NUMERICAL STUDY OF POOL FIRES IN MILITARY WARSHIPS

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ABSTRACT

Fire poses a possible banger to warships both in times of war and peace. Unlike residential and industrial buildings, an fire in a warship is compound by the multi-cabin geometrical configuration, the high conductivity of steel structure and the external wind effect. Recent progress in computers, both speed and memory size enabled the development of mathematical modes capable of handling such a complicated problem as the dynamics of fire in transient three-dimentional muti-cabin configuration. The present study reproduces experimental measurements obtained from the British DRL(Defense Research Laboratories) for a pool fire generated of varying heat release rate in a source of 0.3 x 0.3 m tray. The mathematical model used in the present study SOFIE (Simulation of Fire in Enclosures) has been developed by a consortium of European Institutions and incorporates. The code features of current computational fluid dynamics models including turbulence, combustion, and radiation.

The combustion is modeled by the eddy break-up model. The results shown in the paper include a validation exercise where the simulated values are compared with transient temperature measurements as well as gas velocity and species concentration. The comparison between experimental measurements and predictions is considered reasonably satisfactory based on the selected assumptions regarding the fire growth models and the walls boundary condition, a sensitivity test performed to study the effect of the wind direction and magnitude on the fire scenario. The study demonstrates clearly the amount of experience that can be obtained within economical boundaries for such a rare, but deadly dangerous possibility of fire in warship.

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INTRODUCTION:

Fires burn fast in rooms. This is because the smoke enclosed in the room radiates more heat to the fire. This means that adjacent items can ignite quickly as well.

A fire cannot continue without air. So if all the doors and windows in a room are closed, and the windows do not break, the fire will probably stop.

But if there is an open window or door, fresh air feeding the fire can flow in, and smoky gases will flow out (fig 1) [1]

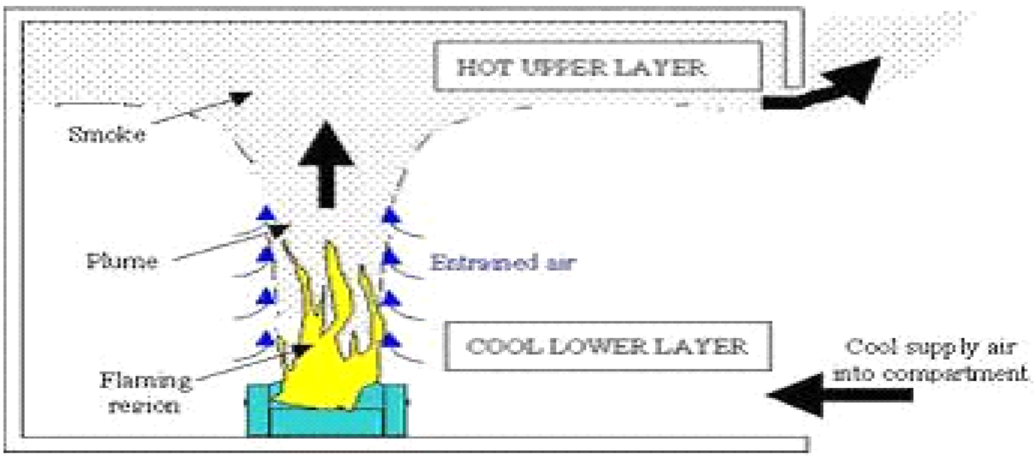

Fig (1) Compartment Fire Environment [1]

Usually the hot smoky gases will form a layer in the top of the room and there will be a clearer layer of cool air near the floor. This air is drawn into, or entrained into the smoke plume that rises from the fire. As the fire grow the smoky layer descends closer to the floor and becomes hotter and blacker.

At this stage conditions are very dangerous for anyone left inside the room. Also the hot smoke that is flowing out of the door is moving around the rest of the building, threatening people who are elsewhere.

The temperature of the hot smoky gases at the time of flashover is about 600°C. This is extremely hot, nearly red hot. But after that the temperature of the room may climb to over 1000°C. The room will carry on burning unit it has consumed all the fuel, or until firefighters put it out

Since fires grow so fast and become deadly so quickly, it is important that we detect them early. There are a number of different ways to detect a fire. Smoke detectors look for reduction in visibility caused by sooty gases. Instead, they may be able to detect the small charge that exists on smoke particles.

TURBULENT MODEL

Turbulent fluid motion is an irregular condition of flow which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned. One way to account for turbulence is to solve the conservation equations expressing the instantaneous flow variables with time in such a manner that they yield the rapid fluctuations of variables with time [2]. Such an approach is called Direct Numerical Simulation. (DNS). The currently available computer storage limits DNS to low Reynolds numbers .Thus at present, the consideration of some types of averaged quantities in turbulent flows is required.

k-ε TURBULENT MODEL

The k-ε model is one of the most frequently used two-equation model[3].

COMBUSTION MODEL

Combustion is a chemical reaction between fuel and oxygen forming products, and transforming the chemical bond energy to thermal energy. There are two major reasons for modeling combustion, namely that:

.It allows for the simulation of fuel-oxidizer process.

.It allows for the prediction of chemical species concentration. There are two combustion models used for different applications, namely the eddy breakup model and the laminar flamelet combustion.

EDDY BREAKUP MODEL

The eddy breakup model combustion is assumed to be infinitely fast and allows a single step stoichiometric chemical reaction[4]. For this reason, it can be assumed that the rate of combustion will be determined by the rate of intermixing of eddies in the turbulent flow field. Three subprocesses will then control the reaction rate; these are the turbulent dissipation of fuel, oxidant and products.

RADIATION MODEL

Radiation plays an important role as a heat transfer mechanism in fires. The radition Models used is a radiation transfer equation (RTE). A method for the prediction of the radiative properties for relevant combustion gases and soot particle. Finally, a suitable solution method is required [2].

RESULTS AND ANALYSIS

The present work provides the validation of the mathematical model by comparing its results with the experimental measurements reported by Yehia et al [5]. The case under consideration is a fire in a multi-room compartment cabin's ship. The effect of radiation on the environmental conditions exhibited inside the compartment is taken into consideration. The model is then used to identify the effect of changing the direction of the wind on the fire and smoke behavior in the military warship's cabin. In the present study, the mathematical model was validated through comparison with experimental results obtained for three wind directions. Wind directions are changed from the east position to the nutral (normal to the vent axis), and to the west position with respect to the vertical line of the inlet west vent [A] as shown in figure (1). The wind had 2.5 m/sec velocity, coming from the west side of the first room-fire room- outer vent with 36^o angle with respect to the horizontal middle vent plane.

GEOMETRICAL CONFIDURATION AND COMPUTATIONAL GRID:

In the second case the wind was 2.5 m/sec velocity, affecting at the center of the outer vent with zero-angle with respect to the horizontal middle vent plane(nutral position). as shown in fig (2a).

The third case, the wind was 2.5 m/sec velocity, coming from the west side of the first room-fire room- outer vent with -36^o angle with respect to the horizontal middle vent plane as shown in table (1). Geometrical grids and boundary conditions are shown in fig (2-c).

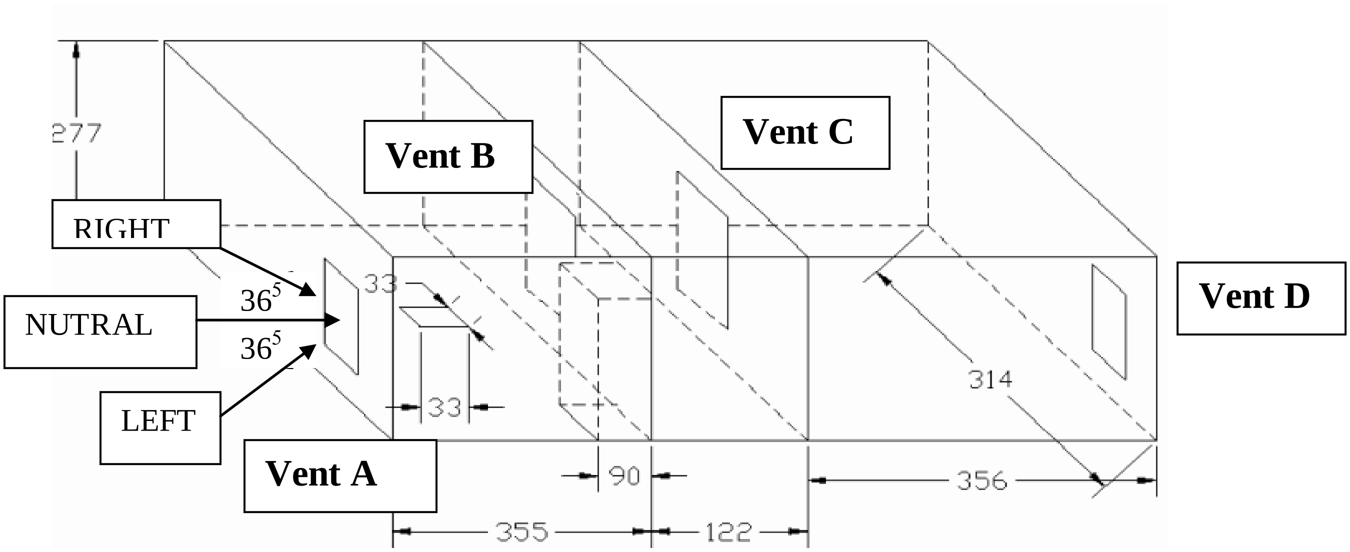

Figure (2a) Schematic of a ship's cabin (all dimensions in mm)

Validations of used experiment

The model under consideration is a transient computational fluid dynamics-based field model. The k- ε turbulence model is adapted to incorporate the effect of buoyancy which gives rise to unstable satisfaction in the rising plume and stable stratification in the ceiling layer in the confined situation [6, 7]. Combustion is simulated by one-step chemical reaction where complete oxidation of fuel is assumed when sufficient oxygen is available, and the local rate of reaction is calculated from a modified version of the well known eddy break up model [8].

In the warship, the fire source is situated near the door with 1.6 m from the door and 1.6 meter from the west wall and 1.8 meter from the side walls.

A schematic and plan of the three compartment configuration of the ship's cabin as used in the experiments is shown in Fig (2b).

The three compartments would be referred to here, for convenience, as 1, 2 and 3. These were 4.13 m in width and 2.27 m in height. The lengths of this compartment were 3.55 m, 1.22 m and 3.56 m respectively. The vertical walls of the compartment were fitted with vents A and D at the end of compartment walls there were smaller than vents B and C.

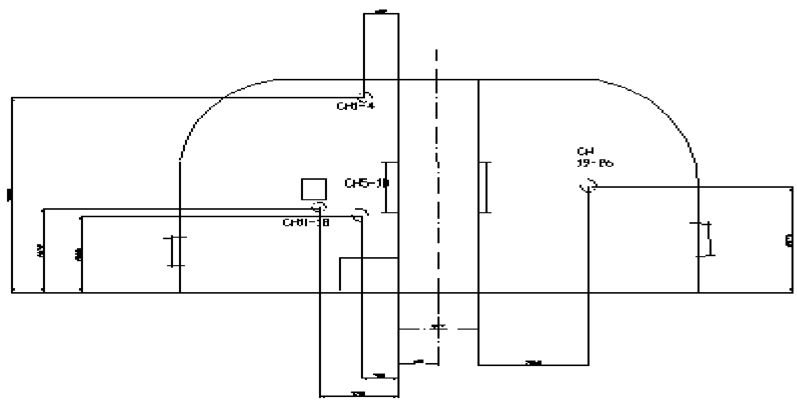

Figure (2-b) Position of aspirated thermocouple columns and radiation thermocouple

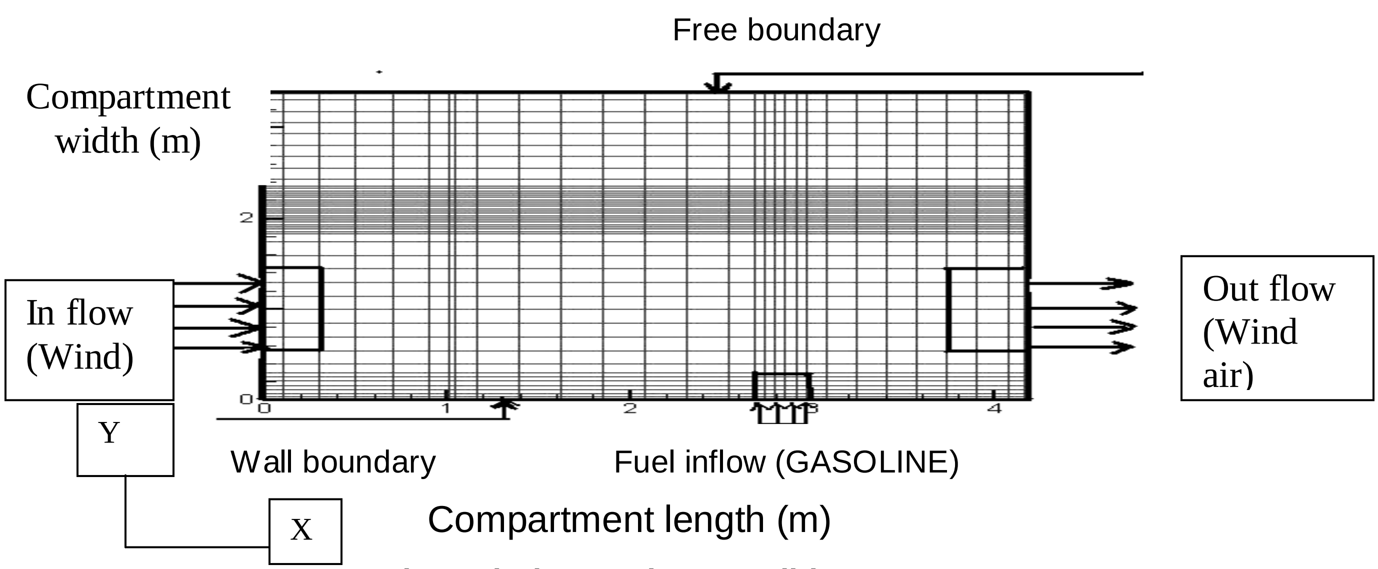

Figure (2c) Boundary conditions

The compartment walls were made of 5 mm thick steel. The thermal conductivity (k_s) density (ρ_s) and specific heat (C_s) of the steel were taken to be 25 w/m^2/°C, 7930 kg/m^3 and 490 j/kg/°C respectively. Fires were produced in compartment 1 by burning diesel fuel in a 330 mm square steel tray. The tray was situated centrally in the compartment. The experiment selected was conducted with vents A, B partly opened to 1/3 rd of its heights and the middle vents B and C fully open. The effect of the external wind blowing at a speed of 2.5 m/s and at angle of 233° relative to the ship's fore was also incorporated. The total burn time for the experiment was about 30 minutes with an average total heat output of 67 KW.

Table (2) demonstrates the locations of the aspirated and radiation thermocouples (see Fig (2b)) for measurement channels 1-3. The radiation thermocouple 1 (at 122 mm from the ceiling) is situated in compartment 1 in a corner diagonally opposite to vent A whereas similar thermocouples 2 (at 120 mm form the ceiling) is slightly off-centered between fire and vent B. The aspirated thermocouples 3 (at 49 mm from the ceiling) are close to the fire in compartment .

Table (2) The locations of measurement thermocouples

Column number	Thermocouple type	Height below ceiling [mm]	Locations
1	Radiation thermocouple	122	In the corner of the fire compartment
2	Radiation thermocouple	120	Close to vent B in the fire room
3	Radiation thermocouple	49	Slightly off-center between fire and vent B

RATE OF HEAT RELEASE FROM POOL FIRE:

The information of the rate of heat release is thus required as an input to modeling.

The classic paper by Blinov and Khudiakov[9], has provided useful data for a wide range of pool diameters of petroleum products such as gasoline, tractor kerosene, diesel oil and solar oil. For a pool fire of diameter d < 0.2 m , the burning rate is controlled by convection and for d > 0.2 m this is controlled by radiation (see, for example, Babarauskas [10]. Where this contributes to approximately 30 % of its total heat output[11]. The flame (radiation) is optically thin for 0.2 m < d < 1 and optically thick for larger pool fires with pool diameter exceeding 1 m (optically thick regime) the free (infinite-diameter) mass burning rate ($m^{\bullet}$ ∞) becomes independent of pool diameter to a steady value of approximately 4 mm/min. For most fuels with 0.2 m < d < 1 (optically thin regime) the mass burning rate (m") can be estimated from the expression Systematic burning rate data for pool fires are available only for steady state burning

$$\dot{m}'' = \dot{m}''_{\infty} (1-e^{-a\beta d}) \quad (1)$$

Where a is the absorption-extinction coefficient of the flame

β is a mean-beam length corrector

$\dot{m}''_{\infty}$ is the mass burning rate (kg/m^2/s).

The rate of heat release can be estimated from the expression:

$$\dot{Q} = \nabla H_c \, \dot{m} \, A_F \quad (2)$$

Where: $\dot{Q}$ is the rate of heat release in the measurement (w).

∇H_c is the heat of combustion (J/kg).

A_F is the area of the pool fire (m^2).

However, a pool fire does not always reach the steady state immediately after ignition and can have a long transient phase. The transient effects [10] in pool fires results from:

(i) The transient conduction heat losses into the liquid pool.

(ii) The progressive heating of the pool container if the pool is shallow.

(iii) Lip effects (i.e. the effects of having a non-zero freeboard height of the pool container above the level of the liquid pool) on convective and radiative fluxes which may be changed progressively if the liquid level is allowed to run down significantly, and the chemical composition of the fuel and its boiling point temperature.

Some experiments by Rasbash et al [9], have reported transient periods ranging from few minutes to fifteen minutes depending on the type of fuel. The geometry of the experiments as described above was modeled by a Cartesian grid in the three-dimensions.The fire source was modeled as a convective source of heat where 30% of its total heat output was assumed lost by radiation to the surroundings [11].

A sensitivity study was carried out by varying the transient period and the gross rate of the fire through using various fires gross curves. A quadratic fire gross rate (t^2-law) was assumed :

$$\dot{Q}_c = \min (0.6\, t^2 \;\; \dot{Q}) \quad (3)$$

Where $Q^{\bullet}$c represents the convective component of the total heat release rate in watts and t is the time in seconds. Assuming that 30 % of the total heat release is lost by radiation of the surrounding 10 the peak convective rate of heat release ($Q^{\bullet}$.) is taken to be 0.7 x 67 KW for the experiments considered in this study. It should be noted that the equation (5) represents a slow developing fires with long transient periods of 7 to 10 minutes.

THE NUMERICAL PRESCRIPTION OF THE PROBLEM:

The momentum losses through the compartment walls were computed by a wall function approach in order to calculate heat losses through the cabin walls.The amount of heat being lost through the ceiling of the cabin will increase the air temperature of its upper deck. Because of the high thermal inertia ($k_s\ \rho_s\ C_s$) of the steel, the increase in outer surface temperature (θ_{out}) the ceiling was assumed to follow the growth rate of the fire and is thus given by

$$\theta_{out} = \min(AQ.\ \theta_{in}) \qquad (4)$$

Where A is a constant which depends on the thermal characteristics of the ceiling (= 2.6 x 10^{-3}). The inner surface temperature rise above ambient (θ_{in}) of the ceiling is obtained from the heat balance at the ceiling boundary by using the lumped heat transfer coefficient approach .The rate of heat lost ($Q^{\bullet}_L$) to the ceiling or wall of the cabin is then given by:

$$Q^{\bullet}_L = h_p\,(\theta_{in} - \theta_p) \qquad (5)$$

Where h_p is the lumped transfer coefficient and θ_p is the gas temperature at the grid cell p adjacent to a wall or ceiling.The wind was not expected to influence significantly the rate of fire growth and the smoke spread inside the cabin. The temperature measured by the radiation thermocouples may be subjected to error because they will depend on its cone angle and reflectivity of the cone θ in surface. Figs (3) to (5) represents the temperature distribution at deferent positions below ceiling, measured in the corner of the fire room, close to vent B in the fire room, and slightly off-center between fire and vent B, while the wind directions were changed from normal to left (with 38 ^{o}) to the right (with 38 ^{o})

positions with respect to the vertical plan of the outer vent A, with a constant speed 2.5 m/sec.The slow transient development of the gas temperatures in figures (3) to (5) can possibly be explained in terms of the long transient period for the diesel pool fire involving heavy hydrocarbons and also due to the transient heat losses to the cabin walls. Figure (3) shows the fire growth slowly the first 10 minutes while the location of measurement at the corner, far from the fire source.The surface temperature will therefore increase with time as the residual liquid fuel becomes less volatile, this regions becomes slowly at the cold layers. While the measuring points nearly nearby to the fire source, the first 10 minutes will growth rapidly more than the fare points, due to the effect of radiation heat sink as shown in Figures (4) decreasing slowly in the cold lower layers .

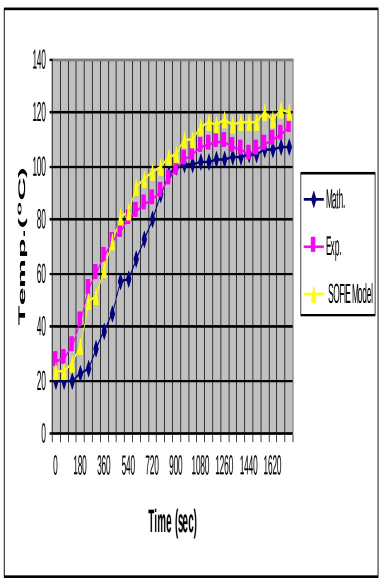

Fig (3) Comparison between experimental measurements, mathematical modeling and the predicted gas temperatures by models SOFIE with radiation thermocouples measurements in a corner of thefire compartment (location CH 1) [122 mm below ceiling].

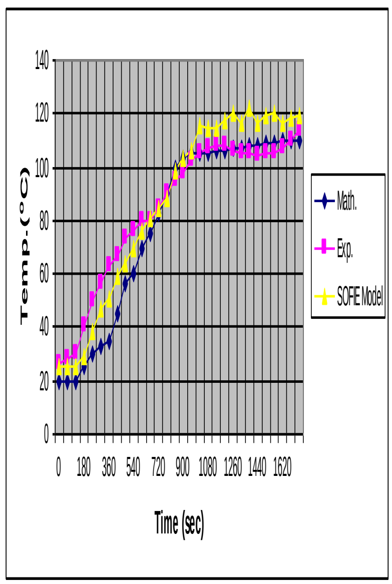

Fig (4) Comparison between experimental measurements, mathematical modeling and the predicted gas temperatures by models SOFIE with radiation thermocouples measurements close to vent B in the fire compartment (location CH 5) . [120 mm below ceiling].

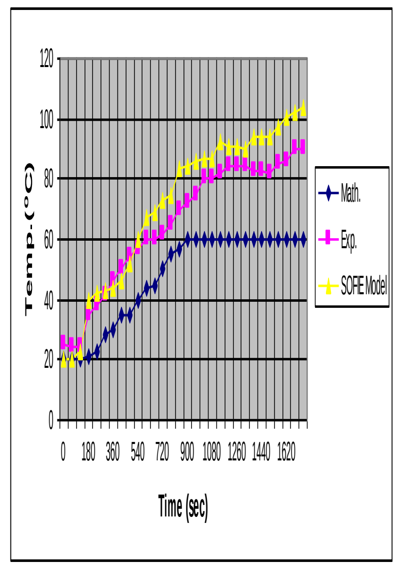

Fig (5) Comparison between experimental measurements, mathematical modeling and the predicted gas temperatures by models SOFIE with radiation thermocouples measurements close to vent B in the fire compartment (location CH 9) [1280 mm below ceiling].

Figures (5) shows the near column to the fire source, so the temperature gradients will grow more rapidly than the far columns.

After 18 minutes, the compartment temperature increases rapidly and there is a substantial temperature gradient in the hot upper layers. After 30 minutes, the expanded surfaces of all combustible items in the room of origin had been burned and the rate of heat release developed to the maximum value (67) KW producing higher temperatures.The spike in the temperature shown in figures (4), (5) is caused by the wave propagation due to the effect of wind in the compartment.

-Some 'ripples' in the predicted gas temperatures in the early growth stage of the fire are found at locations close to vent openings as shown in figure (6).

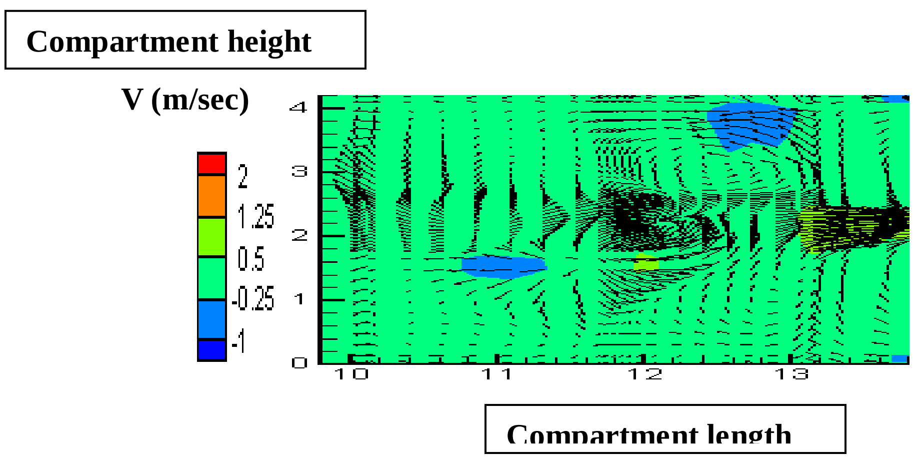

Figure (6) Ripples at locations close to vent openings.

The ripples in gas temperatures are not observed in the measurement possibly because of the low sampling rate.

The distribution of gas temperature within the compartment was measured as a function of time for the 3 probe as shown in figures (3) to (5), and the distribution of CO, CO_2, and O_2 species as a function of height above the fire source shown in fig (7) measured from the fire plume centerline.

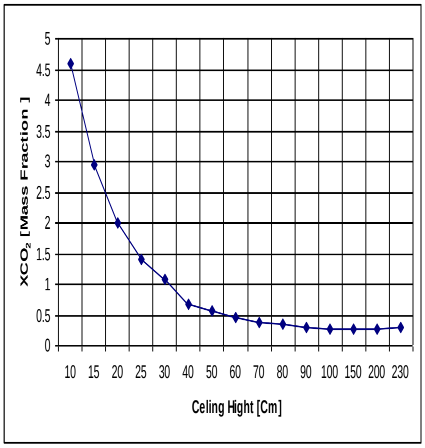

Figure (7c) Carbon dioxide concentration with the ceiling height at the fire source vertical line [after 12 min]

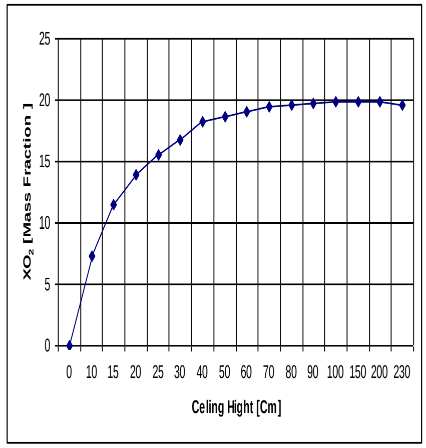

Figure (7b) Oxygen concentration with the ceiling height at the fire source vertical line [after 12 min]

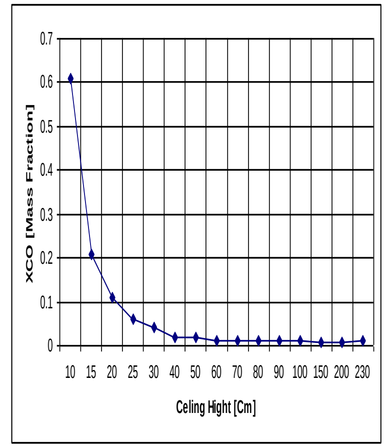

Figure (7a) Carbon monoxide concentration with the ceiling height at the fire source vertical line [after 12 min]

Figure (7a) shows that the carbon monoxide decreases with the ceiling height increases in contrast with CO, CO_2 in figures (7b), and (7c). Figure (7b) shows that the oxygen concentration grew rapidly for the first 50 cm from the burner base and then much more slowly for the rest of height, the oxygen concentration is dropping as the fire consumes.

The oxygen concentration is slightly increasing as air leaks into the compartment and the CO_2 concentration declines as compartment gases are lost by leakage. The gas temperature presented in figure (8) show the temperature variation as a function of height from the flame base.The temperature in the compartment rises as the layer within the compartment descends over the fire, there is a substantial of gas temperature with height, and this gradient is probably associated with heat transfer from the gas to the walls of the compartment that accounts for most of the heat released by combustion within the compartment.

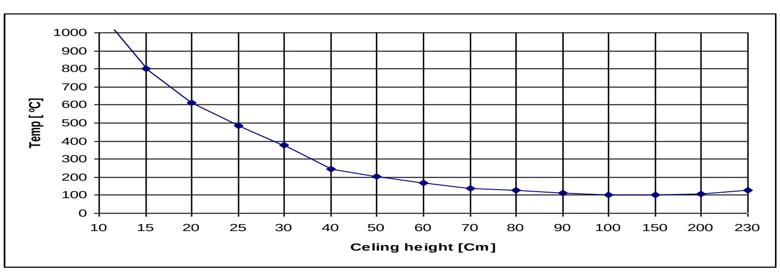

Figure (8) Temperature distribution with the ceiling height at the fire source vertical line [after 12 min]

The strong in flow of air by the wind cause the plume axis to lean away from the door and affect entrainment of gases into the plume. The upper layer expands in volume causing the lower layer to decrease in volume and the vent from the upper layer until the interface reaches the bottom of that soffit.Thus in the early stages the expanding upper layer will push down on the lower layer air and force it into the next

compartment through the vent by expansion as shown in fig (9). Once the interface reaches the soffit level, a door plume forms and flow from the fire room to the next room is initiated. As hot gas flows from the fire room to fill the second room (intermediate one) the lower layers of air in the second room is pushed down as shown in fig (9).

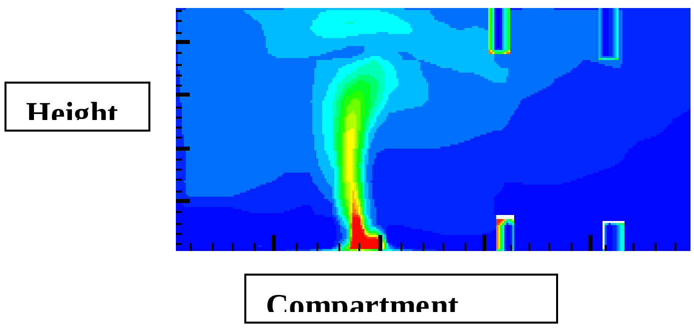

Figure (9) Hot gases flows from the fire room to the middle room.

As a result, some of this air flows into the fire room through the lower part of the connecting doorway (vent). Flow through wind effects fluctuates most rapidly and transfers the greatest amount of enthalpy on an instantaneous basis of all the source terms.The plume of hot, buoyant combustion products impinge on the ceiling, the ceiling jet formed by the impingement process will fan out over the ceiling until it reaches the walls of the room where it will turn downward until the buoyant forces finally fold it back on itself. As this layer becomes thicker, the velocities near the interface will become small and a well-stratified two-layer environment will be formed in which the lower layer contains fresh, cool air, and the upper layer contains hot, vitiated gas will be vented as the interface passes the level of the first vent (B).

The plume rises until it impinges on the ceiling and then spread out along the ceiling until it reaches the walls, this spreading current is reflected from the walls and returns toward the axis of the plume without penetrating toward the bottom of the room.The wind tilting the upward flame by a certain angle with the vertical center plume as shown in fig (10).

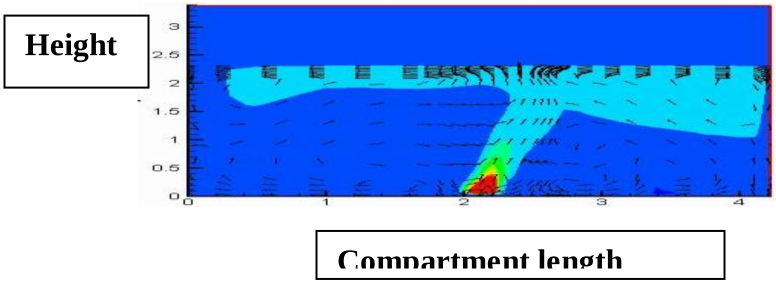

Figure (10) Wind tilting angle.

There are two reasons which give rise to flow through the vents; the first is that of air or smoke which is driven from a compartment. The different locations with two thermocouple were studied, these cases represent validation of experimental work done in [5]. Figure (11) shows the vector plot and temperature contours as obtained for the transient case. It can be seen in the figure that the velocity above the fire source is directed towards the ceiling. The high momentum in the vertical direction is a result of the buoyancy effects on the fire-induced smoke.

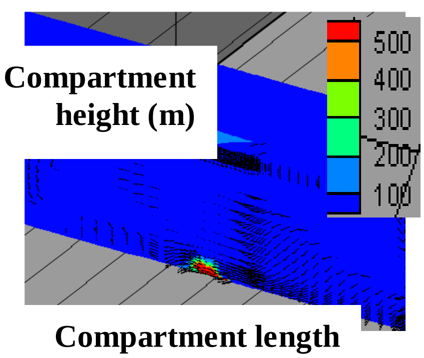

Figure (11a) Vector plot and temperature contours at the right wind angle (^{o}36) at I= 19 in the compartment [after 2 min].

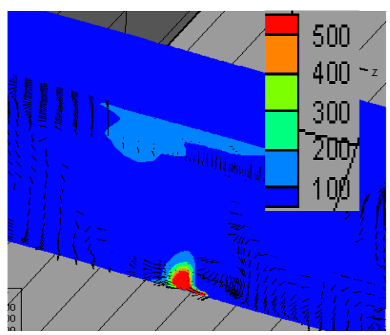

Figure (11b) Vector plot and temperature contours at the left wind angle (^{o}36) at I= 19 in the compartment [after 2 min].

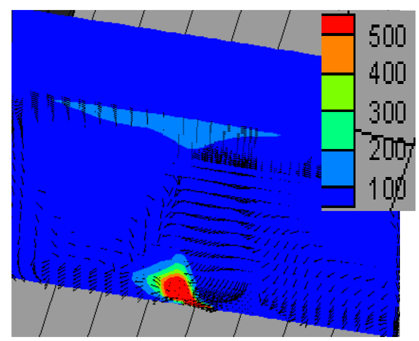

Figure (11c) Vector plot and temperature contours at the normal wind at I= 19 in the compartment [after 2 min].

The wind generates a positive pressure in the fire room and a negative pressure in the adjacent rooms, wind speed causes penetration of smoke of fire to that rooms and expose its residents to high concentration of carbon monoxide. When the wind speed increases as shown in table (3), the mass loss rate increase directly so, the temperature of the upper layers will be higher.

Table (3) cases considered for wind speed

Case no.	Wind speed	Wind position
1	2 m/sec	Normal to vent A
2	4 m/sec	Normal to vent A
3	6 m/sec	Normal to vent A

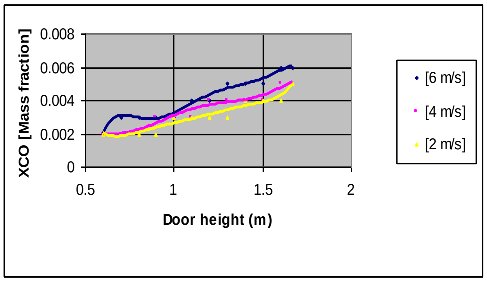

Figure (12a) Carbon monoxide gases distribution in the centre line doorway with different wind speed (2, 4 and 6 m/sec)

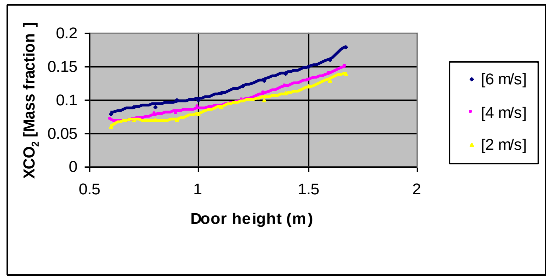

Figure (12b) Carbon dioxide gases distribution in the centre line doorway with different wind speed (2, 4 and 6 m/sec)

Figure (12) shows that increasing of carbon monoxide and carbon dioxide gradually with wind speed increasing, measured from the middle vent A centerline, this is because of the fuels above the fire are brought into closer contact with the upward-moving flow.

CONCLUSIONS:

The model SOFIE used to identify the effect of wind on the fire and smoke behavior in the military warship's cabin.

Wind directions are changed from the left position to the normal, and to the right position with respect to the vertical line of the inlet west vent.The following conclusions may be drawn from the present investigations:

-The fluctuations of the CFD predicted gas temperatures in Figs 10-12 were attributed to the strong turbulence flow caused by the wind effect and the flashover fire.The field model SOFIE Model used successfully predicted the environmental conditions inside a compartment on fire, gave reasonable predictions of carbon dioxide and concentrations of O_2, CO_2 and O_2.

- The model shows that carbon monoxide is produced first, so, multi-sensor (including the carbon monoxide sensor) will be reasonable for the fire detection instead of the ordinary smoke sensors because of the smoke sensor signal may exceed the detection level due to the dust in rooms which produce false alarms, also high- sensitive fire detectors producing frequent false alarms in many kinds of ordinary rooms where miscellaneous non-fire sources are existent (especially in air conditioning rooms).

- Radiative heat transfer is significant even in small fires and successful predictions can only be obtained when taking it into account, it improves the predictions of the upper layer temperature but it tends to over predict the lower layer temperature.

-The fire behavior in the cabin depends not only on the compartment shape, fire size and fuel type but also on the wind speed and directions.

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