13th Congress of Intl. Maritime Assoc. of Mediterranean
IMAM 2009, İstanbul, Turkey, 12-15 Oct. 2009

Numerical fire modelling for passenger ships

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ABSTRACT: Fire vulnerability is nowadays considered as a central issue of ship safety assessment at the design stage. This has motivated the introduction of detailed numerical modelling, in the hope of achieving more realistic evaluation of the growth potential and consequences of fire incidents on board. In this respect, the so called "zone" and "field" models are often discussed in the literature. Both types of models were used in the current work, in order to evaluate several fire scenarios, initially based on simplified geometries. Moreover, a field model was used in order to simulate with more detail the spreading of fire gases in the accommodation spaces of an existing passenger ship. Key habitability parameters were monitored, including temperature, heat release rate, carbon monoxide concentration and soot density. Animated snapshots of the conditions inside the compartments are shown. The main emphasis of the paper is to evaluating the prospect of using numerical modelling for practical fire vulnerability assessments of passenger ships.

1 INTRODUCTION

The fire on board the ferry Scandinavian Star in 1990 opened a new era for the role of fire safety assessment during ship design. The trend was further enhanced by the expansion of the cruise market and the increase in the size of modern cruise-ships which brought to the centre of attention the fact that, a large-scale fire accident could bear catastrophic consequences, threatening even the industry itself.

Detailed provisions of fire protection, fire detection and fire extinction are found in Chapter II-2 of SOLAS, a text that has been very significantly improved after 1990; and also in IMO's International Code for Fire Safety Systems, a collection firstly published in 2001. Unfortunately, there are lessons still to be learnt: The 2006 fire on the Star Princess started on one of the ship's balconies (an area at the time not covered by the regulations) and spread to nearby decks. New regulations for fire in open spaces were subsequently adopted at IMO, as further amendment to SOLAS.

Despite the progress in the prescriptive regulatory framework, innovative design solutions are difficult to adapt to a prescription-based approval process. The so called "performance-based" assessments are thus gaining support, both for ship design and operation. Naturally, assessment methodologies of fire vulnerability with a probabilistic character have already apeared in the literature (Kaneko et al. 2004; Fucuchi & Imamura 2005; Guarin et al. 2007). Even however within the probabilistic framework, the investigation of deterministic fire scenaria on the basis of physics-based numerical models remains as an essential element of the assessment process. In simulating fire growth, the current trend is characterised by a transition from the simpler to the more complex: respective approaches are labelled as "network", "zone" and "field" (CFD) models.

Network models are the simplest of all, with each compartment appearing as a single node. Fire and Smoke SIMulator (FSSIM) is a network model example, developed for simulating fire growth and smoke spread on naval vessels (Floyd et al. 2005).

The Consolidated Model of Fire and Smoke Transport (CFAST), a two-zone fire model, has been developed by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce. It is a code that is primarily used for simulating the impact of fire within a specific building environment. With CFAST one can determine the evolution of gases and temperature in time and in space during a fire, for a number of compartments. The potential of CFAST to aid ship design was acknowledged from quite early (see for example Bailey & Tatem 1995) and attempts to integrate it with risk analysis were presented: for example, in a risk analysis tool called Probabilistic

Fire Simulator (PFS), Monte Carlo simulations were used in order to determine the distributions of the output variables of CFAST (Hostikka et al. 2003).

Inevitably, as more computer processing power becomes available at lower cost, "field" (CFD) models gain in popularity. It is worth noting that, whilst in non-fire CFD models the flow is determined by the boundary conditions, in fire models flows are defined additionally by the combustion process details and thus extra input is required for running such codes. A number of general purpose CFD codes have been used for fire simulation; a well known example is CFX by ANSYS. Also, fire dedicated CFD codes have been developed, such as JASMINE by the Building Research Establishment (BRE, UK). The SOPHIE (Simulation of Fires in Enclosures) is a fire CFD model put forward by a consortium of European Laboratories, coordinated by the University of Cranfield. SMARTFIRE is another CFD fire simulation environment, developed by the Fire Safety Engineering Group (FSEG) of the University of Greenwich.

The Fire Dynamics Simulator (FDS) is a CFD model of fire-driven fluid flow representing, in our view, the state-of-the-art in fire simulation computing technology. It is developed by the NIST in cooperation with VTT Technical Research Centre of Finland. The software 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. The Smokeview (SMV) is a visualization program that can be used for displaying the output of both FDS and CFAST simulations (Forney 2007).

In the present article the aim is to take a few steps towards evaluating the potential of some modern numerical tools for performing fire safety assessments of ships. The article begins with a brief overview of fire phenomena, followed by a discussion of issues connected with the modelling of ship fires. CFAST and FDS are selected for further implementation and characteristic comparisons of predictions between the two models are presented. Thereafter, FDS is considered for more detailed investigation, targetting the conditions inside the realistically modelled accommodation spaces of an existing ferry. The lessons that were learnt from the use of these tools is summarised in the final section.

2 FIRE ESSENTIALS

In our context, the word "fire" is interpreted as unwanted combustion where the "fuel" is not intended as such. Solid and liquid fuels burn only if converted into the gaseous phase. Pyrolysis of solids produces volatiles which form a complex combustible mixture. Fire is an interactive nonlinear phenomenon. A portion of the heat generated by a fire is radiated back to the fuel contributing to pyrolysis. The burning rate of fires and the spread of smoke and hot gases are determined by the turbulent mixing of the fuel vapours and combustion products with the local atmosphere surrounding the fire. Turbulent combustion may be premixed, non-premixed or partially premixed. Chemical reactions take place within thin diffusion zones. A fire may be *fuel controlled* or *ventilation controlled.*

The phenomenon of *flashover* within an enclosure is the rapid transition from the fire growth period to the fully developed stage due to total fuel involvement (Bishop et al 1998; Drysdale 1999). *Backdraft* is a hazardous situation when inflowing air, mixes with unburnt gases creating locally a combustible mixture of gases (Karlsson et al. 1999). *Rollover* and *the trench effect* are phenomena linked to backdraft and flashover. *Door jets* may affect the plume of the fire. The *ceiling jet* of a fire may be crucial for thermal detector activation time.

Practical mathematical models of fire are inherently complex. Fluid mechanics, heat/mass transport and chemical kinetics are involved. Almost all aspects of fire modelling are active research areas. Reasonably, balance is sought between an enormous number of possible scenarios and computing power (McGrattan et al. 2007).

The heat release rate (HRR) is a very important variable in describing a fire hazard. A high HRR is the cause of high temperatures and high heat fluxes. Toxic gases and soot are also correlated with HRR. Since a high HRR indicates a serious threat to life, IMO gives guidelines for the calculation of the total amount of combustible materials per unit area (IMO 2003). The Scandinavian Star incident showed that the laminated plastic coatings on the walls and ceilings of corridors, although only about 1.5 mm thick, had significant contribution to fire growth.

Carbon monoxide is the most important toxic product of fire. The effect of human exposure to carbon monoxide depends on gas concentration and also on the duration of exposure. These factors influence critically the ability of a human to find and pursue an effective escape route. In the Scandinavian Star, within 8 to 12 minutes of fire ignition, most of the corridors where people eventually died were filled with smoke. In that incident, the complex role of the ventilation system was also revealed. While it was operating it prevented the spread of smoke into cabins; but during the initial stages of the fire it determined the route by which the fire spread.

3 MODELLING OF FIRE ON SHIPS

Fire models can be used on standalone basis or in combination with other tools, for a number of tasks:

- For the reconstruction of ship fires during accident investigation and for assessing habitability within ship compartments, often in combination with an evacuation model. With the art of evacuation modelling progressing, the prospect to achieve integration of fire and evacuation assessments has become viable (see FDS + Evac by VTT, and also Vassalos et al. 2008; Deere et al. 2009).
- For evaluating hull strength, as impaired by the fire, by supplementing the investigation with a suitable finite element analysis.
- To perform risk assessment at the design stage.
- To investigate several design issues: for example, it is known that SOLAS includes regulations for the division of the ship into main vertical zones, the separation of accommodation spaces from the remainder of the ship, restricted use of combustible materials, detection of any fire in the zone of origin, containment and extinction of any fire in the space of origin, protection of the means of escape or of access for fire-fighting purposes, readily availability of fire-extinguishing appliances and minimization of the possibility of ignition of flammable cargo vapour. The above matters can be studied and better understood using fire modelling. The role of ventilation equipment like fans, blowers, exhaust hoods, HVAC ducts, smoke management systems and sprinklers may also be evaluated by fire models.

These notwithstanding, several issues need to be considered when a fire model is applied to a ship. For example, codes are usually designed for fires in buildings and they do not take into account ship motions. Also, most validation work has been based on building fires. Notably, it is not unusual even the experimental data to be contradicting.

According to empirical observations of compartment fires, stratification of the combustion products occurs. Zone models, such as the CFAST, are based on the assumption that a zone containing the hot gases and other products of the combustion occupies the upper part of the compartment. A cooler zone remains in the lower part, free of smoke and soot. As the fire grows, the hot products of combustion are convected through the plume to the upper part of the compartment. The zone models are essentially systems of equations describing the dynamic relation between the zones. The modelling equations used in CFAST are derived using the conservation of mass, the conservation of energy, the ideal gas law and relations for density and internal energy. The equations predict, as functions of time, quantities such as pressure, layer height and temperatures, given the accumulation of mass and enthalpy in the two layers. The zone model implies a sharp boundary between the upper and lower layers. In reality, the transition is typically over about 10 % of the height of the compartment and could be larger in a weakly stratified flow.

In field models like the FDS, the user specifies the dimensions and properties of the structure of interest, dividing it into small computational cells. To model the movement of fire gases, the model computes the density, velocity, temperature, pressure and gas concentrations in each cell, based on the conservation laws of mass, momentum and energy. It requires as input the material properties of the furnishing, walls, floors, and ceilings.

One expects field models to provide a clearer understanding of the complex fire mechanisms. However, as a fire model becomes more complex several issues arise, such as computing power management and validation. A good principle is that, routines should consume CPU time in proportion to their importance. An algorithm that increases the calculation time but yields a marginal improvement in accuracy is not likely to be implemented. In FDS, the radiation transport algorithm consumes about 25 % of CPU time, based on the fact that about 25% of the fire's energy is emitted as thermal radiation (McGrattan et al. 2007).

The zone models have less computational complexity and naturally they have found application in a wide range of fire protection investigations. Fewer simplifications imply the need to know a larger number of fundamental parameters that need to be extracted from experiments. A thorough validation of a CFD model would require many thousands of measurements and, in the current circumstances, practically infinite time.

Describing the materials used in ships is a very significant issue. Thermal properties, such as conductivity and specific heat, are the easier to be found. Others, like the burning behaviour of materials, is difficult to obtain. Validation issues with the material database also arise, concerning the reliability of small scale tests when used for reproducing the larger scale behaviour of the material. From the material perspective, the user of the code is responsible to verify and validate the model.

In general, there is lack of sufficient experimental fire data, especially for ship fires (Larsson et al. 2002). When experiments are conducted, often insufficient data are recorded. The burning behaviour of a material may vary with different heat fluxes and it is difficult to find information to the desired extend. A database with material properties would entail a model-specific methodology for obtaining the data in the first place. As it is discussed among the developers and users of the FDS code, the existing standardized test methods have not taken into account the specific needs of fire models for thermal properties, reaction kinetics or radiative characteristics. Since the combustion models of the fire codes continually change, model-specific standardized tests are not easy to define.

Scenario specification is critical for safety assessment. From a philosophical perspective it addresses the interface between technology and society (Brannigan et al. 2000; Skjong et al. 2007; Papanikolaou 2009). However, in the following sections the selected fire scenarios are only illustrative of the use of the CFAST and FDS codes. For fuller understanding of these codes one should consult the relevant documentation (McGrattan et al. 2007; Jones et al. 2005; Peacock et al. 2005).

4. FIRE MODEL IMPLEMENTATION

4.1 *Zone Model*

CFAST predicts the temperatures of the upper and lower gas layers within each compartment, the ceiling, wall, and floor temperatures within each compartment, the visible smoke and gas concentrations within each layer, object temperatures and sprinkler activation time. The timing of specific events, such as the activation of detector or sprinkler, the occurrence of flashover etc., can be estimated.

It is important to state that CFAST does not evaluate the HRR but accepts the HRR curve as an input. Burning constrained by the available oxygen is taken into account. CFAST does not account for increased pyrolysis due to radiative feedback. Consequently, the user must account for interactions between the fire and the pyrolysis rate. Thus, careful selection of the fire size is necessary for accurate predictions. In experimental conditions this is an important consideration. There are limitations inherent in the assumptions used in application of CFAST. For example, the maximum number of compartments is thirty. For many passenger ships, the number of cabins exceeds this number by far so further geometry simplifications would be required.

For a brief demonstration, a deck configuration with simplified geometry was created and the fire's HRR was set to the constant 250kW. In Figure 1 the rough plan of a 20 m long deck with 9.5 m width is shown. A long corridor 20 × 1.5 m is located between two rows of 5 cabins each. The fire is assumed on the floor of cabin R1. At the left end of the corridor there is a safety exit which may be open or closed. The walls are assumed incombustible. No more fire objects were assumed. The model can predict the transport of heat and combustion on the deck. The computational space may be regarded as host of a dynamical system with an excitation characterized by the HRR value. A transient and a steady state response should be expected.

Figures 2 to 5 show the time histories of temperatures and layer heights for cabins R1 and R10 respectively. Two scenarios are presented: one with corridor door open and the other with door closed. While the transient part of temperature and layer height variation is fairly similar in the two scenarios, the steady state parts differ. Difference is observed because the closed door causes oxygen starvation in R1, as is verified from Figure 6. In the open door scenario the height of the lower zone of R1, in the steady state, remains about 1 m, because of incoming air stream to the lower zone. Differences observed to the patterns between R1 and R10 are owed to the fact that, in cabin R1 the incoming air is driven to the lower zone, while in R10 the air is supplied to the upper zone.

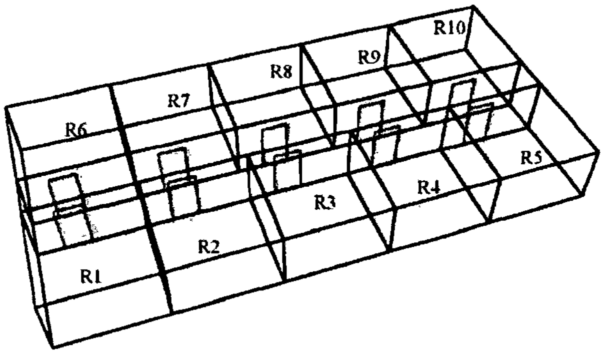

Figure 1. Fire zone with simplified layout.

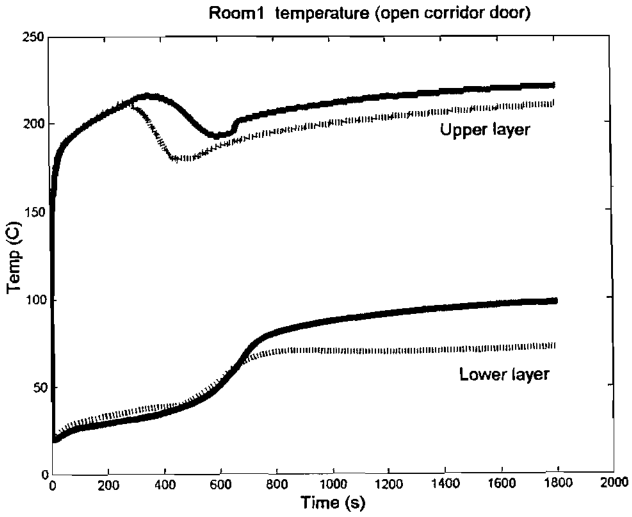

Figure 2. Temperatures in R1. The continuous line corresponds to open corridor door; the dotted line to closed corridor door.

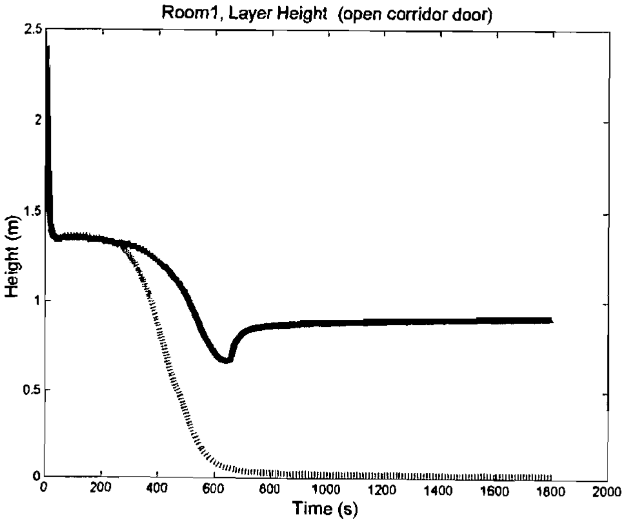

Figure 3. Layer height in R1 (line types defined as in Fig. 2).

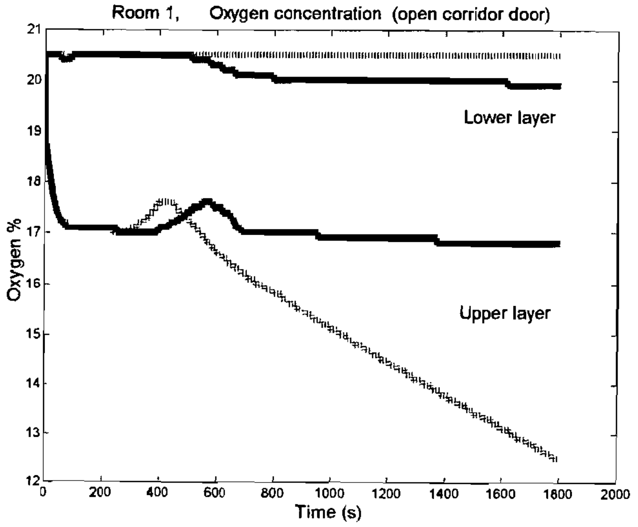

Figure 6. Oxygen concentration in R1 (line types as above).

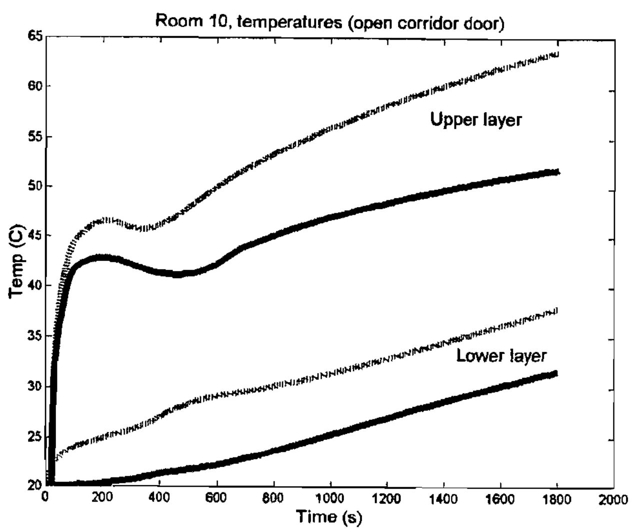

Figure 4. Temperatures in R10 (line types as above).

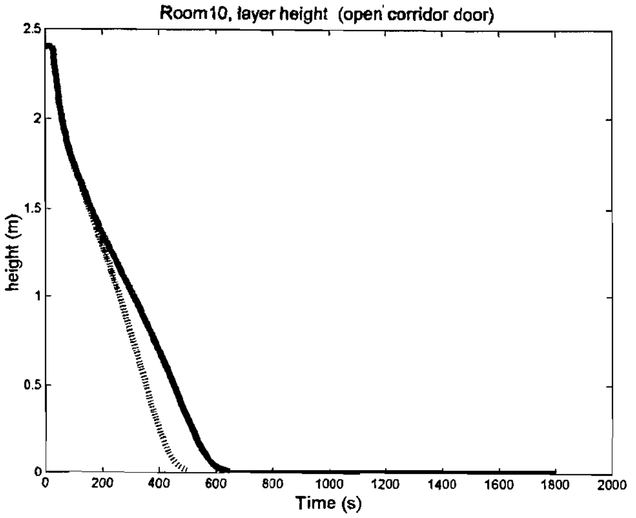

Figure 5. Layer height in R10 (line types as above).

4.2 *Field model*

FDS computes the temperature, density, pressure, velocity and chemical composition within each numerical grid cell at each discrete time step. In addition, FDS computes at solid surfaces the temperature, heat flux, mass loss rate, and various other quantities. Within each cell the gas velocity, temperature, etc., are assumed to be uniform, changing only with time. For a given computational space, the precision of the simulation depends on the number of cells that can be incorporated. This number is practically defined by the available computational resources.

The FDS code includes a hydrodynamic model, a combustion model and a radiation model. Sub-grid scale models describe the phenomena that cannot be solved with the computational grid. In order to reduce the computational load the Large Eddy Simulation (LES) approach is used for the modelling of turbulence. The basic assumption is that the eddies that control the mixing are large enough to be calculated with reasonable accuracy from the equations of fluid dynamics and that small-scale eddy motions can either be crudely accounted for, or be ignored. As a first step, the default values of FDS were used for the critical parameters.

The combustion model uses a single step chemical reaction whose products are tracked via a two-parameter mixture fraction model. A two-step chemical reaction has been recently added to the code, with the first step being oxidation of fuel to carbon monoxide and the second step the oxidation of carbon monoxide to carbon dioxide.

Radiative heat transfer is included in the model via the solution of the radiation transport equation for a gray gas. Liquid droplets can absorb and scatter thermal radiation. This is important in cases involving sprinklers.

Rectangular obstructions are forced to conform with the underlying mesh. Parallel processing is possible. Low gas velocities are assumed (Mach numbers less than 0.3).

The efficiency of FDS is due to the simplicity of its rectilinear numerical grid and the use of a fast, direct solver for the pressure field. This can be a limitation in ships where certain geometric features do not conform to the rectangular grid. Cells must be as uniform as possible. Objects smaller than a single grid cell are either approximated as a single cell, or rejected. Cells that have an aspect ratio larger than 2 to 1 may cause numerical instabilities. Due to the above limitations, simulation of thin walls between cabins of a ship may result in a great number of cells of the computational space. Cell uniformity issues are induced by the small height to length ratio of decks.

a) Comparison with CFAST

The simple geometry scenarios of Figure 1 were also run using the FDS code. The data obtained from the two codes, although in some agreement, have also differences in nature and quantity. The two models are more easily comparable at early stages of the fire, when the properties of the surrounding materials do not play significant role. Flashover can be studied by both CFAST and FDS. However, backdraft or other explosive phenomena, where flow speeds approach the speed of sound, cannot be studied by either code.

In order to show the difference in the results, in Figures 7 to 9 are illustrated some details of the distribution of temperature inside the cabin R1 which could not be derived by using CFAST. Moreover, the processes of ceiling jet and upper/ lower zone formation which are hardly treated by CFAST, can be handled in detail by FDS. It should be noted here that, some part of CFAST's output is basically insensitive to variations in the input. For example, the position of an opening between two compartments does not affect the results.

Unlike CFAST, FDS may be sensitive even to the mesh density. Figure 10 illustrates temperature fluctuations calculated by FDS when only the mesh density varies. The data converge, but in many cases the observed convergence seemed ambiguous. By increasing mesh density, precision is linearly increased but accuracy is still a question.

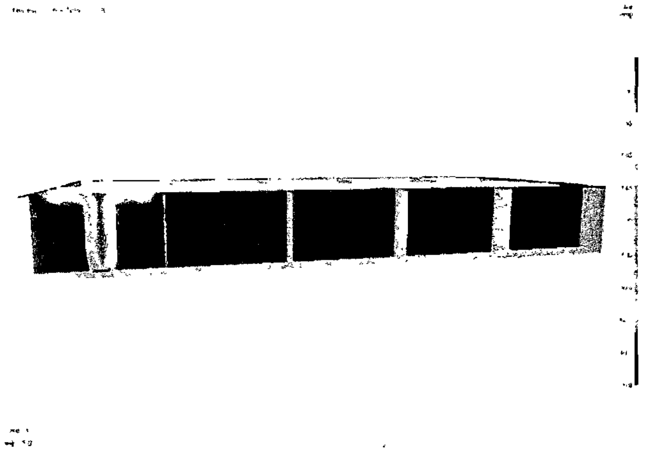

Figure 7. Temperature distribution in a vertical slice. Ceiling jet in R1 using FDS.

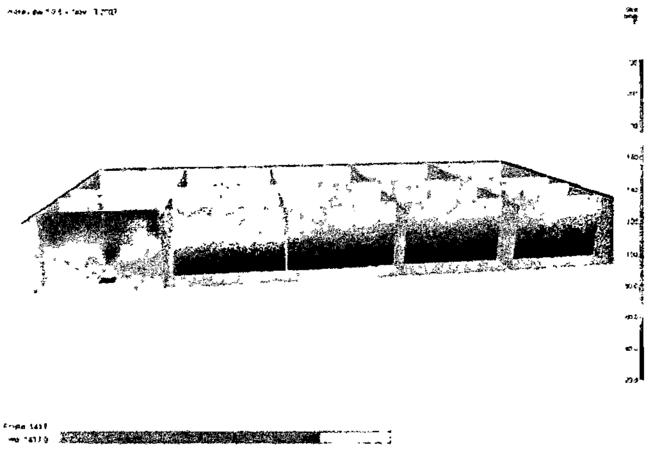

Figure 8. Temperature distribution in a horizontal slice.Upper zone formation in R1 as calculated by FDS.

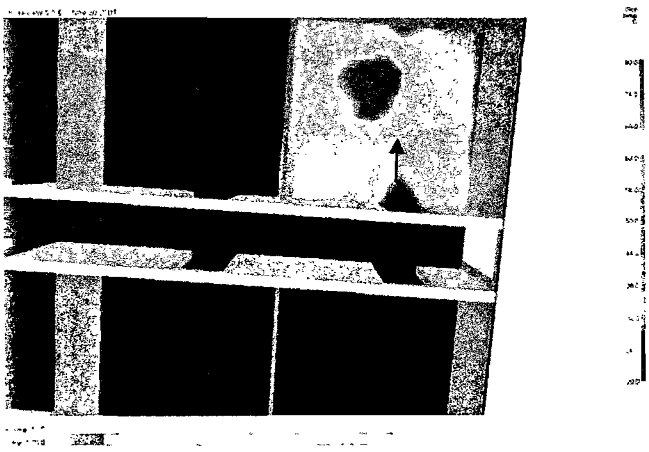

Figure 9. Temperature distribution in a horizontal slice in the lower zone of R1. Incoming air stream is calculated by FDS.

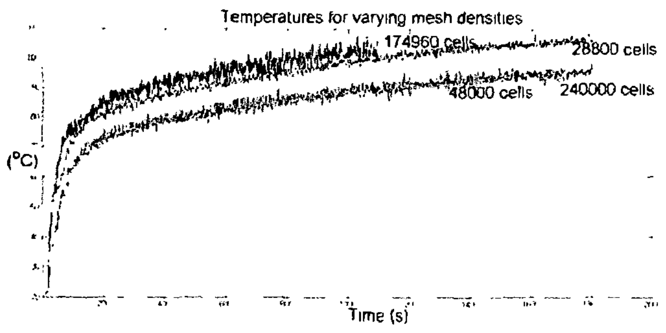

Figure 10. Fluctuations of temperatures at two different points calculated by FDS when only the mesh density varies.

b) Detailed modeling of fire on a ferry's deck

In Figure 11 the top view of the deck of an existing passenger ship is shown. The width of the deck is approximately 17 m. It has three main vertical fire zones (MVZ) and the length of each zone is approximately 24 m. Combustible furniture and floor/wall linings are assumed. Fir ignition is assumed to have taken place in a cabin.

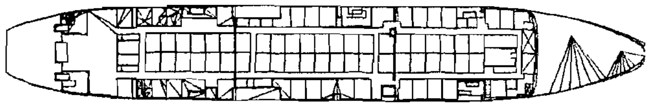

Figure 11. The investigated deck of the existing passenger ship.

In Figures 12 to 13 are shown two instants of soot propagation inside the relevant fire zone. The so called "slice files" are used for storing the soot density and other gas concentrations at any node of the computational space. In Figures 14 and 15 can be seen the condition in the corridor, as determined by the concentration of soot, during the transient phase of upper zone formation. In Figure 16 are shown the time histories of the temperature in the corridor, recorded at various distances from the point of ignition.

Although CFAST allows some time for upper zone formation in long corridors, FDS is much more precise on those transient phenomena which are very significant for fire detection and passenger escape. In Figure 17 is shown the effect of the duration of the initial fire. The continuous line illustrates the HRR when the initiating fire is maintained throughout the whole simulation time. The dotted line shows the HRR when the initial fire is kept only for 40 s. One observes that the pattern of HRR is simply delayed. In Figure 18 the extinguishing effect is shown of a sprinkler on the HRR.

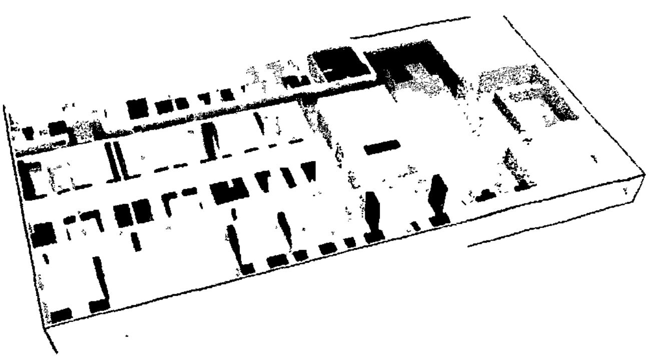

Figure 12. Initial stage of soot propagation in a fire zone.

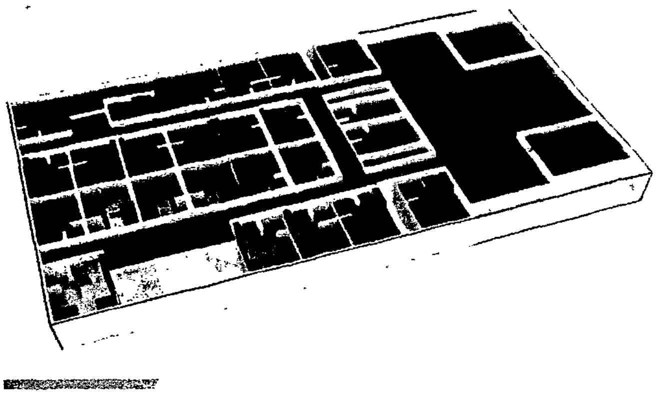

Figure 13. Advanced stage of smoke propagation in a fire zone.

Figure 14. Formation of upper zone in corridor.

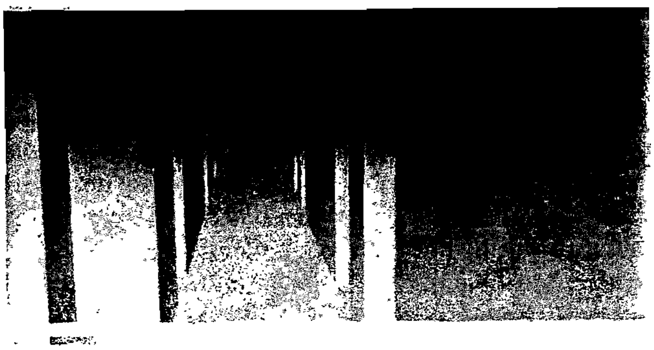

Figure 15. Further stage of upper zone development.

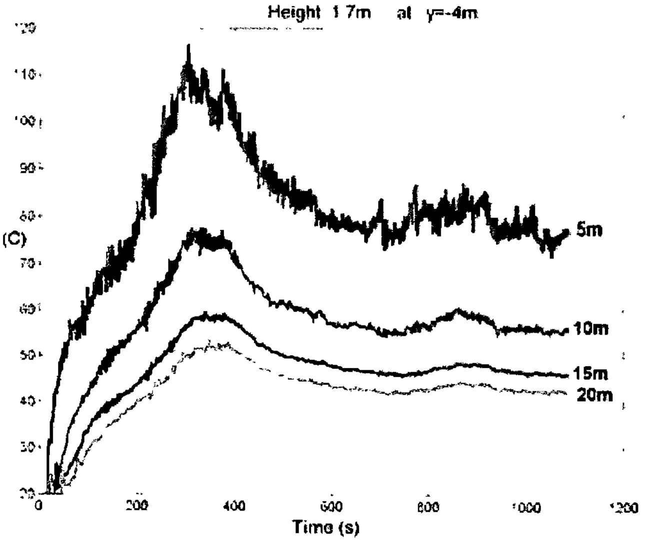

Figure 16. Histories of temperature in the corridor, at several distances from the point of ignition.

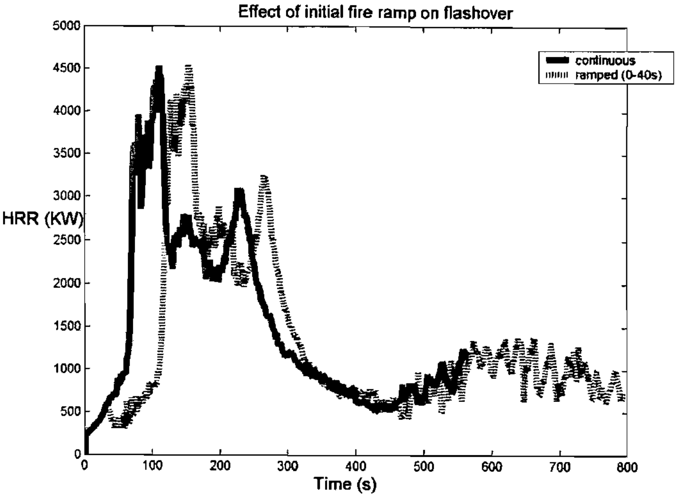

Figure 17. Effect of initial fire duration on HRR

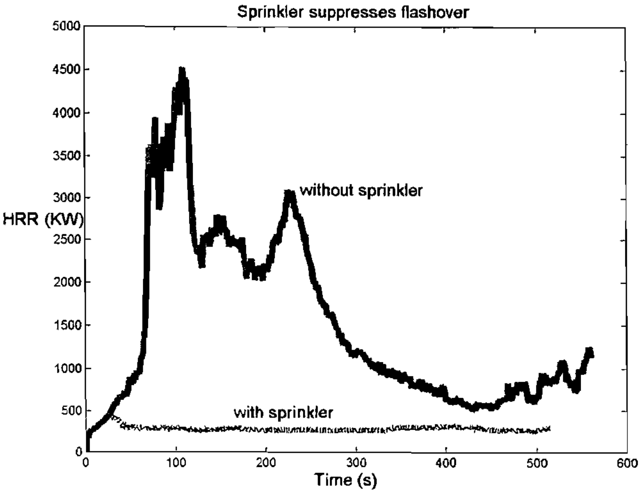

Figure 18. Effect of sprinkler on HRR. The sprinkler is activated at 74°C.

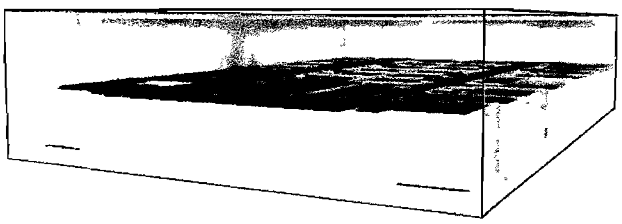
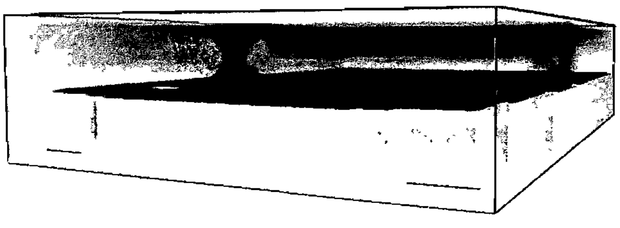

Figure 19. Soot propagation on the upper deck (deck plate has become transparent for better illustration).

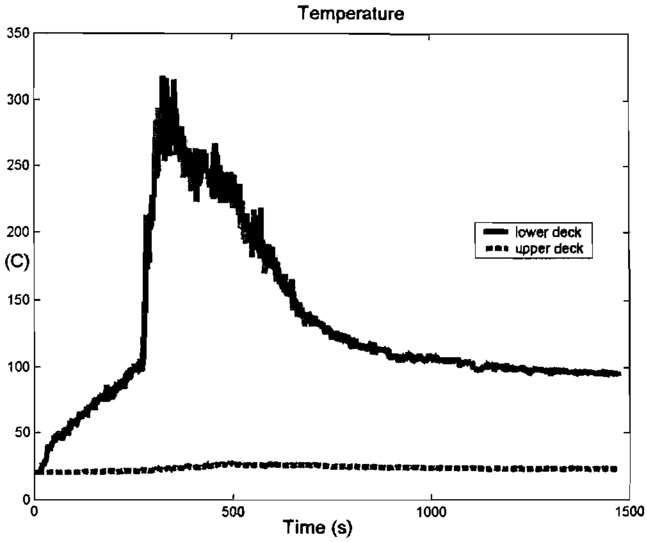

Figure 20. Comparison of temperature (upper and lower deck).

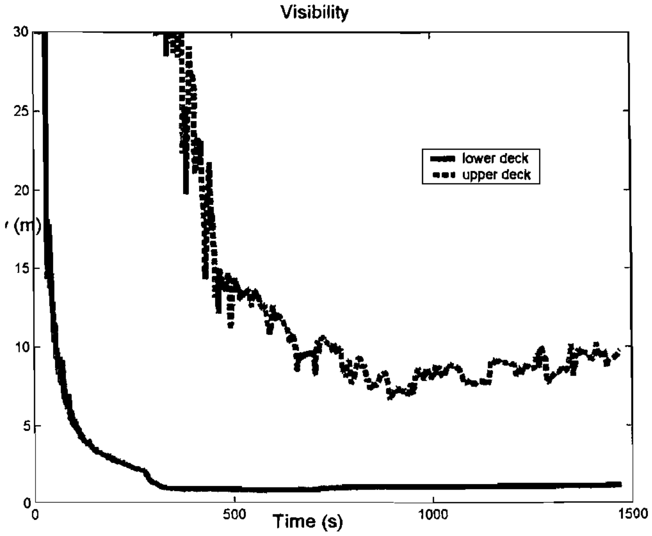

Figure 21. Comparison of visibility (upper and lower deck).

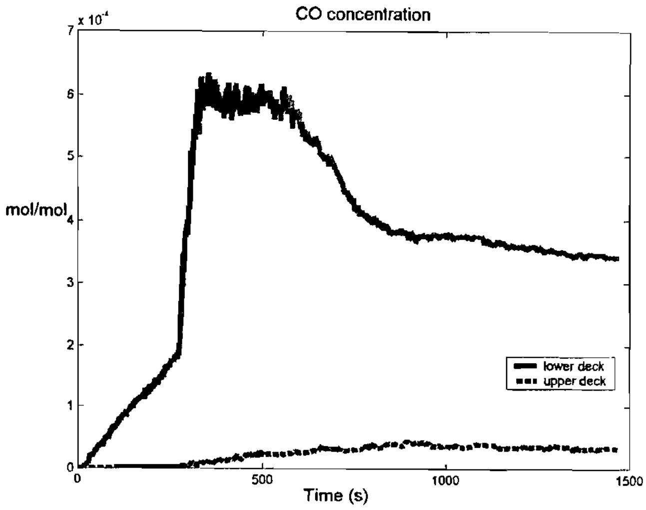

Figure 22. Comparison of CO concentration.

Figure 19 refers to a more advanced scenario: the effect on the upper deck of a fire that had started at the lower deck, within the same vertical zone. Soot propagates to the upper deck through the stairs. The upper deck has been simulated as a uniform space. The ceiling of the lower deck appears as transparent, in order to facilitate the visual obsrvation of the two decks. In Figures 20 to 22 are shown comparisons of temperature, visibility, and carbon monoxide between two points of the lower and upper deck. As noticed, the main hazards are the CO and the soot.

FDS could simulate several effects that CFAST could not. In CFAST, the exact position of several objects did not affect the results and multiple fires were treated as totally separate entities. A burning object near an opening did not affect the inflow of air and the entrainment of gases into the plume. FDS could detect mixing between the layers at their interface, caused by ventilation. Door jet mixing has been included in CFAST, but downward wall gas flow due to reduced buoyancy is not included. FDS can take into account interactions of gases and walls.

The CPU time for the above scenarios was about 2.3 s/simulation step, when the simulation time step is 0.02-0.03 s (CPU Pentium 3.4 GHz, RAM 4GB). Days or weeks may be required, depending on the length of real time and on the variables that are required to be calculated or recorded during the run.

CONCLUDING REMARKS

As general conclusion, the understanding of the basic principles of fire models combined with appreciation of their potential and limitations are crucial factors for a valid and reliable application of such models in ship fire safety assessments.

CFAST may be suitable for "design fires", prescribed either by regulatory authorities or by engineers, interested to model the transport of smoke and heat. However, fires in open spaces, like cabin balconies, cannot be analysed using zone models. The maximum number of compartments allowed in CFAST, due to instabilities, poses a limitation on the number of cabins in scenarios of passenger ship fires. In later stages of the fire, results from CFAST are more likely to be in disagreement with results from FDS.

FDS is an open source deterministic model, but its complexity may lead to its use as a 'black box'. Fire growth and spread requires a higher level of user judgment. While the analysis of toxic gas propagation is a mature field, the study of the production rate of toxic gases is still undeveloped. In a decision context for ship design, uncertainties of various types are included and many hundreds of executions of the code may be required, resulting in enormous computational time. In order to make the field model practicable for ship design, uncertainties must be reduced. Epistemic uncertainties, which have often reducible nature, call for a systematic model validation of ship fire conditions. Aleatory uncertainties on other hand about the input of the model, which have a rather irreducible nature, are inevitably present. For example, the behaviour of crew or passengers may alter some basic fire scenario assumptions. The furniture of a ship during its function may differ from that assumed at the design phase. Sprinklers may fail, smoke control system may not work. In order to reduce aleatory uncertainties, the effect of data inadequacy on the prediction capabilities of the field model needs to be systematically explored.

As mentioned, thermal properties of materials are more easily found. If the structural strength of a ship that is under fire is analysed, a better accuracy of the thermal properties of stucture materials may be required and less uncertainty may be tolerable.

Unfortunately, the values of material properties needed for solid phase combustion introduce both types of uncertainties. There are no standardized test methods combatible with FDS parameters and the respective values must be searched at different sources. In case of inadequate experimental data, a suggestion among the users is, to use FDS in order to set up a virtual cone calorimeter and adjust the material properties until the calculations match the given experimental data.

However, to make FDS useful in ship design, it is necessary to build a stadardized combustion database combatible with FDS parameters. Building of such a database is not a trivial task, because the combustion models of fire codes are a very active research area and the required parameters may change in number and in content.

It is understandable that the development of robust and accurate field models represents groundbreaking work that goes along with the improvement of computational resources. As computing power is increased and combustion models evolve continually, it is likely that in the future, inclusion of the compressibility effects will allow analysis of explosion phenomena too. Toxic gases may be more effectively induced in combustion models.

On the other hand, the zone models, due to their simplified assumption of uniform gas zones, cannot be systematically improved. However, for probabilistic analysis, the relative insensitivity of zone models to the input and their simplicity, still render them a useful tool, of course with some rigid limitations. In one known case, zone model results were combined with the results of field models (Hostikka 2008). However, if the results of the two models differ considerably, whereabouts the true solution lies is still a question.

ACKNOWLEDGMENTS

This work have been partly supported from the project VELOS, funded by the Greek General Secretariat of Research and Technology; and also from the project FIREPROOF funded by the European Commission.

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