OPTIMIZATION OF FIRE SUPPRESSION USING FIRE DYNAMICS SIMULATOR

Venkatesh PL[1], Harish D[2], Mohamed Nihal H[3]

[1] *Venkatesh PL, BE Mechanical Engineering, RMK Engineering College, Chennai*
[2] *Harish D , BE Mechanical Engineering, RMK Engineering College, Chennai*
[3] *Mohamed Nihal H , BE Mechanical Engineering, RMK Engineering College, Chennai*

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Abstract-- *In fire-prevention designs for buildings, the major concerns are ensuring safe evacuation in the event of a fire and preventing the fire from spreading.The adoption of a performance based design approach in the regulatory frame work and the accessibility of advanced computing have provided an incentive for fire engineers to use more sophisticated and computational intensive numerical simulation . The use of fire dynamics simulator (FDS) has allowed the description of fire in complex geometries and wide variety of physical phenomenon. Fire inevitably involves many uncertainties, such as the site of the fire source, whether or not a window is open, erroneous operation of prevention systems, and soon, which increases the risk leading to a large disaster. It is very important to consider these uncertainties to design a safe fire-prevention system. In this paper, the optimum design for smoke-control systems in buildings and water mist fire suppression is developed using fire dynamics simulator (FDS). The optimum design method proved to be useful in terms of the fire-prevention system design. The approach will be conducted for other urban safety design.*

Keywords: FDS, Safe evacuation, Fire extinguishment, Smoke control, Optimum design.

1. INTRODUCTION

In modern society, the everyday safety is more or less taken for granted. Without spending too much thought on it, we largely depend on correct safety designs as well as the professional skill of the rescue or fire brigades. As civilization grows, becoming increasingly complex, methods for protection and preserving will inevitably have to develop continuously. In order to understand, predict and describe the course of a fire and its influence on its environment different scientific methods are employed, including practical experiments and mathematical modeling. Performing full-scale experiments is expensive and requires considerable work. Of course experiments are not used in ordinary building design but are more used as a tool for the scientists. Often small-scale experiments are performed in which the geometry is scaled to more convenient proportions, for example to 1/3 of the true scale. Using the results from these experiments mathematical models, hand calculation methods and computer-based models can be derived and/or evaluated. It should however be kept in mind that experimental results are not necessarily entirely accurate. There are always measuring errors present, sometimes more and sometimes less significant but as a rule of thumb one can say that measuring errors can be approximately 30 percent.

The idea that the dynamics of a fire might be studied numerically dates back to the beginning of the computer age. Indeed, the fundamental conservation equations governing fluid dynamics, heat transfer, and combustion were first written down over a century ago. Despite this, practical mathematical models of fire are relatively recent due to the inherent complexity of the problem. The difficulties revolve about three issues: First, there are an enormous number of possible fire scenarios to consider due to their accidental nature. Second, the physical insight and computing power required to perform all the necessary calculations for most fire scenarios are limited. Any fundamentally based study of fires must consider at least some aspects of bluff body aerodynamics, multi-phase flow, turbulent mixingand combustion, radiative transport, and conjugate heat transfer; all of which are active research areas in their own right. Finally, the “fuel” in most fires was never intended as such. Thus, the mathematical models and the data needed to characterize the degradation of the condensed phase materials that supply the fuel may not be available. Indeed, the mathematical modeling of the physical and chemical transformations of real materials as they burn is still in its infancy.

FDS is a Computational Fluid Dynamics (CFD) model of fire-driven fluid flow. The model 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. Smokeview is a companion program to FDS that produces images and animations of the results. In a sense, Smokeview now is, via its three-dimensional renderings, an integral part of the physical model, as it allows one to assess the visibility within a fire compartment in ways that ordinary scientific visualization software cannot.

Due to progressive urbanization, there has been a rapid increase in complex buildings over recent years. As is already well known, Buildings are strongly associated with environmental, energy and safety issues. In order to minimize their impact on these issues, sophisticated strategies to control building systems operations must be handled by the designers, planners and engineers. Computer simulation-based control of building systems is recognized as an effective approach. Such simulations can capture a building's dynamic characteristics over time thus providing a more reliable basis for control of its behavior. This paper focuses on the safety issue and the use of an optimization program coupled with fire Dynamics simulator (FDS) simulations to optimize a smoke-control system, which provides a refined and robust design for the building's safety control. In terms of safety, optimization design has been widely conducted in evacuation processes; little research is found for smoke control systems. For smoke-control system designs, three-dimensional distribution of physical characteristics during the fire is necessary. Therefore, it is thought that a similar optimization approach coupling FDS and optimization method could also be applied to build designs for fire prevention.

Due to the growing use of water mist systems, there are several issues which need to be resolved. Currently, a water mist system must be designed for a specific location by carrying out extinguishing tests for a relevant setup. The only standard for water mist systems, NFPA 750,states that a water mist system should be listed for the specific purpose. This is very costly and drastically limits the use of water mist systems, as every new system has to be designed and test dseparately. For marine applications, water mist has been used in smaller compartments and full-scale tests have been performed. This is expensive however, and in some cases also unrealistic, especially when it comes to water mist systems for buildings. Today, there are no guidelines available for dimensioning water mist Systems. It would be desirable to obtain enough knowledge in the area to enable performance based design of water mist systems. Simulations could be carried out using computational fluid dynamics using relevant models to account for the spreading and extinguishing effects of the water mist.

The research work summarized here is focused on the first stage of development, verification and validation of a numerical tool capable to simulate fire scenarios in order to perform water mist protection strategies effectiveness assessment and smoke movement control. The interest in this task raise from the increasing number of applications in road and subway tunnels and from the uncertainty associated mainly with the interaction between water mist droplets, hot smoke and ventilation flow. Indeed, these phenomena are very important to maintain adequate safety levels for the occupants and the fire brigades in terms of temperature, visibility and concentration of combustion products, and so their evaluation is of great importance to estimate the consequences of a strategy against fire, combustion, smoke.

Although FDS was designed specifically for fire simulations, it can be used for other low-speed fluid flow simulations that do not necessarily include fire or thermal effects. To date, about half of the applications of the model have been for design of smoke control systems and sprinkler/detector activation studies.

2.OPTIMIZATION OF WATER MIST FIRE SUPPRESSION SYTEM USING FDS.

Man has used water for fire extinguishing for millennia. So why write a thesis about using water to put out a fire? Everyone knows it works! However, dividing the water into fine droplets, a so-called water mist, gives old water new properties and possibilities, which should be explored. According to Särdqvist, the fire brigade often uses more water and larger nozzles than necessary in order to control a fire with water. Further the use of water is not very efficient - in another study, Särdqvist showed from a number of controlled experiments that the amount of water required to control a fire was between 0.15 kg/m2 and0.35 kg/m2, whereas actual fire tests showed that in real fires the amounts used were between 10 kg/m2 and 4,000 kg/m2. This gives an extra usage of water for extinguishment thirty to twenty five thousand times larger than necessary, which can only lead to water damage to property and the environment. One possible solution to this problem is the use of water mist. Water mists are fine droplets, where 99% of the droplets are less than 1mm in diameter. Typically, the droplets are much smaller, in the range of 20 µm to 500 µm, depending on the water pressure and method used to create the droplets.

2.1 Problems with dimensioning water mist systems

Due to the growing use of water mist systems, there are several issues which need to be resolved. Currently, a water mist system must be designed for a specific location by carrying out extinguishing tests for a relevant setup. The only standard for water mist systems, NFPA 750,states that a water mist system should be listed for the specific purpose. This is very costly and drastically limits the use of water mist systems, as every new system has to be designed and test desperately. For marine applications, water mist has been used in smaller compartments and full-scale tests have been performed. This is expensive however, and in some cases also unrealistic, especially when it comes to water mist systems for buildings. Today, there are no guidelines available for dimensioning water mist systems. It would be desirable to obtain enough knowledge in the area to enable performance based design of water mist systems

2.2 Methodology

Step 1:A fire experiment without water mist is performed to validate the prediction of FDS software against the experimental data..

Step 2: The models of fire situations in a building will be designed with *Pyrosim* 2010 and the computations will be done by an open source software for solving numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on temperature, oxygen concentration, extinguishing time.

Step 3: And then bench scale experiment is done in a 1.5m x 2m x 1.5m compartment with a water mist nozzle of solid cone type at the top, one thermocouple is placed 1.6 m high from the floor and oil pool is made at the floor

Step 4:A flow meter is installed at the pump outlet to measure the overall system flow rate. A long steel rod, wrapped with cotton cloth at one end is used as an ignition instrument.

Step 5: The experiment is carried out by varying density, velocity, diameter, flow rate of water mist. Fire suppression time is calculated at different conditions.

Step 6: These readings will be used for creating a code for fire analysis and will be used to benchmark the fire scenario and it is compared with numerical results.

2.3 Instruments & Accessories For Experiment

1: THERMOCOUPLE.

2: PUMP.

3:WATER MIST NOZZLE.

4:TUBINGS.

5: FUEL PAN.

6:FUEL (DIESEL).

2.4 Experimental Setup

The experiments are performed in a steel-walled enclosure (1.5 m × 2 m × 1.5 m).The fuel pan is placed at the centre of the floor and water mist nozzles are installed at 1.6 m high from the floor. Gas temperatures are measured by aluminium sheathed K-type thermocouples. Two thermocouples are installed to measure the temperature difference between upper and lower layers. Experiments are performed with diesel pool fires to investigate the effect of oxygen consumption rate on fire suppression. A circular steel pan is prepared with the dimensions of 30 cm radius.

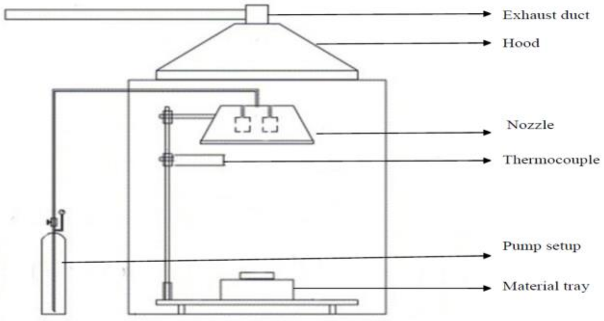


Fig-1: Experimental setup

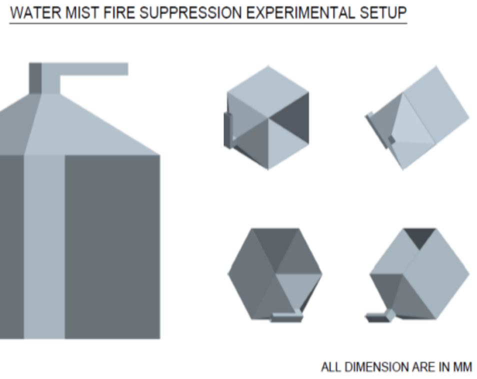


Fig-2: Experimental setup in 3D

Fig-3: Fabrication of Box Section

Fig-4: Fabrication of Taper Section

Fig-5: Setup with Oil Pan

Fig-6: Pump Connection To Setup

2.5 Test Procedure

The fire size was chosen so that steady state conditions without extinguishment were achieved. Measurements have been carried out on a hollow cone water mist nozzle .A series of pre-test procedures were conducted before the start of the test. The test conditions were set up. The analyzers were calibrated. The water recirculation system was filled with clean water. The video camera alignment was checked. The pan was filled with the appropriate amount of fuel. After these tasks accomplished, the video recording and data acquisition system were started to begin the test. The fire was manually ignited 50 seconds. The mist units were activated and the fire was extinguished and values are noted. At the completion of each test the compartment was vented and cleaned. The water loss in the recirculation system and the water condensed out in the ducting were measured to find a total mist generation rate. The remaining fuel in the fire pan was also measured to reaffirm the extinguishment by the mist.

2.6 Extinguishing Mechanism

When water mist is discharged into fire, the heat released from the combustion of the fuel is used to heat the fuel–air mixture, and water droplets. The discharge of water spray brings extra air into the flame. The fire can be extinguished, when water mist cools the reaction zone to below the limiting adiabatic flame temperature, resulting in the termination of the combustion reaction of the fuel–air mixture. For most hydrocarbons and organic vapours, this lower adiabatic temperature limit is approximately 1600K .The fire can also be extinguished, as the rate of supply of fuel vapour or burning rate is reduced due to the cooling and could not be sufficient enough to support the flame. For fuels with a high flash point, such as cooking oil, woods and solid fuels in electric equipment, their surface temperatures during burning are high leading to significant radioactive heat losses from the fuel surface.

The heat loss to water is also significant when water drops hit and evaporate on the hot fuel surface. The fires can be extinguished with water mist through cooling the fuel surface. For most freely-burning liquids, their surface temperature is close to, but slightly below their boiling point. Therefore, for flammable liquid fuels that has a low boiling point or low surface fuel temperature, such as heptanes, their radiative heat losses from the fuel surface and the heat losses to water droplets through evaporation can be ignored.

If the fuel surface temperature is low in suppression, it is very difficult to extinguish the fire through cooling the fuel surface, as heat loss from the fuel surface is much smaller than the heat gained from the flame. The burning rate of the fuel could be increased during fire suppression as the discharge of water mist enhances the heat convection between the flame and the fuel.

The influence of cooling of water mist on the burning rate of flammable fuel is limited, because the heat loss from the fuel surface is limited, while for fuels with a high surface temperature,the cooling influence on the burning rate is significant.

2.7 Fds Simulation and Computation.

The Fire Dynamics Simulator (FDS, Ver.3.0) is used to simulate the interaction of fire plume and water mists .Fire-driven flows in FDS is simulated by LES (Large Eddy Simulation) turbulence model, mixture fraction combustion model, finite volume method of radiation transport for a non-scattering gray gas, and conjugate heat transfer between wall and gas flow. Two-phase flow between water droplets and gas flow is modelled by Eulerian–Lagrangian method. In the present study, the Rosin–Rammler distribution is used for the initial droplet size distribution at the nozzle exit. The secondary break-up of water droplets is modelled by Reitz and Diwakar model. In this model, two droplet break-up regimes are considered. FDS code is based on the orthogonal grid system; inclined surface of the compartment is represented by Stepwise grid approximations. A mesh of 338,688 cells is used to discretise the domain. There are 84 cells in the length and the width of the compartment and 48 cells in the height. Prior to simulate the fire suppression, the preliminary test is performed to validate the predictions of FDS code against the experimental data for diesel fires without water mist.

The use of smaller mesh elements in a CFD simulation generally increases the accuracy of the results. Spatial gradients are approximated using more points and, for large-eddy simulations, a greater proportion of the flow vortices are modelled directly without resorting to a turbulence model. The drawback of higher resolution meshes is their increased computational cost. A mesh resolution should be chosen which yields results with the desired accuracy but also takes into account limitations on available time and computational resources. For CFD simulations of fire scenarios, mesh refinement is most important in the combustion volumes, plume boundaries and thermal layer interfaces. combustion models require fine enough mesh resolutions to accurately model the production of heat and fire products. Plume boundaries and layer interfaces represent areas of relatively high gradients in the flow and require small mesh elements to accurately predict entrainment and mixing rates.

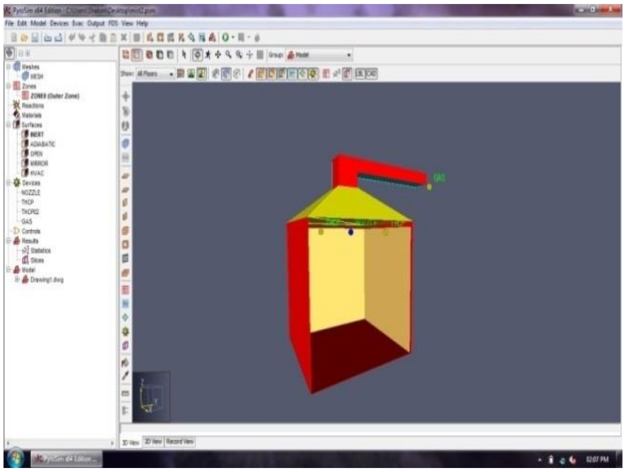


Fig-7: Experimental setup in fds software

2.8 Validation of Fds Prediction against Experimental Data.

The preliminary test is performed to validate the predictions of FDS code against the experimental data for diesel fires without water mist. The temperature generated inside the experimental setup by firing diesel oil in oil pan is recorded and viewed through digital temperature indicator connected with K-type thermocouple which is fitted in the test setup. The temperature inside the setup is also taken from the fire simulation done using FDS software.

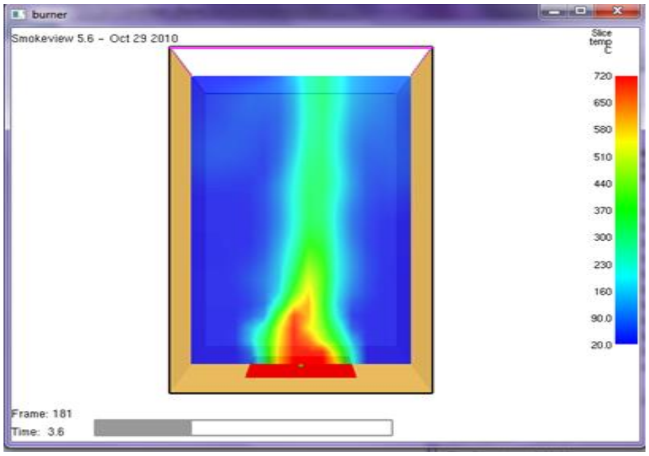
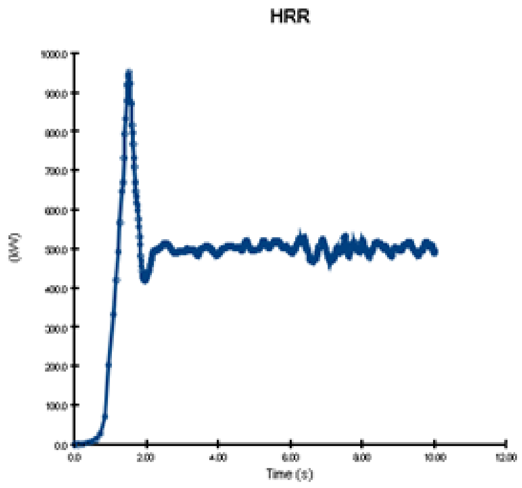
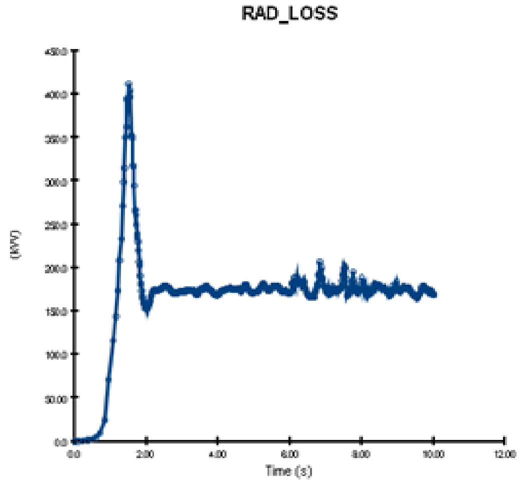
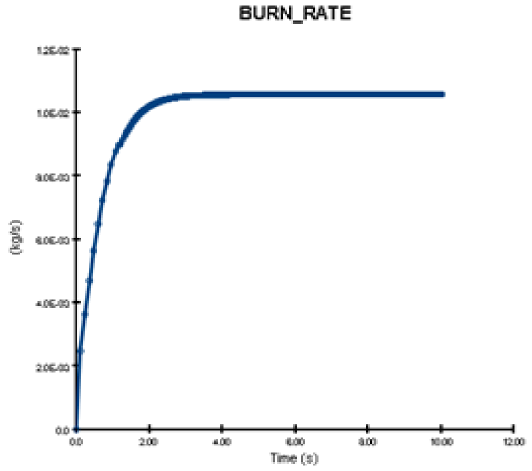
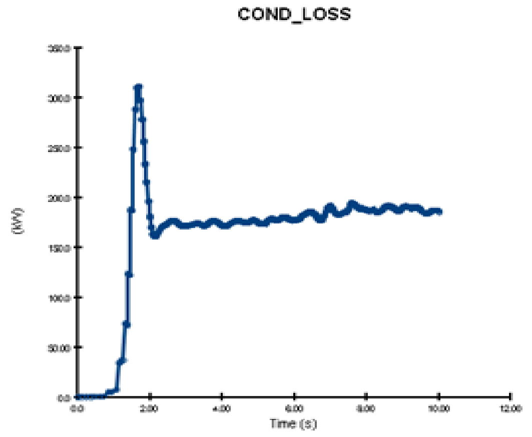


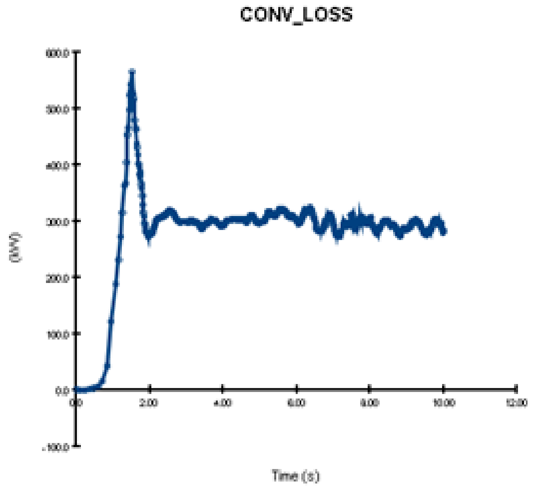
Fig-8: Temperature Profile inside the Experimental Setup











The simulated results are in good agreement with experimental results.After validating the experimental result of temperature generated inside the setup with simulated results; the diesel fire is generated inside the test setup. After 50 seconds water mist was activated and allowed to extinguish the fire. The two nozzles used for water mist are downward-directed hollow cone type single orifice pressurized swirl type with a capability to produce droplet of size 50 and 100 microns respectively, spray pattern is 90degree,pressure from the pump is 3 bar, with a pumping capability of 1 GPM. The extinguishing time is 25s and 30s after mist injection for 50 and 100 micron nozzles respectively.

Table 1: Extinguishing time for varying droplet size

Fuel	Nozzle type	Nozzle height (m)	Spray angle(º)	presse (bar)	Extinguishing time(s)
Diesel	7G-5(100 µ)	1.6	90	3	30
Diesel	7G-5(50 µ)	1.6	90	3	25

When a water mist is discharged into a hot smoke layer, water mist will cool down the fire compartment and prevent the fire from propagating into flash-over. The present study investigates the cooling effect of water mist on the suppression of diesel pool fire.

The injection times of water mist system are 50s for both cases. When water mist is discharged from nozzles, generally, water mists absorb heat from the surrounding gas phase and quickly evaporate. At the same time, discharge of water mist makes a strong dynamic mixing in the compartment and consequently temperature gradient between upper and lower layers decreases.

We can observe three different regimes, namely, (a) the initial fire growth regime, (b) the sudden cooling regime, and (c) the gradual cooling regime. Our interest is only focused on two regimes (b) and (c) because these regimes mainly contribute to suppress the fire after water mist operates. In regime (b), the temperature of smoke layer decreases rapidly as time goes on. It means that the rapid evaporation of droplets occurs in this regime because of very hot smoke layer. Unlike this, the regime (c) shows that the mean ceiling temperature gradually decreases with much lower rate than that of regime (b). It results from the fact that the temperature difference between droplets and smoke layers are relatively lower than that in regime (b) because thermal energy accumulated in the regime (a) is mostly lost in the regime (b). Now let us determine a critical cooling time during which the regime (b) maintains since the injection start of water mist. This parameter may be useful in discriminating between regimes (b) and (c) and in examining the fire suppression characteristics. Regime criterion between regimes (a) and (b) can be easily determined by a maximum temperature, whereas the critical cooling time is difficult to be defined clearly between two regimes (b) and (c).

The present study uses the auto-correlation function in determining the critical cooling time. The critical cooling time tends to decrease with increasing water flow rate. The information about the critical cooling time in sudden cooling regime may help us in determining the performance of water mist system for the initial fire suppression.

Nevertheless, FDS code does not consider this variation of burning rate. Thus, further theoretical and experimental studies for the water mist and smoke movement should be performed as a future work in order to complement the present combustion model.

3. CONCLUSION

Fire suppression characteristics of water mist for diesel pool fire have been studied experimentally and numerically. It is found that the cooling of smoke layer with time is divided into two regimes such as sudden and gradual cooling regimes, and the critical cooling time is determined from the autocorrelation function. The oxygen concentration in the lower layer significantly decreases after discharge of water mist because of strong mixing in the compartment.

Additionally, three-dimensional simulations using FDS are performed and their results are compared with experimental data for mean ceiling temperature and oxygen mole fraction. The temperature predictions show good agreements with the measured data within 10◦C for diesel fire. However, the present simulations fail to predict the fire extinguishment in diesel fire because of lack of modelling for fire extinction. More elaborate models are thus required for better predictions of the fire extinguishment characteristics using water mist.

The extinguishing mechanisms of water mist systems have been identified as: cooling of the fuel and flame, displacement of oxygen and fuel vapour, and radiant heat attenuation, with additional kinetic effects. Although all of these mechanisms are involved to some degree in fire extinguishment, only one or two mechanisms play a dominant role in any specific fire suppression scenario. Water mist does not behave like a "true" gaseous agent in fire suppression.

The effectiveness of a water mist system in fire suppression is dependent on spray characteristics (the distribution of droplet sizes, flux density and spray dynamics) with respect to the fire scenario (shielding of the fuel, fire size and ventilation conditions). Other factors, such as the enclosure effect and the dynamic mixing created by the discharge of water mist, also affect water mist performance in fire suppression.

Due to the complex extinguishing processes, the relationship between a fire scenario and the characteristics of a water mist system is not well enough understood to apply a “first principles” approach to the design of a water mist system. A combination of laboratory and computational modeling studies with validation by fire tests is needed to make the development of water mist systems much more efficient and effective.

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BIOGRAPHIES

Venkatesh PL
BE Mechanical Engineering
RMK Engineering College
Anna University(Chennai).

Harish D
BE Mechanical Engineering
RMK Engineering College
Anna University(Chennai).

Mohamed Nihal H
BE Mechanical Engineering
RMK Engineering College
Anna University(Chennai).