CFD SIMULATION OF OPTICAL OBSCURATION DUE TO FIRE IN ENCLOSURE

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ABSTRACT

In order to ensure safety of Nuclear Power Plants (NPPs) in the event of occurrence of a fire, the fire modelling is often recommended in the fire safety guides prepared by the national regulatory bodies. The analytical simulation of fire propagation and validation of the physics of several processes involved while using them for application to NPPs. Limited work has been done to validate the capability to predict optical density in the smoke laden fire atmosphere for most of the fire model. In present paper four full-scale experiments from open literature were simulated in a CFD code to evaluate this predictive capability. These four scenarios are: a propane burner in a small enclosure, a hospital bed in a large room, a wood stack fire and solid polyutherene fire in enclosure. The analysis has been carried out with the correct value of the grid size based on earlier experiences. The predicted visibility of the four scenarios at top corner of the enclosures by the current analysis is compared against the earlier reported experimental data and our own earlier prediction. from a zone model based code. The CFD results are much improved over the zone model based predicts with similar assumptions in input and fire scenario simplification. The studies have extended the utility of field model based tools to model the particular useful separate effect aspect like predicting visibility conditions for fire and validate against experimental data. The present study have several applications in such as conventional room fires, fire in nuclear reactor containment, post fire accident management, identifying fire escape route, visibility in tunnel and designing fire exit sign etc.

INTRODUCTION

The fundamental knowledge of fluid flow and heat transfer associated with fire growth, its after effects and the modelling of the same is vital in the assessment of fire safety. Guide lines to be followed in the installation of fire detection systems often require a priori knowledge of the smoke density and visibility in the atmosphere. National Fire Protection Association Standard 130[1] , stipulates that if there is any smoke in the emergency evacuation path, its optical density or light attenuation be maintained below a certain value such that emergency exit signs may be visible and evacuation is not impeded. For this, NFPA-130 also recommends that smoke obscuration levels be such that a sign illuminated to 80 lux is discernable at 9 meters distance and that doors and walls are discernable at 6 m distance [William D Kennedy et al.[2]]. Despite their importance these parameters are noted to be generally grossly ignored in the overall fire propagation analysis. The conventional fire propagation analysis generally does not addresses these issues. The behaviour of hot combustion products which include the sooth particle and other optical blocking substances which rise up along the buoyant plume and distributes all along the flow arena. Research studies on visibility conditions arising out fires and other situation where visible cloud forms have been of great importance due to their high probability of occurrence in engineering industry and even in the domestic places. Apart from the earlier experimental work the advance CFD techniques are now being capable of studying this phenomenon in details. Clarke and Shaw (1993)[3] produced a correlation to predict the presence of a visible cloud. A CFD model based upon the commercial code CFX-4 has been developed which is able to predict the formation of a 'condensation cloud' immediately downstream of the discharge from the moisture-laden calciner stacks by Brown and Fletcher (2005) [4] however the visible obscuration or visibility conditions have not been addressed (may not be required in calciners). Kawabata and Wang(1998)[5](1999)[6] attempted numerical study on real scaled tunnel fires. There are a number of factors visibility depends upon: smoke concentration , brightness or luminance of objects, daylight or electric lighting conditions, distance of an individual to an object, as well as visual acuity of an individual (human perception) , background contrast level [Gobeau et al., (2002)[7]. Visibility are frequently evaluated and represented in terms of a tenability limit [Purser (1995)[8], Kang (2007)[9], Mulholland (1995)[10]). Some other reported studies on visibility reductions are enlisted (Blake and Suo-Anttila, (2008)[11]; Gobeau and Zhou (2004)[12]; Zigh and Kang(2000)[13]]. Light obscuration is not lethal by itself but the resulting reduction in visibility is likely to yield a longer evacuation time and extend the duration of the exposure to the toxic smoke [Milke, (1995)[14]]. Meo[15] in his doctoral work used CFD code JASMINE and CFX for finding of safe visibility distances in tunnel for escape .Several special-purpose and general-purpose software packages have been developed in recent years. Fire Dynamics Simulator (FDS) [16] and Smart Fire [17] are popular special-purpose software, and CFX [18], FLUENT [19] and PHOENICS [20] are among the popular general-purpose CFD software. This study took one of the special-purpose CFD software packages, FDS [21], as an example, to investigate the feasibility of using this program and for validation for the visibility reduction due to fire in an enclosure. RANS CFD packages [22] [23] [24] [25] however, are quite commonly used in field modeling of fire phenomena. The main criticism leveled at the RANS approach targets the validity of the turbulence models employed to provide closure to the governing equation set. These turbulence models contain empirically determined parameters that can only be considered applicable for the specific flow cases where they have been validated. This narrows the range of validity for the RANS CFD approach. Large Eddy Simulation (LES) is a branch of Computational Fluid Dynamics (CFD). It differs from other CFD approaches, in that LES explicitly calculates the large-scale turbulent flow structures from first principles. The small-scale turbulent motion not calculated directly from the governing equations has its influence on the resolved flow field modeled. The simplest and most common form of SGS turbulence model used in LES is the Smagorinsky model [26] [27]. This is the default SGS model used in the FDS fire code. The Smagorinsky model uses the eddy viscosity approach to quantify the stresses that the turbulent velocity fluctuations place on the mean flow. In this modeling approach, the Reynolds stresses are assumed to relate to the local mean velocity gradient. The present work has been carried out using the code FDS. The code FDS have been extensively validated using salt water modeling experiments[28,29], gravity current modeling [30,31,32], isolated plumes[33,34,35,36], buoyant plume in cross flow [37], enclosure fire dynamics [38,39,40] and by qualitative observations in above mentioned studies. A detailed systematic validation exercise for the FDS hydrodynamic model can be found in reference [43]. Authors have also used the validated tool for various applications in nuclear industry [42]. The aim of present paper is to study the corner fire characteristics in a compartment which have been an area of keen interest worldwide. Numerical prediction of above situations has been compared with the experimental and numerical results available from open literature. Simulations have been carried with finer grid sizes based on our earlier studies [43].

FIRE DYNAMICS SIMULATOR (FDS)

Fire Dynamics Simulator (FDS) is a field model based software developed by NIST (USA) and has built-in dedicated computational fluid dynamics (CFD) model to describe and analyses fire in multiple compartment geometries. The code solves numerically the set of governing equations of mass, momentum (Navier-Stroke) and energy conservation appropriate for low-speed, thermally-driven flows of multispecies gas mixture to describe the smoke and heat transport arising from fires. In this paper, Smagorinsky sub-grid model [26,27] was used in the fire-enclosure to get the fire generated three-dimensional flow field. The basic set of equations for conservation of mass, momentum and energy respectively [16]: The details of formulation of the equations and the choice of numerical algorithm available are contained in a companion document, called Fire Dynamics Simulator – User and Mathematical Reference Guide [16].

Visibility Modeling in Fire Modeling Codes

Among the current national and international fire design guidelines and regulations, the NFPA "Standards for smoke detection and management systems in malls, atria and large spaces" (NFPA, 2005)[45] are widely referred. The output from the analytical fire models consists of gas layer temperatures, concentration of oxygen, carbon dioxides, velocity etc. based on the solution of the conservation equations. Certain transformation models have been employed that used the output from the conservation equations and calculate the smoke density, optical density and visibility parameters. The generation of combustion products in fires is generally associated with a reduction in visibility. The smoke yield of the fire is expressed in terms of obscuration potential per gram of material burned. The opaque portion of the products reduces visibility by light absorption and scattering, letting only a certain fraction of light to pass through. Various researchers have utilised approaches based on correlations in terms of oxygen depletion, mass fraction of combustion products, temperature rise etc. to calculate the optical density. The optical density D of smoke is defined as $D=\log(I_0/I)/l$. Where, I_0 is the initial intensity of the light and I is the final intensity of the light passing through the smoke layer of thickness l. The fraction of the light passing through the smoke layer is expressed by Beer Lambert law: $(I_0/I)=e^{(-K.l)}$. Here, K is the extinction coefficient (m^{-1}), which is the function of a mass concentration of smoke, C_s. The optical density per unit optical path length can then be expressed as $D/L=K_m\ \rho Y_s$. Where, Y_s is in Kg/m^3 and K_m is the specific extinction coefficient of smoke or particle optical density (m^2/Kg).

For an open system , the smoke mass concentration takes the form $C_s=Y_sG_f/V_T$ Where, Y_s is Yield of smoke (g/g), G_f denotes the local mass flow of vapour of burning material and V_T is the total local volumetric flow rate of the mixture of fire product $D/l=\xi.\ Y_sG_f/V_T = D_{mass}G_f/V_T$. The value of parameter $D_{mass}(m^2/g)$ called mass optical density, is given in standard handbooks for different materials or need to be obtained experimentally. The ratio G_f/V_T is approximated by the fact that the amount of fuel involved in the generation of smoke within the control volume is directly proportional to the amount of oxygen consumed neglecting the amount of unburned fuel. Let Y_0 denote the local mass fraction of oxygen, Y_∞ is the mass fraction in undisturbed air and r_0 is the stoichiometric oxygen to fuel ratio. The optical density can be expressed as $D= D_{mass}\rho(\ Y_0- Y_\infty).l/r_0$. The equation of the optical density can alternatively be formulated in terms of local mass fraction of combustion products rather than the mass fraction of the oxygen.Various experiments have shown a constant ratio between the optical density and the temperature rise in the gas. Evans and Stroup [Soren et al., (1997)[46]] have reported a model to use smoke temperature as a measure of smoke density that takes into account the individual properties of the different fuel.

$D/\nabla T=3330.\rho\ C_P\ Y_s/Q$. Where Q is the convective heat release rate per Kg fuel burnt.

The optical density can also be expressed in terms of extinction coefficient, which is defined as $K= 1/l*\ln(I_0/I)$. The difference between the extinction coefficient, k, and the optical density, D, is the use of natural lgorithms and logarithms with the base 10.

$K=2.303 \times D$

Model Used in Zone Model Based (BRANZFIRE)

In code BRANZFIRE (BRANZFIRE 99.)[47] the following approach has been utilised.

Average extinction coefficient , $K_{avg}=K_mC_{soot}$ with $C_{soot}=Y_{soot}\rho_\infty T_\infty/T_u$. Where, Y_{soot} is yield of smoke, T_∞= Ambient temperature, T_u =Upper layer temperature, ρ_∞ =Ambient density and K_m particle extinction cross section (m^2/ kg soot), given by Beyler for flaming combustion as $K_m=10750\exp(1\text{-}4.95Y_{soot})$.

The maximum distance an observer can recognise an object, usually an exit sign, when viewing the object through smoke is by Beyler defined as the visibility, V,. He states that it has been widely found that the product VK_{avg} is a constant for a given object and lighting condition. The model uses a value of 2 for reflective sign and 5 for illuminated sign.

Model Used in CFD code Fire Dynamics Simulator (16)

The intensity of monochromatic light passing a distance L through smoke is attenuated according to $(I_0/I)=e^{(-K.L)}$. The light extinction coefficient, K, is a product of the density of smoke particulate, ρY_s, and a mass specific extinction coefficient that is fuel dependent $K = K_m\ \rho Y_s$ Estimates of visibility through smoke can be made by using the equation (S =C/K) where C is a non-dimensional constant characteristic of the type of object being viewed through the smoke, i.e. C = 8 for a light-emitting sign and C = 3 for a light-reflecting sign (Jin (1978))[48]; Mulholland, (2000)[49]. Since K varies from point to point in the domain, the visibility S does as well. This get converted into quantity Optical density via K/2.3 ($D= K \log_{10} e$)

Other Alternative Route for Visibility in CFD

From CFD calculations we get also estimate smoke layer height by using some simple calculation - quantity. The critical time t_{crit} to describe a typical exit sign fading to the smoke, The critical time tcrit gives us the visibility V in meters, which is the same as the path length, if whole path is along smoke layer. The more details about the approach and the related validation study is available in Rinne et al., (2007)[50].

CASE STUDIES FOR VALIDATION

The four full-scale experiments that have been simulated with CFD are a hospital bed in a large enclosure (Hans Hultquist, 2000)[51], a propane burner in a small enclosure (Gandhi, 1994[52], Hans Hultquist, 2000)[51], wood-stack fire in enclosure linked to staircase and polyurethane fire in enclosure. The test configurations, test data from these experiments and assumptions made while modelling these experiments are presented in the following sections. Soot yield values are used in all the simulations are taken from Tewarson (2002)[53].

Hospital Bed in Large Enclosure: This experiment consists of a typical Swedish hospital bed (made of polyester) in a *5.6 X 5.6 X 6* m (Length X Width X Height) enclosure. The material in all the walls, the ceiling and the floor was concrete. The only connection to the outside was a small opening, *0.4X0.2* m (Width X Height), down by the floor. The actual heat release rate of the single hospital bed is about 1.1 MW based on the amount of polyurethane (45 Kg) for a dimension of 1mX2m given by Yii (2000)[54] .

Propane Burner in Small Enclosure: This is a *3.66 X 2.44 X 2.44* m (Length X Width X Height) enclosure with a *0.76 X 2.13* (Width X Height) doorway opening in one of the short ends. The propane burner heat release was 40 kW for the first eight minutes and then increased to 160 kW . A composite material was mounted on the walls. However, this composite material didn't contribute very much to the flame spread and the heat release (Gandhi, 1994)[52] and hence effect of wall combustible material has not been modeled in the present study for flame spread the approximation that there is only propane burning is made.

Wood-Stack Fire in Enclosure Linked to Staircase: The fuel is a stack of wood-strips (pine) with a total weight of 100 kg. The enclosure in which the fire is present is of size *4.2 X 2.8 X 2.6* m (Length X Width X Height) with a *0.8 X 2.1* m doorway leading to the staircase. There are four stories in the staircase, floor 0 at ground level and floor 3 at top level. The experimental value of the optical density, here given as *OD*, is measured at floor 2 in the staircase. In the simulation the available heat release rate from naturally ventilated wooden crib fire test in the "blasted rock tunnel" has been used [Carvel, 2004][55].

Polyurethane fire in enclosure: The enclosure in which the fire is present is of size 2.5 *X 2.5 X 2.5* m (Length X Width X Height) with a *0.2 X 0.2* m slit leading to the atmosphere. The fire source consisted of one piece of polyurethane foam. From the DELTA experiment it was assumed that the heat release rate increased linearly from 0 kW at t=0 to 2.0 kW at t=80 seconds . The perforated suspended ceiling of the experiments is assumed to be absent in this simulation.

COMPUTATIONAL DETAILS

FDS was used as a tool to calculate the temperature field generated by the burner inside the room. The model used in this study does not incorporate fire spread, and the experiments also did not result in flame spread on the linings, which were non-combustible. Wall was modeled as heat conducting media using conjugate heat transfer approach. For this, the computational domain was made up of the indoor gas domain, 0.1m-thick ceiling, 0.1m-thick walls and 0.1m-deep solid floor. In this case, the computational domain and the boundary were extended to the exterior wall surface to take into account the heat transfer into the wall. FDS solves the radiation Transport equation (RTE) for radiation modeling. As the fire-generated buoyancy driven flow is turbulent, and results into natural convection, the LES turbulence model was employed to resolve the subscale turbulence. The fire source is taken as the input parameter, which is either a stable heat release rate that was designed to represent the experimental measured HRR by the calorimeter or equivalent HRR taken from reported data.

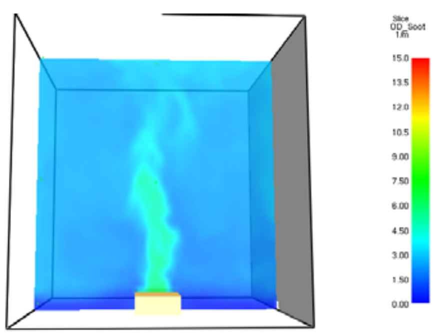

Fig. 1: Sooth optical density contour at 148.5 sec for Hospital Bed in Large Enclosure

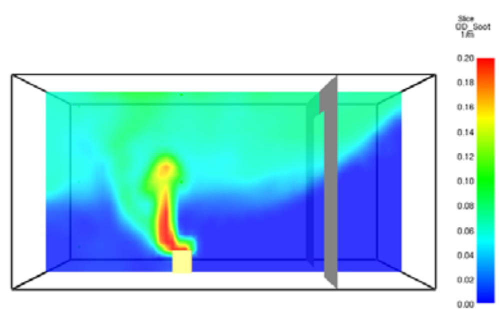

Fig. 2: Sooth optical density contour at 150.3 sec for Propane Burner in Small Enclosure

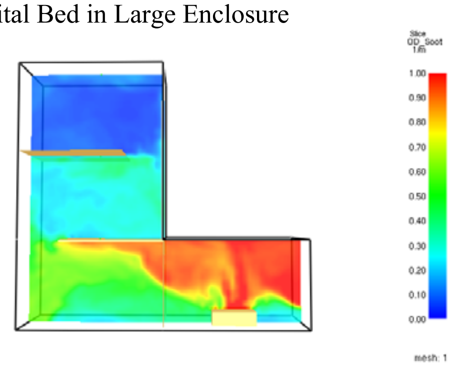

Fig. 3: Sooth optical density contour at 151.5 sec for Wood-Stack Fire in Enclosure Linked to Staircase

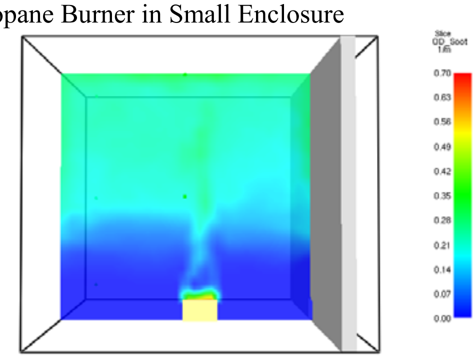

Fig. 4: Sooth optical density contour at 151.5 sec for Polyurethane fire in enclosure

RESULTS & DISCUSSION

As a fire scenario is transient, a smaller time step is taken in the initial stage of the fire to resolve the transient. The computational domain was divided in sufficient number of cells based on our earlier studies. From Fig. 1 to Fig. 4 depicts smoke soot optical density contours from these four experiments are extracted at around 150 sec for a quantitative physical interpretations. For more simulative view is in form of 3D iso surface of smoke sooth obtained from these simulations has also been studied. Simulated visibility from iso surface clearly gives a feel of vision obscuration due to fire generated smoke. In first experiment the smoke density is so much that we are not able to see the white background and the modeled bed . Visibility conditions are better in second experiment. The third experiment isosurface depicts that in the top staircase the white background is visible where as in the burn room the white back ground is not visible and infact the yellow wood crib equivalent object is also less visible. The fourth experiment has less visibility then second experiment but more visibility then third experiment. This qualitative visibility construct(not shown in paper due to page limitations) however depends on the defaults values of sooth and associated image processing procedure available in companion post processing software Smokeview. In order to validate the CFD code numerically obtained values at the top corner in the enclosure are compared with the experimental observation which are shown from Fig 6 to Fig. 9 respectively for all the experiments. The results are also compared with the authors earlier zone model based predictions. In all the simulations zone model predictions are generally found to be agree fairly well in the developing stage of fire. At this stage the smoke density value is very important for designing the fire detection system. At the developed stage of fire the zone model predictions do not closely match with the experimental values. But, the CFD computations are in good agreement with the experimental data for the complete fire duration. This studies conclude that the engineering CFD calculation are cable of simulating the visibility conditions in fire . This information is also useful for planning of escape routes for evacuating and access routes for fire fighting. In the fully developed stage of fire the CFD predictions marginally differ from the experimental values. These differences may be attributed to several unknown parameters in the available experimental data such as time to ignition, rate of consumption of burning material and to the lack of aerosol processes in present study. The fact that the present does not account for smoke particle adsorption on the building surfaces may be one of the reasons for the observed differences. Based on these studies it is concluded that the CFD based prediction are more reliable as compared to zone model based predictions and for engineering design and safety purposes the CFD based procedure can reproduced the visibility the fire affected enclosure.

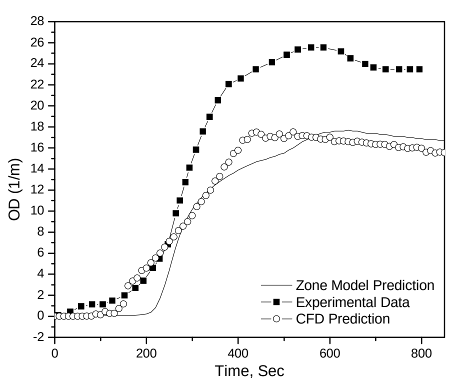

Fig 6: Sooth optical density contour at 148.5 sec for Hospital Bed in Large Enclosure

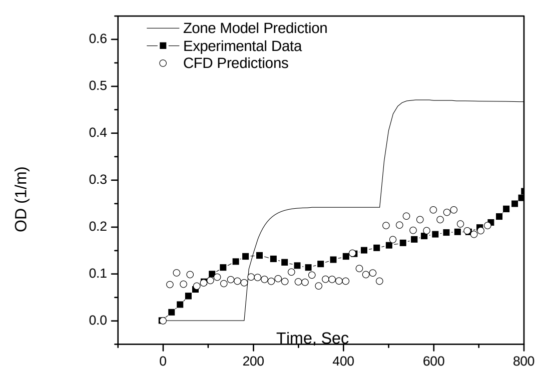

Fig. 7: Sooth optical density contour at 150.3 sec for Propane Burner in Small Enclosure

6. CONCLUSION

An attempt has been made to assess the capability of the present LES based CFD code Fire Dynamics simulator to predict optical density in the smoke-laden atmosphere of the fire-affected zones. The predictions of the code generally were in good agreement with the reported test data in the every stage of fire. It was noted that with similar input and assumptions the CFD based predictions were much improved as compared to zone model based predictions.

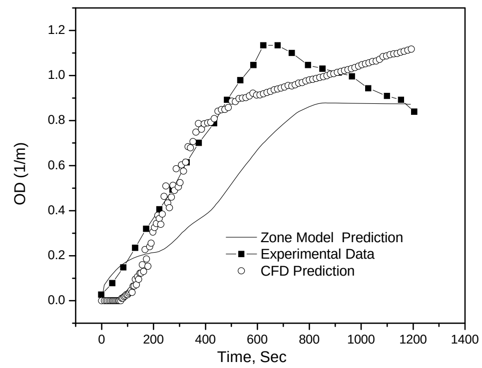

Fig. 8: Sooth optical density contour at 151.5 sec for Wood-Stack Fire in Enclosure Linked to Staircase

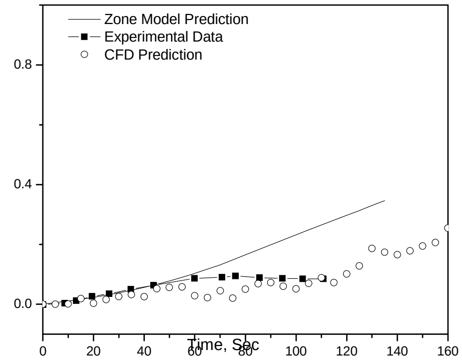

Fig. 9: Sooth optical density contour at 151.5 sec for Polyurethane fire in enclosure

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