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NUMERICAL SIMULATION OF MARINA STORAGE FIRES USING MEASURED COMPOSITE FIRE AND THERMAL PROPERTIES

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ABSTRACT

Fire test data of boats in rack storage are needed to establish more specific requirements for fire control and protection for this type of vessel in high piled rack storage configurations. Since there is no current large or full scale fire test data available, we have embarked upon testing fire and thermal properties of boat material, fiber reinforced polymer (FRP) composite, by using Differential Scanning Calorimetry, and Cone Calorimeter in order to determine the most effective method to provide sprinkler protection to an indoor boat storage facility. Fire and thermal properties of FRP were obtained from experiments and incorporated into the fire dynamics simulator (FDS) model, to simulate fire growth, fire spread, and the capability of the sprinkler system on fire control in a proposed indoor marina dry boat storage facility in Florida. The simulations indicated that in-rack sprinklers, combined with high water density ceiling sprinkler systems, are important to control fire spread in the storage warehouse. Understanding material properties and incorporating them appropriately into the FDS model could help us better understand fire growth in a marina dry storage facility, and enhance fire safety design.

1. INTRODUCTION

Marina storage facilities have become more and more popular because waterfront property has become scarce and relatively more expensive. As a result, as in any building and storage technology, going up becomes more attractive than spreading out. Marina storage facilities can also provide protection from weather and extreme temperatures, which is an increasing concern as the cost of boats increase. However, fire spread on boat material (typically fiberglass reinforced polyester), and from boat to boat in rack storage arrays are not well understood. Since the typical boat material has a potentially high fire load, the stack configuration can present significant challenges to the activation and distribution of water droplets from automatic sprinkler systems. Therefore, how to protect the boat and storage structure from fire becomes our major concern.

The National Fire Protection Research Foundation recently released a literature and data review about marina and boatyard indoor rack storage sprinkler protection [1]. Fire test data of boats in rack storage are needed to establish more specific requirements for fire control and

protection for this type of vessel in high piled rack storage configurations. Since there is no current large or full scale fire test data available and the performance of any sprinkler design scheme will likely not be known, we have embarked upon testing fire and thermal properties of boat material, Fiber Reinforced Polymer (FRP) composite, by using Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), and Cone Calorimeter in order to determine the most effective method to provide sprinkler protection to an indoor boat storage facility [2]. Fire and thermal properties of FRP, such as specific heat, thermal conductivity, density, ignition temperature, mass loss and mass loss rate, heat release rate, and heat of combustion, were obtained from experiments and incorporated into the fire dynamics simulator (FDS) model [3], a computational fluid dynamics (CFD) model developed by the National Institute of Science and Technology (NIST), to simulate fire growth, fire spread, and the capability of a sprinkler system on fire control in a proposed indoor marina dry boat storage facility in Florida.

The goal of the study is to identify ceiling sprinkler and in-rack sprinkler locations that would control the expected fire scenarios based on the size of boats expected to be installed in this building. Considering that the presence of people in the storage facility is rare, the safety goal is to prevent fire spread and flashover, instead of occupant evacuation.

The proposed facility will be an approximately 6,208 m^2 single storage building. The building height will be approximately 14 m above the grade. A maximum of 260 boats can be stored in the building at a time. Cushions, rubber, plastics and other flammable materials on the boat can result in a quick fire spread across the large area over a short period of time. Four scenarios were designed, including different sizes of boats, fires at various rack locations to predict sprinkler linked temperature, and peak heat release rate under different type of the sprinkler protection. The visualization software Smokeview was used to display the results. The hypotheses defined in the scenarios include: 1) without considering explosion; 2) the point of ignition will not exceed one; 3) the sprinklers are all functionally working whenever there is a fire. The simulations indicated that in-rack sprinklers, combined with high water density ceiling sprinkler systems, are important to control fire spread in the storage warehouse. Understanding material properties and incorporating them appropriately into the FDS model could help us better understand fire growth in a marina dry storage facility, and enhance fire safety design.

2. MODELING

2.1 CFD Model Overview

A Computational Fluid Dynamics (CFD) model – Fire Dynamics Simulator (FDS) developed and maintained by the National Institute of Standards and Technology (NIST) [3] was used to do the boat fire analysis. FDS numerically solves the conservation equations of mass, momentum, and energy that govern low-speed, thermally driven flows with an emphasis on smoke and heat transport from fire. It has been designed specifically for fire safety applications and uses a mixture fraction based combustion model. The main equations used in the models are listed as follows.

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \quad [1]$$

The first term describes the density ρ changes with time t and the second term defines the mass fraction. \mathbf{u} is the vector describing the velocity in the u , v , and w direction.

Conservation of momentum:

$$\frac{\partial}{\partial t}(\rho u) + \nabla \cdot \rho u u = -\nabla p + \rho g + \nabla \cdot \tau + f \quad [2]$$

The left hand side represents the increase in momentum and inertia forces, while the right hand side comprises forces acting on it. These forces include pressure p , gravity g , an external force vector f , and a measure of viscous stress tensor τ acting on the fluid within the control volume.

Conservation of energy:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho h u = \frac{DP}{Dt} + q''' - \nabla \cdot q_{rad} + \nabla \cdot k \nabla T + \phi \quad [3]$$

The left hand side describes the net rate of energy accumulation, whereas the right hand side comprises of the various energy gain or loss that contribute to this energy accumulation. These include the pressure work term $\frac{DP}{Dt}$, the energy driving system q''' , the radiative heat flux vector $\nabla \cdot q_{rad}$, the convective term $\nabla \cdot k \nabla T$, and the energy change associated with species inter-diffusion ϕ .

Mixture fraction combustion model:

$$\rho \frac{DZ}{Dt} = \nabla \cdot \rho D \nabla Z \quad [4]$$

The above is the conservation equation of the mixture fraction Z .

Thermal radiation model:

$$s \cdot \nabla I_{\lambda}(x, s) = k(x, \lambda)[I_b(x) - I(x, s)] \quad [5]$$

Where $I_{\lambda}(x, s)$ is the radiation intensity at wavelength λ , $I_b(x)$ is the blackbody radiation intensity. s is the unit normal direction vector, and $k(x)$ is the absorption coefficient.

Sprinkler action model:

$$\frac{dT_l}{dt} = \frac{\sqrt{|u|}}{RTI}(T_g - T_l) - \frac{C}{RTI}(T_l - T_m) - \frac{C_2}{RTI}\beta|u| \quad [6]$$

Here T_l is the link temperature, T_g is the gas temperature in the neighborhood of the link, T_m is the temperature of the sprinkler mount, β is the volume fraction of (liquid) water in the gas steam, and $|u|$ is the velocity of the air streaming by the sprinkler. The sensitivity of the link is indicated by the Response Time Index (RTI). The amount of heat conducted away from the link by the mount is indicated by the C-factor, C . The constant C_2 has been empirically determined to be $6 \times 10^6 \text{ K}/(\text{m/s})^{1/2}$

When using FDS to model fire development and smoke movement, a three-dimensional virtual model of the space is assembled within the computer. This ‘‘computational domain’’ is divided into several hundred thousand cells, and the conservation laws for mass, momentum, species, and energy, are solved at each cell. Time marches forward with small incremental time steps. The end result is a three-dimensional representation of the temperature, smoke, and velocity distributions throughout the computational domain as a function of time.

One of the most critical steps in performing a CFD analysis of fire is taking the real-world configuration and translating it into terms that can be understood by the computer software so that an “adequate” model of reality can be generated within the computer. This involves not only specifying the geometry of the problem being studied, but also prescribing many “input parameters” that affect the simulation results or the manner in which data is reported. The material properties derived from the cone calorimeter test were used as input into the FDS model. The main assumptions made for the simulations are: 1) a) the thermal properties such as the thermal conductivity and the specific heat are constant. b) The heat release rate properties such as the heat of combustion and the heat of reaction are constant. Time average values are derived from the Cone Calorimeter test data and are used. FDS has been validated against various experimental data and results can be visualized via Smokeview.

2.2 Experimentation and Results

Thermal properties such as thermal conductivity, and specific heat capacity of FRP composites were determined by DSC thermal test. Decomposition kinetics parameters, such as mass loss, heat of decomposition were obtained by TGA test. In addition, series of Cone Calorimeter tests were performed to obtain heat of combustion, and heat release rate of E-glass/polyester composites. The sample size used in the Cone Calorimeter test is $100\text{ mm} \times 100\text{ mm} \times 6.2\text{ mm}$. The tests were done following ASME standard E1354 procedures [2] [4] under heat fluxes from 25 kW/m^2 to 65 kW/m^2 .

First we compared heat release rate data from the FDS predictions and the cone Calorimeter tests. The purpose is to check whether the material properties measured from small-scale experiments (and used as input in the FDS model) are able to provide reasonable prediction of the experimental test results before they are used for simulation of boat fires. This step is important since there is no full scale fire test data available to validate boat storage fire modeling results. Figure 1 (a), and (c) shows the comparison data from the Cone Calorimeter tests and FDS model prediction at 25 kW/m^2 , and 45 kW/m^2 exposure heat flux respectively. Overall FDS results over predicted the heat release rate. This is because we assumed that constant thermal properties were existed in the fire experiments, however in reality these parameters are all time dependant. Therefore the thermal properties of the specimen were adjusted to reflect a better prediction. Figure 1 (b), and (d) shows the FDS results with calibrated values at 25 kW/m^2 , and 45 kW/m^2 exposure heat flux respectively. The calibrated values, i.e. thermal conductivity of $0.05\text{ W/m}\cdot\text{K}$, density of 1529 kg/m^3 , specific heat of $\text{kJ/kg}\cdot\text{K}$, heat of reaction of 3000 kJ/kg , heat of combustion of 18000 kJ/kg were used in the final simulation. To limit the number of simulations, only the thermal conductivity, density, specific heat, and heat of reaction were adjusted as the thermal conductivity, density and specific heat affects the ignition temperature, and the heat of reaction affects the heat release rate.

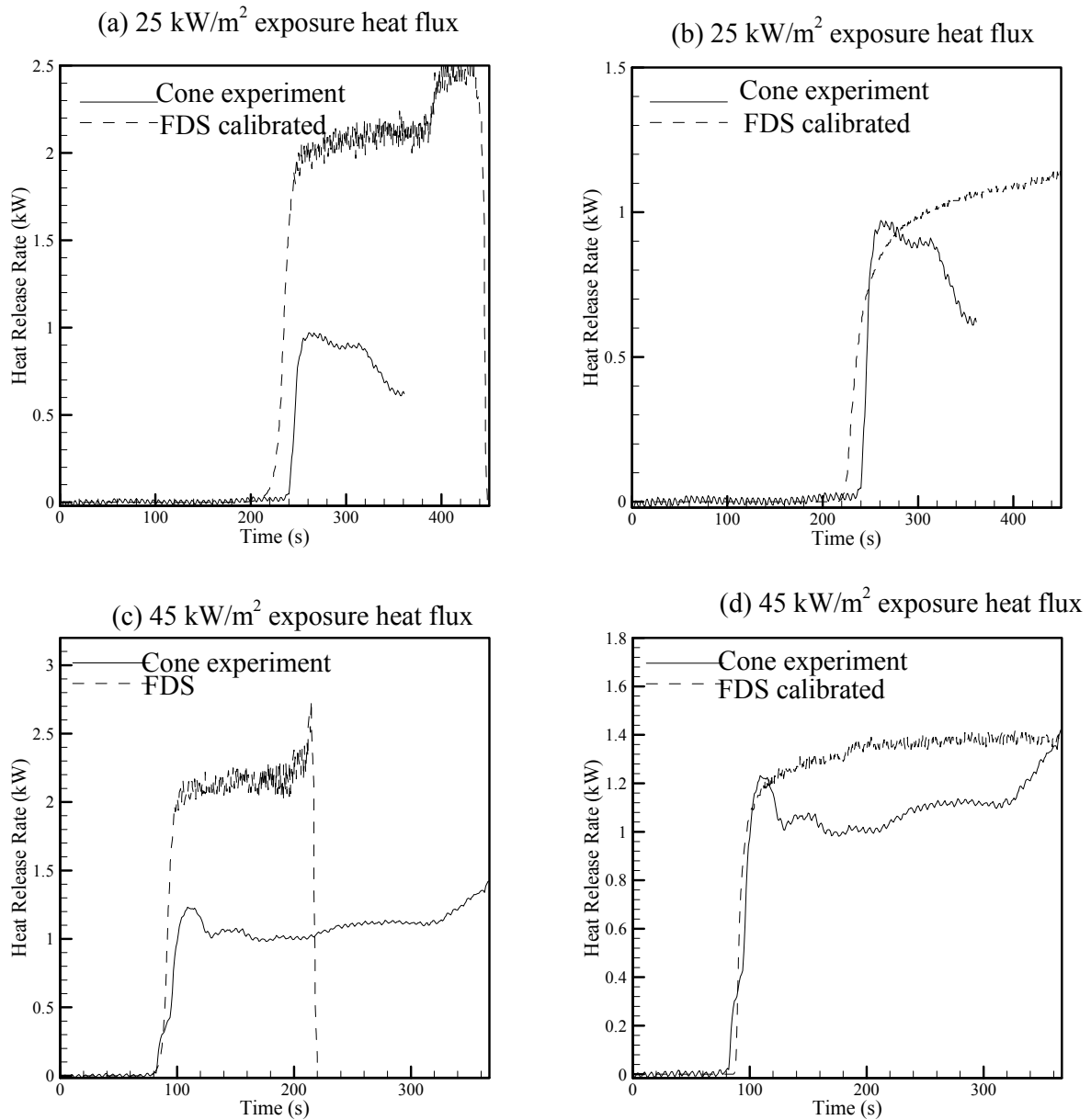


Figure 1. (a) FDS prediction and the experimental heat release rate curves at 25 kW/m² exposure heat flux. (b) FDS prediction with calibrated values and the experimental heat release rate curves at 25 kW/m² exposure heat flux. (c) FDS prediction and the experimental heat release rate curves at 45 kW/m² exposure heat flux. (d) FDS prediction with calibrated values and the experimental heat release rate curves at 45 kW/m² exposure heat flux.

2.3 Maria Storage Conditions

The dry-dock storage spaces can store up to 260 boats. Boat width keeps as 9 m wide and height keeps as 3.5 m high. The length varies from 2.5 m to 4 m long. Figure 1 shows the boat storage facility. The facility is approximately 6,208 m² single storage building and is fully sprinklered. The building height will be approximately 14 meters above the grade. Two 6×6 m doors are

located on the north and south side of the walls. The boats on the first tier are placed on the floor. The boats on the second and third tiers are placed on the beams. The beams were arranged with 4.5 m vertical distance between them. There are one to three boats in a row between the beams depending on the spacing of the beams. The horizontal distance between the beams varies from 7m to 10m. Above the floor 7m, the wall opens a row of vents. Although the geometry of building design under consideration is fairly simple, it is quite large. To model the whole building a large number of grid cells need to be considered which results in heavy demands on computer resources, requiring a large amount of RAM and potentially a long running time. To keep problems down to a reasonable size, a uniform grid size of 0.5 m was used and a total of approximately 7.8 million cells were generated for each fire models. All of the building doors and windows keep closed. The wall and ceiling materials are set up as metal which has thermal property typical of steel. The floor has the concrete property. Boats are filled in the whole storage facility to simulate the worst condition. Fig.2 provides illustrations of the model geometry in its native form via Smokeview.

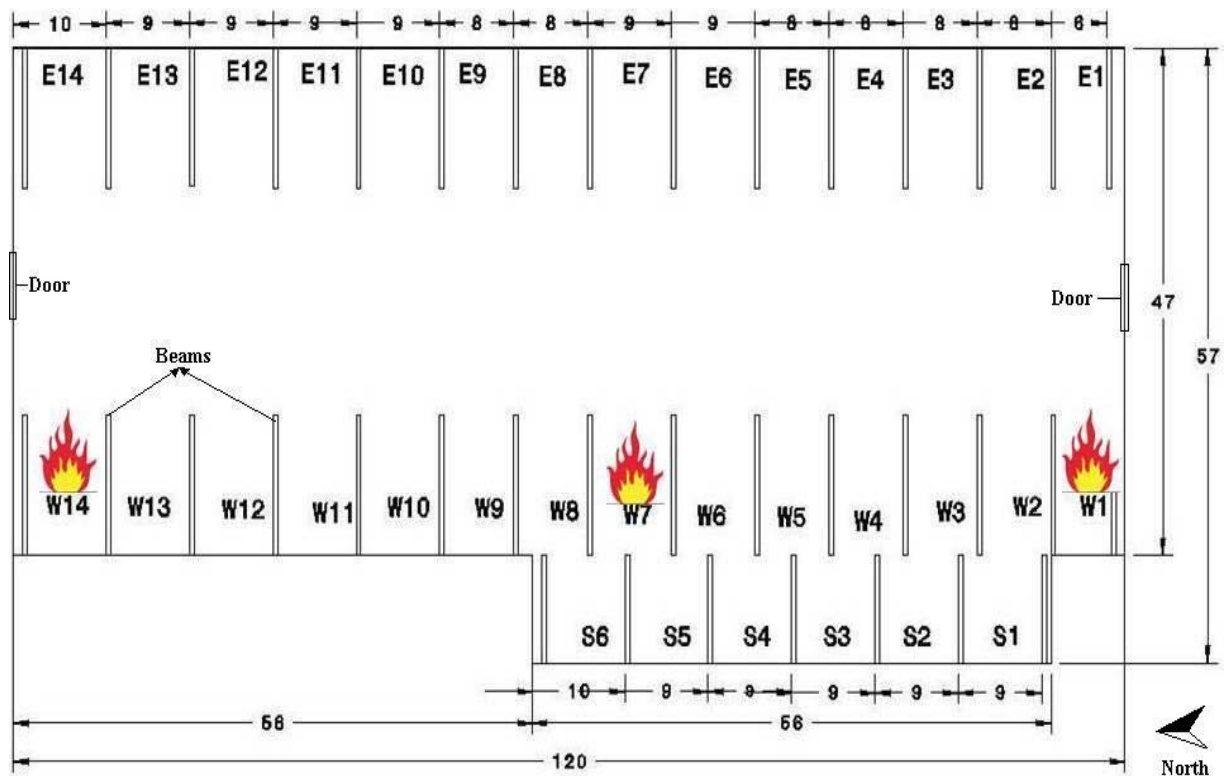


Figure 2. Boat storage facility schematic plan. Dimension in meter.

Overview Looking North	Interior Looking East
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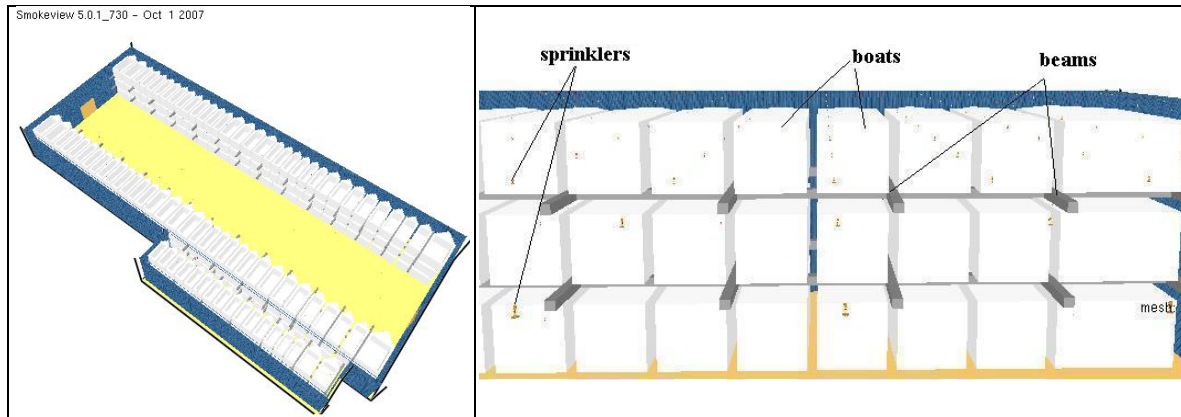


Figure 3. FDS model screen shots

2.4 Evaluation Scenario

Since the building is for storage only, there is no process work carried out within the building. The ceiling, floor and wall of the facility are all made of non flammable materials, the potential for ignition from the building is small. The only possible ignition source would come from the boat. For example trashes. According to the statistics for the various trash fires from the National Institute of Standards and Technology, the peak heat release rate of a trash fire can be ranged from 50 kilowatts (kW) to 450 kW from the nominal 136 liter trash container [5]. The ignition material can be all kinds of debris. E.g. paper, cups, cardboard, food wrappers, and paper bags. Considering the ignition location and wind conditions, in the real fire safety analysis we take the safety factor 1.5 to the peak heat release rate so that a 700 kW continuous ignition source would be our first consideration. After quoted numbers of peak release rate for various products in the warehouse [6], 1200 kW would be the high end value due to arson fire with accelerant. Therefore after adding in the safety factor, 2 MW fire would be our further investigation in the boat storage facility. The size of the ignition source was assumed to be $1m \times 1m$ and remain constant throughout the simulation. The ignition source was set on the centre of the boat on the second rack in the middle of the building to simulate the worst scenario. Two doors on the north and south side of the walls were kept open during the simulation. Four scenarios were considered in the study as described in the table 2. Scenario one: trash fire as size of 700 kW . This scenario is to simulate the fire due to ignition of the trash or flammable liquid placed in the centre of the boat. Scenario two: arson fire as size of 2 MW . Scenario three: same as scenario two, but change the flow rate of in rack sprinkler from 30 liter per minutes to 140 liter per minutes. Scenario four: same as scenario two but without sprinkler protection. The location of the scenarios can be seen from Figure 3.

2.5 Sprinkler Design

The facility is used to store the boats and boats can be stacked to two to three rows high. It is hard for the automatic sprinklers to control the rack storage fire because of the increased numbers of burning surfaces, combustibles hold in a stable arrangement. It also presents challenge for sprinkler water to penetrate through narrow vertical spaces in the rack to control the fire. The boat size varies from $44 m^3$ to $285 m^3$, *NFPA 13* requires higher ceiling sprinkler densities in storage configurations with narrow aisles [less than 2.4 m wide].

Table 2. Four scenarios selected in the study.

Scenario 1	Fire due to burning trash or flammable liquid placed on the seat in the center of the boat on the first row of racks. Ignition source size is 700 kW, location is W1 as indicated on Figure 1. Flow rate of in-rack sprinkler is 30 liter per minutes.
Scenario 2	Arson fire. Ignition source is located on the seat in the center of the boat on the first row of racks. The size is 2 MW. Location is W1 as indicated on Figure1. Flow rate of in-rack sprinkler is 30 liter per minutes. The same scenario rerun to test the impact of the different flow rate of in-rack sprinkler on fire control. The flow rate of in-rack sprinkler changed from 30 liter per minutes to 114 liter per minutes.
Scenario 3	Fire due to burning trash or flammable liquid placed on the seat in the center of the boat on the first row of racks. Ignition source size is 700 kW, location is W7 as indicated on Figure 1. Flow rate of in-rack sprinkler is 114 liter per minutes.
Scenario 4	Arson fire. Ignition source is located on the seat in the center of the boat on the second row of racks. The size is 700 kW. Location is W14 as indicated on Figure1. Flow rate of in-rack sprinkler is 30 liter per minutes.

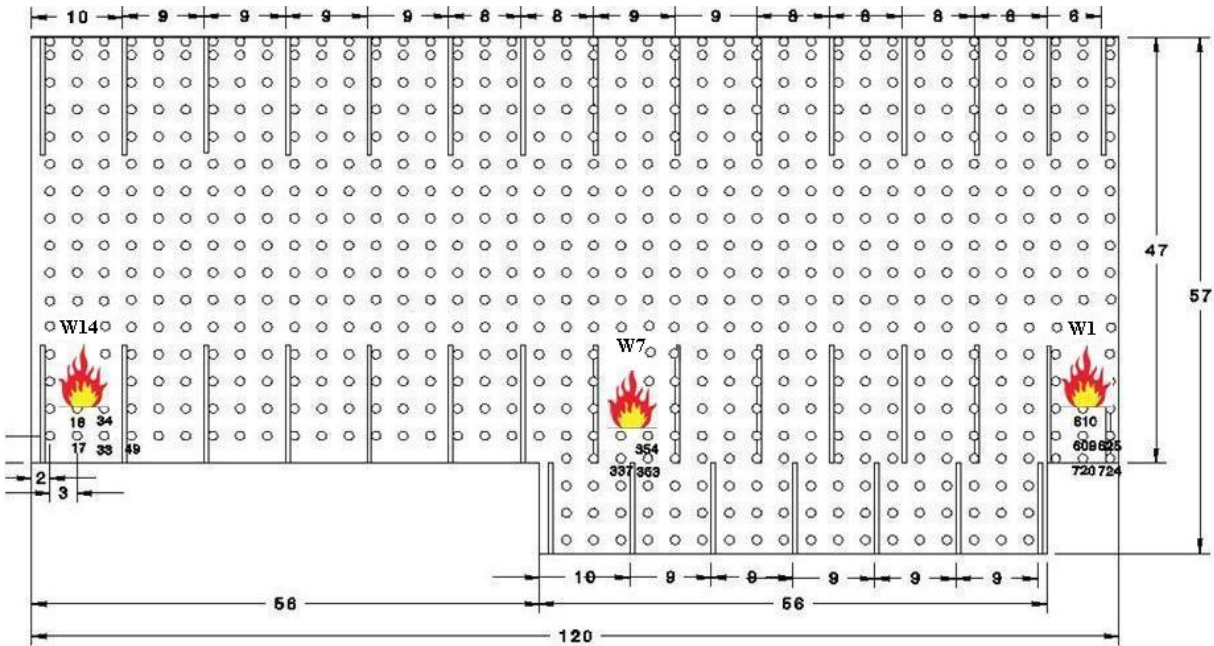


Figure 4. A plan view of the sprinklers arrangement in four fire scenarios. The circles represent the locations of the sprinklers but not in the actual size. The numbers next to the sprinklers represent the activated sprinklers in the design fire. Dimension in meter.

In-rack sprinklers would be mandatory in multiple-row racks, depending on the rack depth, commodity classification, and storage height [7-10]. The sprinklers were positioned 3 m by 3 m to give a spacing of 9 m² per sprinkler, which is typically a conservative spacing. The in-rack sprinklers were placed under the center of the beam about 0.15 m. There were four in-rack sprinklers in a line. The vertical spacing between the in-rack sprinklers were kept as 3 m. There are totally 724 ceiling sprinklers and 370 in rack sprinklers. The high-temperature of 138 degree

Celsius ceiling sprinklers and ordinary temperature of 74 degree Celsius in rack sprinklers were arranged in the design. The flow rate of the ceiling sprinklers is 340 liter per minutes. The flow rate of 30 liter per minutes and 114 liter per minutes were used for the in rack sprinklers to see the differences. Figure 3 shows a plan view of the sprinkler arrangement in four fire scenarios.

3. RESULTS

Simulations of a fire on a typical boat were run to determine the effectiveness of sprinklers on the results of the fire. Each scenario was simulated for 1200 s. The computers used for the simulations were Intel® Pentium 4®, which has 3.0GHz CPU, and 2GB RAM. The times taken to complete the simulations were between 52 to 68 hours. The results were displayed by the visualization software Smokeview 5.5.3.

3.1 Scenario one

There were five ceiling sprinklers activated in scenario one. The activated sprinkler numbers are marked in Figure 4. The sprinkler link temperature profiles are shown in Figure 5 (a). A FDS snapshot at 122 s is shown in Figure 5 (b). Since the thermal response elements for the ceiling sprinklers was rated to actuate at 138 degree Celsius, once the sprinkler head was exposed to this temperature long enough to overcome the thermal lag associated with the element, the sprinkler would be expected to actuate. As indicated in the Figure 5 (a), the first activated sprinkler is number 609, which is right above where the fire was originated as shown in Figure 4. The sprinkler reaches its activation temperature at 121.1 seconds into the fire. The activation of sprinkler 609 is followed by the activation of sprinklers 625, 720, 610, and 724. Their activation times are 121.2 s, 123.5 s, 128.0 s, 128.7 s respectively. The sprinkler activation times were a direct result of their orientation and the origin of the design fire. As expected the most remote sprinkler 724 had the slowest activation time compared to other activated sprinklers.

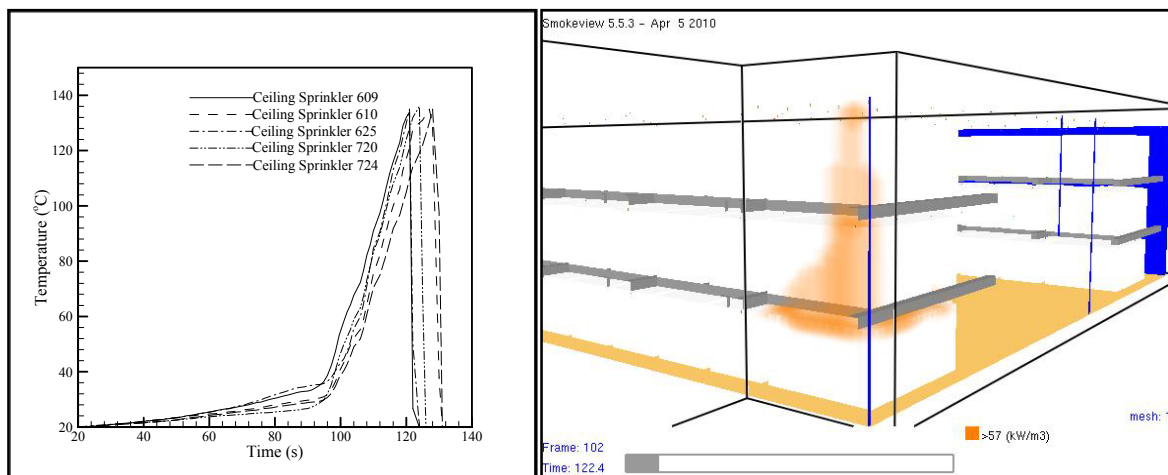


Figure 5. (a) Sprinkler link temperature profiles in scenario one. (b) FDS snapshot at time 122 s.

3.2 Scenario two

There were seven sprinklers activated in scenario two. Five are ceiling sprinklers and two are in-rack sprinklers. Figure 6 (a) shows the sprinkler link temperature profiles in scenario two, and Figure 6 (b) shows FDS snapshot at 59 s. The first activated sprinkler is ceiling sprinkler 625,

which activated at 59.6 s. then the ceiling sprinkler 609 activated at 60.3 s. After it, the in-rack sprinkler 4 activated at 60.4 s, which is located on the right side of the origin of the design fire. Following it, ceiling sprinklers 720, 610, 724, and in-rack sprinkler 3 on the left side of the origin of the design fire activated as well. Comparing scenario two to scenario one, we can see as the size of ignition source increased, the sprinkler activation time decreased significantly, and in-rack sprinklers have a greater impact on larger fire suppression. The same scenario was run again to test the impact of in-rack sprinkler on the fire control. This time the flow rate of in-rack sprinkler changed from 30 liter per minutes to 114 liter per minutes. From the peak heat release rate measurements, we found that the peak heat release rates from the two simulations were same, which are 13.7 MW. The peak heat release rate information tells us that the flow rate of in-rack sprinklers does not have much impact on the fire control.

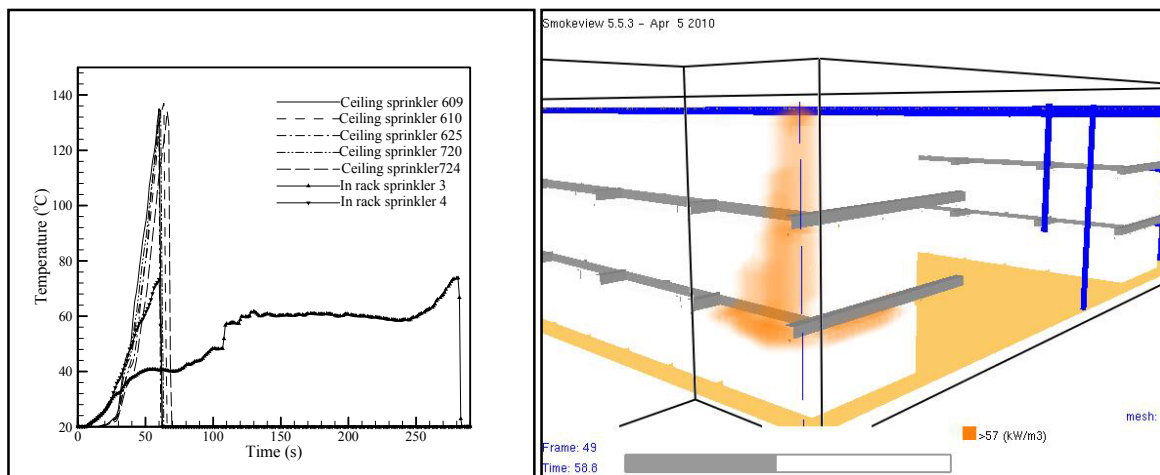


Figure 6 (a). Sprinkler link temperature profiles in scenario two, (b) FDS snapshot at 59 s.

3.3 Scenario three

In scenario three, there are three ceiling sprinklers and two in-rack sprinklers activated in the design fire. Figure 7 (a) shows the sprinkler link temperature profile in scenario three, and Figure 7 (b) shows FDS snapshot at 277 s. Ceiling sprinkler 354 activated at 275.3 s first. Following it in-rack sprinkler 4 on the right side of the fire activated at 285.2 s. Ceiling sprinklers 370, 337, and in-rack sprinkler 3 on the right of the fire activated at 300.4 s, 300.8 s, 306.2 s respectively right after it. Comparing to scenario one, there are more sprinklers activated in scenario three. Especially two in-rack sprinklers helped control the fire to the great extent. The peak heat release rate from scenario three and scenario one examined here. It was found that the peak heat release rate of 16.8 MW from scenario three is much higher than the peak heat release rate of 12.7 MW from scenario one. Since the only differences between scenario three and scenario one are the location of the ignition source and the flow rate of in-rack sprinklers. We can conclude that the ignition source in scenario three, which is in the middle of the storage facility facilitated the fire spread in different directions, whereas the ignition source in scenario four is at the corner of the storage facility, which prevented the fire from spreading in multiple directions. From the peak heat release rate of scenario three and scenario one, we can also see the higher flow rate of the in-rack sprinklers in scenario three did not have much impact to control the fire comparing to the standard flow rate of the in-rack sprinklers in scenario one.

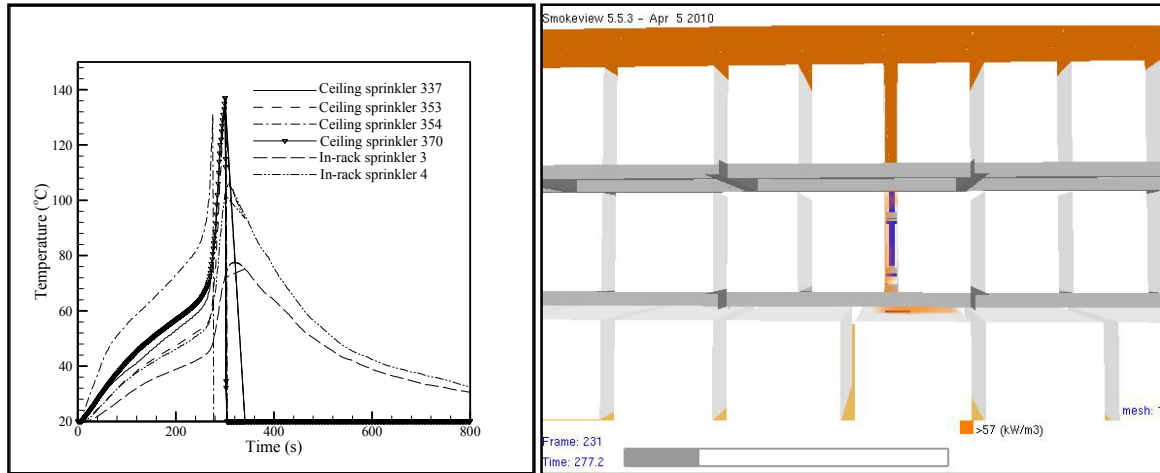


Figure 7 (a). Sprinkler link temperature profiles in scenario three, (b) FDS snapshot at 277 s.

3.4 Scenario four

Figure 8 (a) shows the sprinkler link temperature profiles, and Figure 8 (b) shows a FDS snapshot at 198 s in scenario four. In scenario four, there are five ceiling sprinklers 17, 18, 33, 34, 49 and one in-rack sprinkler 4 activated in the design fire. The first ceiling sprinkler 18 activated at 195.6 s. Following it, in-rack sprinkler 4 on the left side of the fire, ceiling sprinklers 33, 34, 17, 49 activated at 196.2 s, 198.6 s, 200.5 s, 200.7 s, 210.2 s respectively. The reason of only the in-rack sprinkler on the left side of the fire activated is because between the beams, there are two boats stored on the rack. The boat ignited first is close to the in-rack sprinkler under the left beam. The peak heat release rate from scenario four compared with the peak heat release rate from scenario one. It was found that the peak heat release rate of 15.5 MW from scenario four is much higher than the peak heat release rate of 12.7 MW from scenario one. Since the only difference from scenario four to scenario one is the location of the ignition source (changed from the first tier to second tier), we can conclude that the space between the ignited boat and other boats in vertical orientation in scenario four increased the convection, which resulted in the higher peak heat release rate in scenario four.

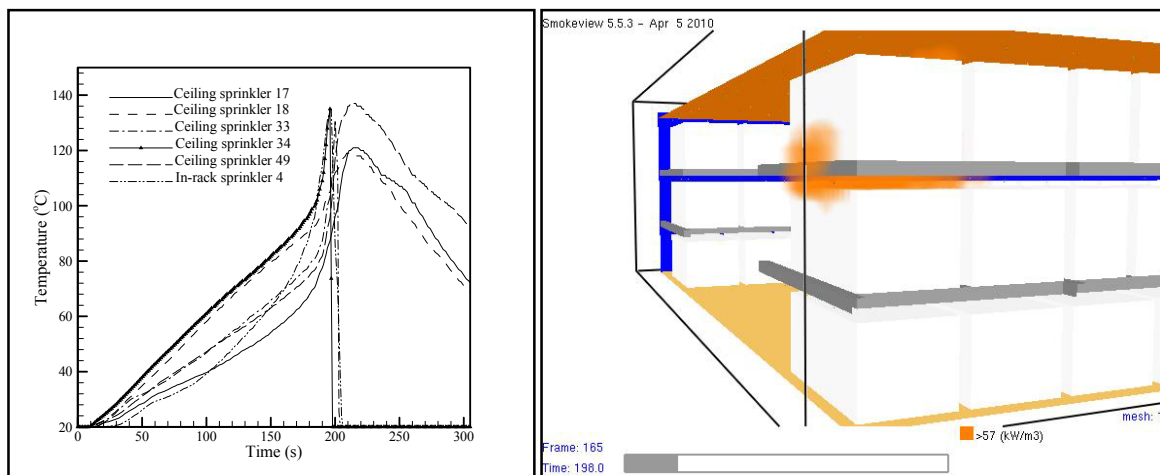


Figure 8 (a). Sprinkler link temperature profiles in scenario four, (b) FDS snapshot at 198 s.

4. CONCLUSIONS

In order to simulate fire growth and spread within a marina dry storage facility, a series of experiments were performed first to obtain the material thermal properties. FDS prediction results indicated that measured thermal properties of the material from the cone calorimeter tests could not be used directly in the fire model to accurately predict fire growth and spread in the storage facility, instead calibrated values were used in the final simulations. The modeling results indicated that ceiling sprinklers have greater impact on the fire control in the large storage facility than the in-rack sprinklers. The flow rate of in-rack sprinklers does not have much impact on the control of fire growth and spread. In-rack sprinklers are important when the fire size is large and could decrease the fire suppression time significantly. Understanding material properties and incorporating them appropriately into the FDS model could help us better understand fire growth and spread in a marina dry storage facility, and enhance fire safety design.

5. FUTURE WORK

The thermal properties will continue to be verified by the mass loss rate data from the cone calorimeter tests and the temperature data obtained from ICAL test. A general procedure will be developed to derive suitable thermal properties of the material from the small-scale tests, which could be used in the fire model.

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