is chosen for analysis. Heptane fuel pan (2.16 *m* × 2.16 *m*), corresponding to a fire size of UL: 20 B (fuel mass flow rate of 0.35 *kg/s*), is located centrally on the floor. All walls are assumed to be of concrete with 0.3 *m* thickness. Properties of concrete used are density = 2200 kg/m^3, conductivity =1.2 *W/mK* and specific heat of 0.88 *kJ / kgK*. Three heights 7.6 *m*, 11 *m*, and 13 *m* were chosen. Central roof exhaust sizes chosen were 7.2 m: 2.16 *m* × 2.16 *m*, 11 *m* and 13 *m*: 3 *m* × 3 *m*. Enclosure with 13 *m* high exhaust has curved roof. Figure 1 gives a schematic representation of major geometries tried.

Flat roof

Figure 2a shows the geometry and boundary conditions used for flat roof configuration. n-heptane pool fires of size greater 2 *m* diameter approach an asymptotic burn rate of 75 g/m^2s [**4**]. This translates to a heptane fuel flow rate of 0.35 *kg/s* (14.7 *MW*) for 2.16 *m* × 2.16 *m* pool surface. Maximum soot yield is chosen to be 0.013 [**6**].



a. flat roof **b. curved roof**

Fig. 2 Geometrical details and boundary conditions *(Inset: c/s dimensions of inlet duct indicating width of air inlets)*

Inlet configuration consisted of a duct of size 0.6 *m* x 0.8 *m* height all round the wall as shown in Fig. 2 which would act as a plenum for ensuring low velocity air flow towards the pan. Total inlet total area is 30.8 m^2. Extra region is included into the computational domain to simulate the plume region over the roof also to ensure boundary conditions at central roof exit are realistic. Central 4 *m* x 4 *m* region of the domain around the pan consisted of refined grid with 27 *mm* x 27 *mm* x 50 *mm* nodes up to a height of 14 *m* to capture the details of fire driven flow. Calculations were started with a stoichiometric air flow rate of 5.25 *kg/s* into the domain. Pressure in the enclosure is monitored during the run. As and when pressure dropped to values below the ambient value of 101325 *Pa*, air supply into the domain is increased by increasing velocity of supply air. The inlet air flow velocities and the time instants when they were ramped are also indicated in Fig. 2a.

Curved roof

A second calculation with a curved roof configuration described in Fig. 2b. The geometry and grid details are broadly similar to that of flat roof configuration. The height of roof is increased by 2 *m* in the central region. Walls are at 11 *m*. The roof has a 4 *m* wide flat central region along the longer side with curvature along the shorter side as indicated in Fig. 2b. A 3 *m* x 3 *m* x 3 *m* high chimney is provided above the central 3 *m* x 3 *m* roof exit 13 *m* above the ground. Material of the chimney is chosen to have the same properties as the roof material. Extra plume region of 12 *m* height is included into the computational domain to ensure proper boundary conditions at the exit of the chimney. A larger inlet duct size with an area of 52.08 m^2 is provided to accommodate the envisaged higher mass throughput. Calculations were started with an inlet flow velocity of 0.76 *m/s* (40 *kg/s*) and increased to 1.3 *m/s* at 8.12 *s* to ensure positive pressure within the enclosure. During these calculations numerical instability is experienced which is overcome by fixing time step to 0.0008 *s*.

RESULTS AND DISCUSSION

Flat Roof

Calculations are performed for duration of about 60 *s*. In flat roof configuration an average mass flow rate of 47 *kg/s* maintained between 25 to 50 *s* of simulation with a positive pressure in the chamber. Figure 3a shows the pressure data along the 18 *m* long side of the room for flat roof case. It is seen that pressures in the chamber are positive (ambient: 101325 *Pa*) throughout the period for the chosen mass throughput at boundary. Pressure in the flame region is lower at all vertical levels indicating flow into the flame region. Vertical pressure profile at the centre of the plume (x=0) indicate near constant pressure excess (8-10 *Pa*) up to 6 *m* height beyond which it shows an increasing trend signaling a thermal discontinuity (smoke level) at 6 *m*. Figure 3c and 3e give velocity and temperature distribution. Peak velocities of about 12.5 *m/s* are seen in the region across the pan at the roof level. Interestingly, velocity at the thermal discontinuity layer (~6 *m*) is higher than the velocity at the roof. Temperatures decrease along the *z* direction indicating dilution of product gases by surrounding air.

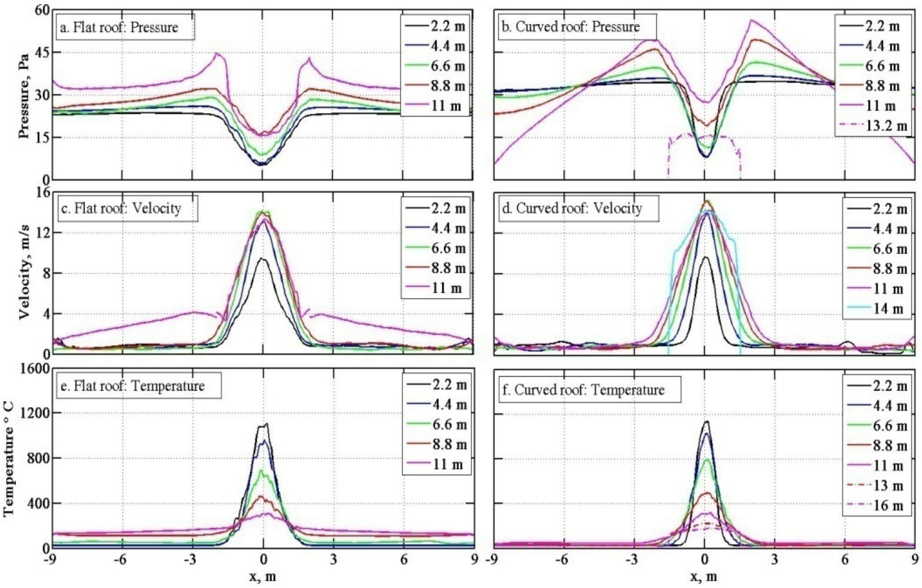


Fig. 3 Pressure, velocity and temperature distribution at 5 equidistant levels in flat and curved roof calculations along vertical central plane of 18 *m* long side

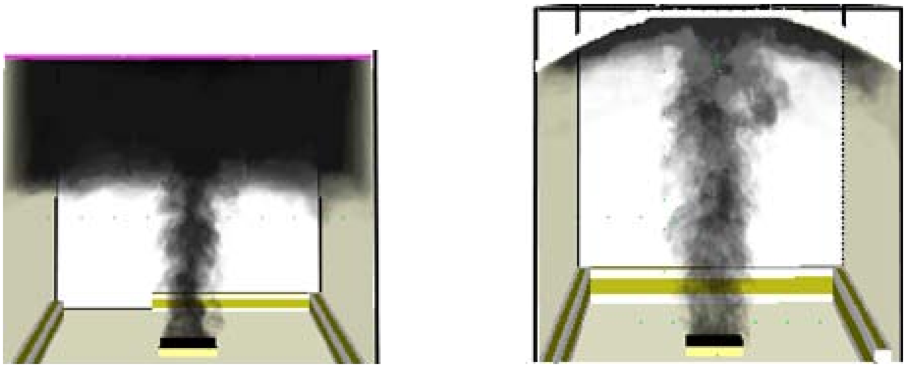
A thermodynamic analysis for constant pressure condition within the enclosure also confirms the fact that a mass throughput of 47 *kg/s* is required for roof exhaust average temperature of 312 ℃ (based on Alpert correlation) and a radiative fraction of 0.35. Time averaged (25 *s* average) roof exit peak velocity is 12 *m/s* and temperature is 300 ℃ with smoke layer stabilizing at about 5 *m* from the roof. Peak perturbation pressure is 50 *Pa*. The flame radiation fraction is 0.35. Heat release rate is balanced by sum of convective and conductive losses.

Curved Roof

Calculations are performed for duration of about 60 *s*. In curved roof configuration an average mass flow rate of 70 *kg/s* is maintained between 25 to 45 *s* of simulation with a positive pressure in the chamber. Figure 3b gives pressure distribution in the central plane along 18 *m* side of the enclosure. Computed pressures at corresponding levels are higher compared to flat roof calculation as the mass throughput is larger with same exit area of 9 m^2. The difference is seen to increase with height. Large pressure differences are seen between edge of roof exit and wall between 8.8 and 11 *m* height indicating strong recirculation. Figures 3d and 3f give velocity and temperature profiles with 13 *m* high roof. Predicted velocity profiles in curved roof configuration are seen to be similar to flat roof configuration. Peak velocities are seen to be about 10% higher compared to flat roof at 11 *m* height. Radiated fraction is found to be 0.35 in this case too. Average temperatures at roof exit (13 *m* height) are about 80 ˚*C* lower than flat roof configuration.

SMOKE GENERATION

Prediction of smoke in FDS is based on a soot fraction of 0.013 *kg/kg fuel*. That is for a heptane burn rate of 0.35 *kg/s* amount of soot emitted 4.5 *g/s* during the entire operational duration of 50 *square feet* size engineered pool fire.



a. Flat roof **b. Curved roof**

Fig. 4 Comparison of predicted instantaneous smoke profiles at 50.2 *s*

Figure 4 shows instantaneous smoke layers at 50.2 *s* in both configurations. Effect of increased mass flow rate is evident as almost no smoke accumulation is seen in the curved roof configuration while smoke layer is at about 6 *m* level (between 25 to

50 *s*) from the floor in flat roof configuration (region around the flame base is smoke free). Exit gas temperature at roof exhaust due to larger entrainment in the increased height case is beneficial to roof structural material. Soot in the upper zone (above thermal discontinuity) even in flat roof calculation is 45 mg/m^3. Maintaining high mass throughput is important to ensure operator safety in enclosures with large power level short duration fires.

CONCLUSIONS

This study is concerned with the simulation of the aero-thermo-chemical behavior of large pan fires in enclosures. The study on two alternate configurations shows that the curved roof geometry allows for the smoke to be exhausted and a small layer remaining towards the top region. Therefore, it appears as a more attractive choice between the configurations studied.

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