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FIRE SUPPRESSION ANALYSIS FOR INDUSTRIAL BUILDINGS USING WATER MIST

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Abstract

The present research is using a Fire Dynamics Simulator FDS tool for computational design the fire spread and distribution of fire exhaust particles. Therefore, knowing the program capabilities are very important for modeling this problem. Nowadays, many different applications are using FDS, such as modeling for flow of smoke in different ventilation conditions, fires in tunnel and multi-floors buildings. The effectiveness of using various water mist flow rate amounts, different water mist particle sizes and two different fire source positions (corner and center) on the fire extinguishing time, are investigated through various scenarios of fire suppression by design and build a 1/5-scale of water mist system throughout FDS model "using PyroSim program", which shows a pronounced effected result. The firefighting time is reduced with decreasing the water mist droplet size (up to 30 µm). The fire suppression time decreases as a result of increasing the flow rate of water mist spraying (up to 40 l/min).

Introduction

The fire suppression researches (fire safety) have globally captured more attentions; as a result of heavy losses of people and property as a result of these fires.

Using water mist in fire extinguishing is widely considered as an alternative to the methods of gaseous fire suppression. In the last years a lot of commercial activities have been occurred to develop the fire suppression technology systems based on water mist. Although the researchers in the 1950's have recognized the dominant mechanisms of fire extinguishing, recent experimental work has a particular fire scenario, and is essential for the algorithms development of the computer models which using water mist on fire suppression systems.

The regulations of Fire safety have a major impact on many different aspects of the design of buildings overall; include cost, aesthetics, layout and function. Rapid developments in the technology of the modern buildings in last decades are often have been resulted in design solutions unconventional structures. Buildings physical size are continually increasing, also there is a tendency to build a shopping complexes, warehouses and large car parks underground. A new factor of risk regarding fire spread and smoke are introduced through many buildings interior design which have large light shafts, patios, and covered atriums within buildings connected to horizontal corridors or malls [1], [2] and [3].

Statistics from the National Fire Protection Association help support the fact that the high-rise buildings are generally among the safest structure's types[4]and[5]. Less than one percent of the dead due to fires accidents occur in high-rise buildings, and only a small number of major fires reported damages over $250 000 in high-rise buildings [6]. The spread of fire, smoke and gases between floors should try to be limited in high-rise buildings. A study conducted in 1971 showed that ten percent, or 5 out of the 51 high-rise building fires studied, spread outside the windows to the upper floors.

A number of full-scale fire tests have been conducted in laboratories in different parts of the world Tran and

Jansen [7] constructed a full-scale industrial building and studied the fire growth over wall lining for different materials, also Motavalli, Ricciuti [8], and Motavalli and Marks [9] studied the characteristics of ceiling jets in fires for both confined and unconfined enclosures, Arnaud Trouvé, [10].

The dimensions of the fire dynamic simulator "FDS" model hanger rebased on a 1/5-scale of typical industrial building model (hanger) of a gypsum board triangle polygon ceiling, and a rectangular base of dimensions of (6.0m x 2.0m and a height of 2.5m) with an opening door dimensions of (0.6m x 0.5m), and (6opening windows), (3 on left wall) and other (3 windows) on triangle ceiling (all of same dimensions 0.75m x 0.3m) are designed and been built for predicting geometry of fire spread and particles distribution of water mist. The heat release is obtained from a cubic burner of (0.2m) side length that used nylon fuel and a heat release of (500 kW) that is kept constant throughout the study. The model is subjected to study different cases, all results are based on above scaled described standard model simulation for various water mist characteristics along with fire source position.

The nozzles spraying a tiny droplet of water mist that is varies from (50 μm to 30 μm), after the water mist has enters the injection area, it quickly encapsulates the fire source and reducing the concentration of oxygen. In addition, the evaporation of these tiny droplets of water mist can reduce quickly the fire temperature, meanwhile the water mist effect reduces concentration of oxygen gas like the physical effect of using a gas on fire extinguishment, beside its very excellent performance of blocking the transfer of thermal radiation which can block effectively the intense heat radiation.

Firefighting methods and practice in particular the use of water mist as a fire suppression system is presented and analyzed in this paper, investigating its effect on the fire spread in industrial buildings such as a hanger, through using same heat release with different water mist droplet size, water mist flow rate amount.

Model Formulation

The specifications of the (FDS) model that presented in this paper, which consists of a simulation of hanger with inclined ceiling, fixed nozzles configuration, and various water mist flow rates along with different droplets size, which plays a vital role to suppress the fire in the two different positions (center and corner) [11]. Also, a comparison between the present FDS simulated model and experimental results of NFPA 750 [12] is done. The used model has more ventilation in walls and ceiling as per the guidelines of NFPA 204 [13] and [14].

The fire simulation is created through a cubic burner which is positioned inside the cubicle, also in the presence of the of water mist. The input of the model, the output and the solution of the governing equations are also given in the present work.

Tested Building Configuration

The dimensions of the FDS model hanger are (6 m length x 2 m width x heights 2.5 m) with an opening door which is located at the front of the compartment, its dimensions are (0.6 m x 0.5 m) and (6 opening windows), (3 on left wall) and other (3 windows) on triangle ceiling (all of same dimensions 0.75m x 0.3m). The FDS simulation of the fire is created by a cubic burner of 0.2 m side length placed inside the cubicle in the presence of water mist nozzles.

In this model, three nozzles are used, and nylon is used as a fuel in the simulation.

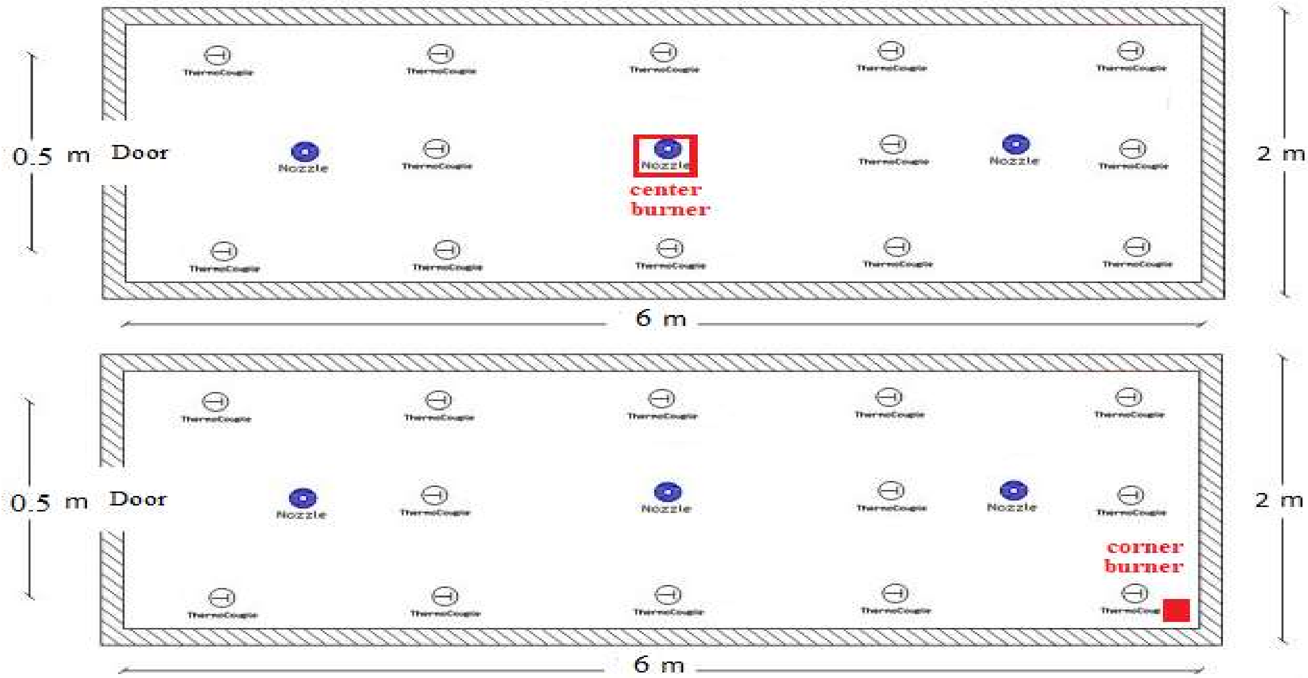


Figure 1. “Plan of hanger model”

Figure 2. “Elevation and Side View of hanger model”

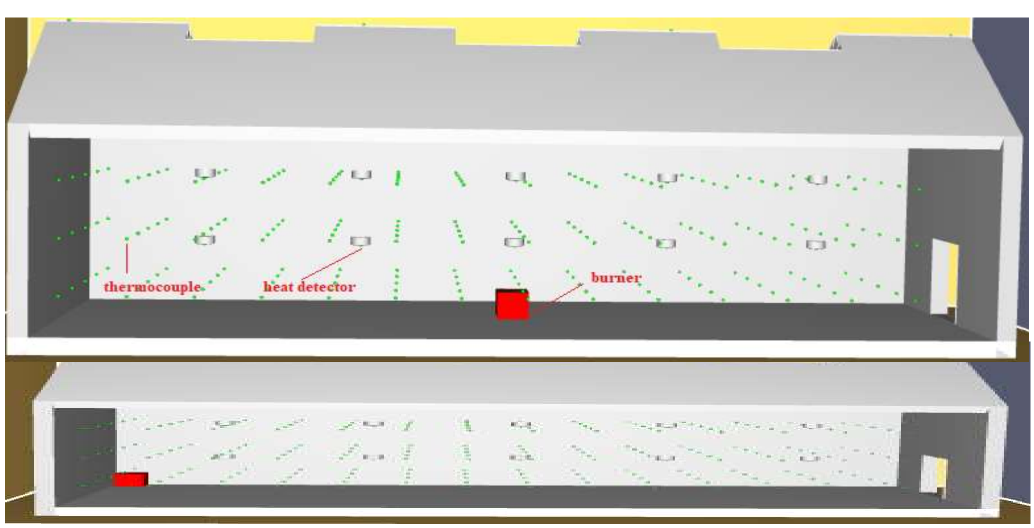


Figure 3. "Schematic 3D view of hanger model (FDS)"

Resolution of the Grid Cells

A grid cell is 0.09 m is selected for the model basic hanger, with the total cells of 73,689. This simulated model took at least around 48 hours for each run. The specified size of the mesh is taken according the FDS User Guide [15], the size of mesh is appropriately determined through a ratio of D*/dx between 4 to 16. In that ratio, dx is the basic mesh cell size, and D* is a fire characteristic diameter that is defined in here below equation:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty * C_p * T_\infty * \sqrt{g}} \right)^{2/5}$$

The $\dot{Q}$ is the rate of heat release, air density is ρ_∞ (1.204 kg/m^3),air specific heat is C_p (1.005 kJ/kg.K), temperature of ambient is T_∞ (293 K), and gravity acceleration is g (9.81 m/s^2). D*/dx equal to 16 is the ratio that results best mesh size to be used.

The Main Equations

A six unknowns are presented through the following partial differential equations, all functions of three spatial dimensions and time: where ρ is the density, the velocity three components U = [u; v; w], p is the pressure, and T is the temperature T.

The Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

The Navier-Stoke Equation

$$\frac{\partial u}{\partial t} = -(u \cdot \nabla)\, u + \nabla \cdot (\square\, \nabla u) - \frac{1}{\rho} \nabla \rho + f$$

Energy Equation

$$\frac{\partial}{\partial T}(\rho H) + \frac{\partial}{\partial Xj}(\rho vjH) = \frac{\partial p}{\partial T} + \frac{\partial}{\partial Xj}\left[\frac{\lambda}{Cp} \frac{\partial h}{\partial Xj} - \dot{q}_j^r \right]$$

The delay measurement in gas true temperature caused by the thermocouple is mainly calculated through its bead size. It is calculated through solving here below thermocouple temperature equation, T_{TC}

$$\rho_{TC} c_{TC} \frac{dT_{TC}}{dt} = \varepsilon_{TC}(U/4 - \sigma T_{TC}^4) + h_c(T_g - T_{TC}) = 0$$

The release heat rate is given by the equation

$$\dot{q}^m = \dot{m}_F^m \Delta H_F$$

The Model Confirmation by NFPA 750 experiment

The NFPA 750 experiments are modelled by using a computational shaped area of a rectangular of height equal 1.5 m, the width equal to 0.5 m and the length equal to 0.5 m. The computational area is open on all sides. The all nozzles were placed at 0.1 m from the top of the computational domain while measurements were carried out at 1 meter below the nozzle [13], Table (1) summarizes the used nozzles parameters [13]:

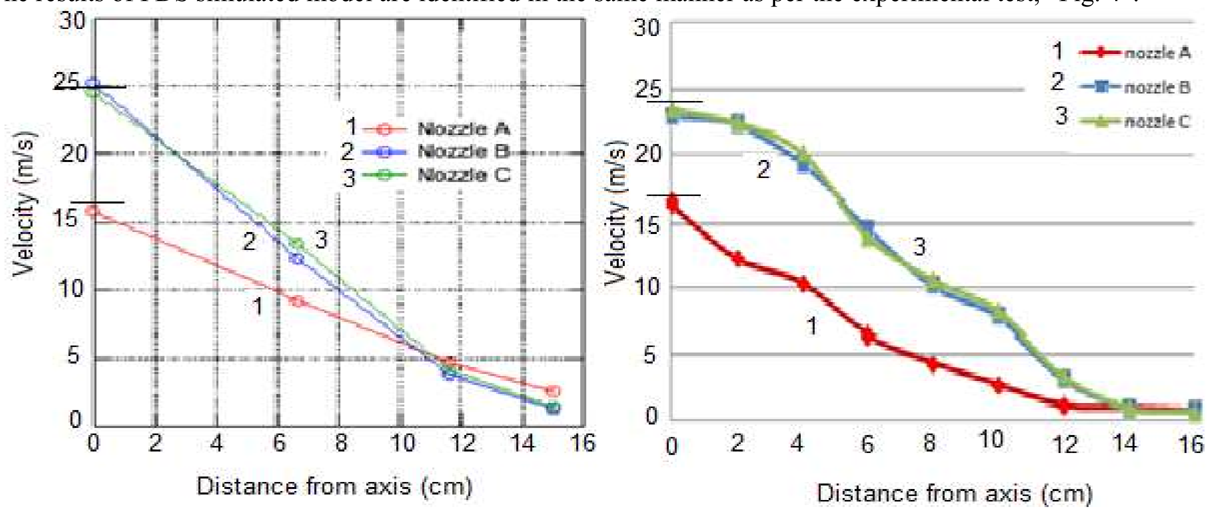
Table 1. "Parameters for nozzles A, B and C. [13]"

nozzle	K (l/min/bar^{½})	ϕ (deg)	d_m (μm)	γ	σ
A	0.2	10	83	2.9	0.4
B	0.433	12	79	2.26	0.5
C	0.767	14	102	2.59	0.52

A 2 cm grid is used for the modeling, with a total of 46875 cells.

The velocity distributions of water mist droplet for nozzle A, B and C are validated with FDS model.

The results of FDS simulated model are identified in the same manner as per the experimental test, "Fig. 4".



Experimental results Simulated results

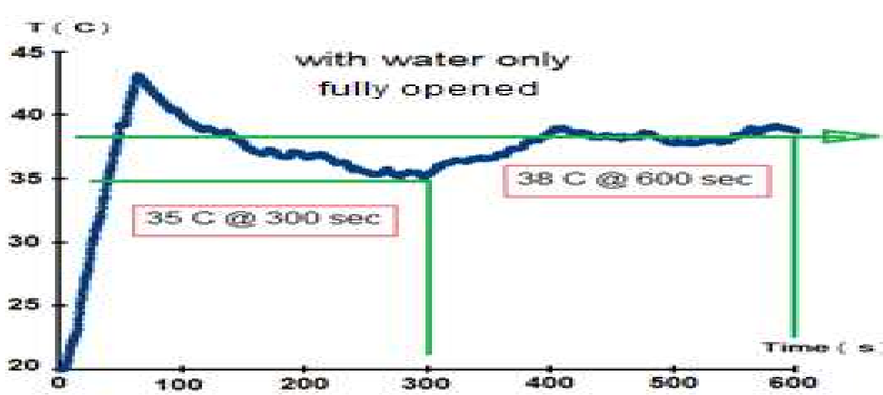
Figure 4. "Experimental [13] and simulated data for nozzles A, B, and C"

Results have shown a fair agreement between FDS model and the experimental data as shown.

Results and Discussion

The effect of using the water mist on fire spread in hanger through various scenarios of fire suppression "as shown in Figs 1, 2 and 3" is presented through using different water mist flow rates amount, various water mist particles size and different fire source positions (center and corner) at constant amount of heat release on fire extinguishing, the phenomena is investigated through building and design a 1/5-scale of water mist system throughout FDS model.

The following fig. no. 5, a simulated trial of fire extinguishing using water only is presented to show the effective difference between results after starting using the water mist.

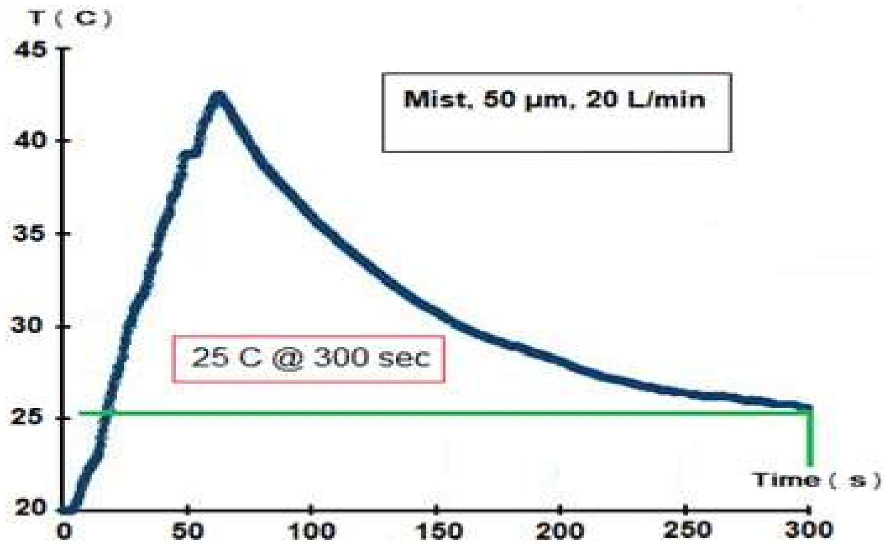


This figure reflects the poor effect of using water only on the fire extinguishing, during 600 sec the sprayed water couldn't extinguish the fire

Figure 5. “Average Temperatures of Using Water only”

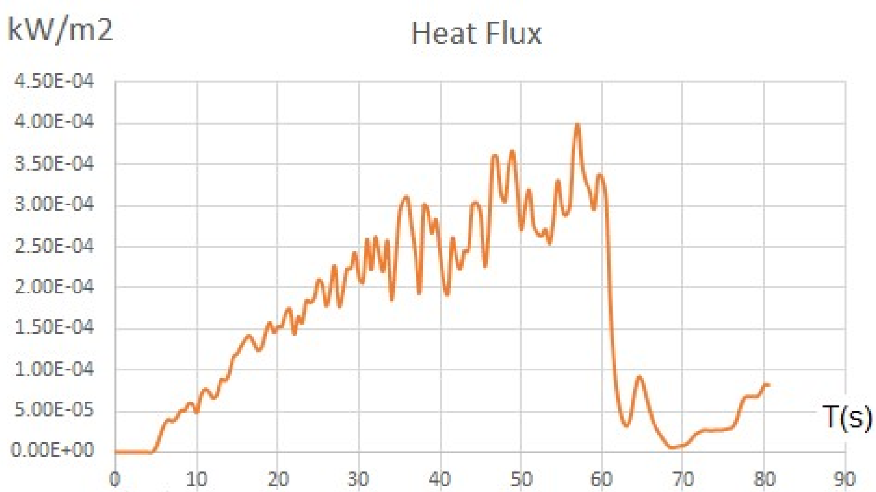
- **A discussion of the effect on fire extinguishing time while using water mist :**

❖ ***Scenario I:***



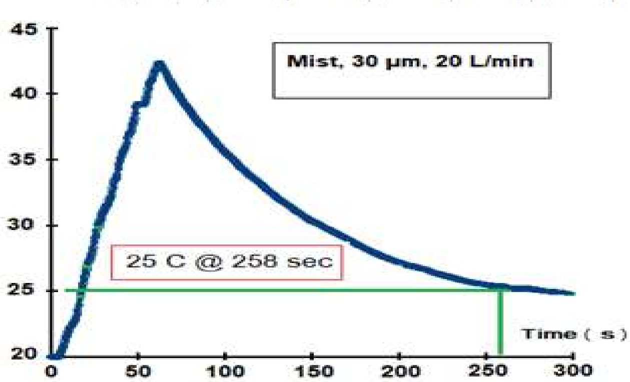
In this fig. no. (6), once applying the water mist fire suppressing system to the same model of previous fig. no. (5), a pronounced effect has been occurred, and finally the fire is extinguished @ 300 sec.

Figure 6. “Average Temperature of Using Water Mist ($Q= 500\ kW/m^2$, q= 20 l/min (per nozzle of three), Di= 50µm)”



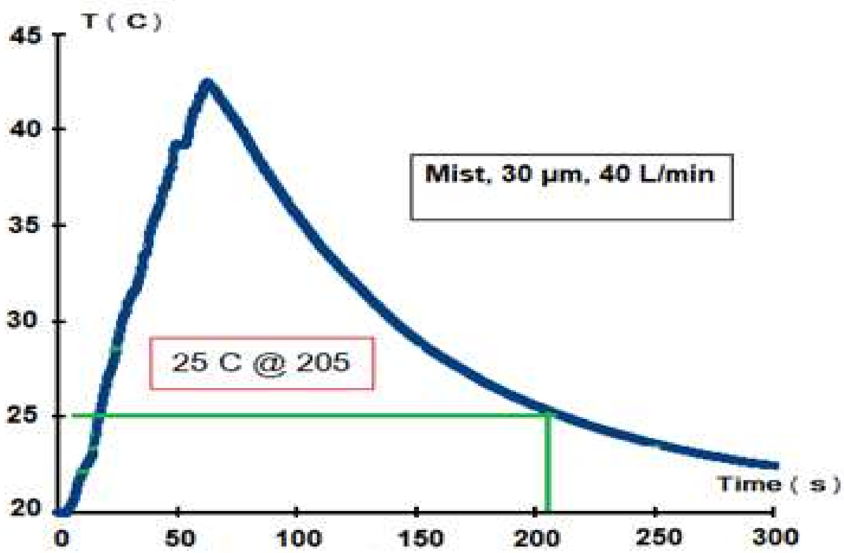
Moreover, this figure shows the positive effect on prevent heat flux spread.

Figure 6.a. “Average Heat Flux of Using Water Mist ($Q= 500\ kW/m^2$, q mist= 20 l/min (per nozzle of 3), Di= 50 µm)”



A smaller droplet size has been used while keeping all previous conditions of fig. no. (6) constant, the extinguishig time has been enhanced to be 258 sec

Figure 7. "Average Temperature of Using Water Mist
(Q= 500 kW/m², q= 20 l/min (per nozzle of three), Di= 30 µm)"



After double the quantity of flow rate amount to be (40 l/m), maintaining all conditions the same as previous fig. no. (7), an enhancement in time of fire extingiuishing has been occurred by more than 50 sec to be reached 205 sec

Figure 8. "Average Temperature of Using Water Mist
(Q= 500 kW/m², q= 40 l/min (per nozzle of three), Di= 30µm)"

- **Effect of Droplet Size of Water Mist**

The droplets size varied from (50 to 30 µm), after the fire ignition, the water mist is actuated and discharged by the nozzles, through direct cooling the fire would be suppressed by mists, the evaporating cooling, and by the displacement of O_2.

Application of water in smaller droplets diameters offers many advantages [17], [18] and [19]. Water mist droplet has a large surface area and small size. When the ambient temperature rises, the droplet can quickly vaporize, while the surface heat transfer coefficient value has become larger. In a very short time numerous of the very tiny water droplets rapidly absorb heat. From the laws of thermodynamics: when one gram of water increases by 1 ºC, 1 card heat would be absorbed in this progress; when 1 gram of water vaporizes, about 600 calories would be absorbed.

The hot gas layer temperature is drastically cooled down after water mist nozzles activation due to the removal of heat of evaporation by the mists. After the fire becomes extinguished by mists, the temperature of hanger would gradually decrease. Under the same conditions, simulations are conducted to investigate the mechanism of fire extinguishment for a water mist with different sizes of water droplets, as shown is figures no. (6 and 7). Smaller droplets discharged from a water mist would be evaporated quickly. This phenomenon causes a surrounding gas cooling and a reduction in concentration of O_2, due to generation of a large amount of steam, [20].

In better heat transfer and more rapid evaporation, smaller droplets would be resulted due to higher temperature from the fire, therefore causing a sudden increase in the steam fraction along the droplet flow trajectory. After droplet evaporation, an enough steam surrounds the fire. In the meantime, the generated steam would displace the rest of gases including O_2, causing a great reduction in its concentration. Therefore, the water mist with finer droplet size has a positive effect and better performance on fire suppression, [21].

- **Effect of Nozzle Flow Rate**

Figure (8) shows the time of fire suppression along with average temperatures, using the spray nozzles with double amount of flow rates (from 20 to 40 l/min). In this figure, after injection of water mist, the droplets of water mist begin to be sprayed downward then cool the burning surface, absorb heat from the hot gases, the fuel and the surrounding objects and surfaces.

While the nozzles continue spraying, more water mist droplets being converted to steam and penetrate through the fire plume, then significantly cooling the flame zone and reaction zone, which affect the chemical reaction rate inside the plume, [22], [23] and [24]. Consequently, the fire is extinguished as a result of decreases the temperature of fire plume to be low as much as enough.

The time of fire suppression decreases as a result of increasing the rate of water mist sprayed flow, as shown in Fig. (8). The higher sprayed rates of flow result in the higher momentum of water mist droplets and consequently cause more droplets to penetrate into the fire plume.

- **Another scenario after changing fire source location is presented:**

❖ ***Scenario II:***

- ***Corner:***

A new different case scenario has been simulated for the same model, the heat release still maintained at 500 kW/m², and also the water mist flow rate still kept at (20 l/min, per nozzle), the droplet size of the water mist is (50 µm), fire place has been changed to be located at the corner of the hanger.

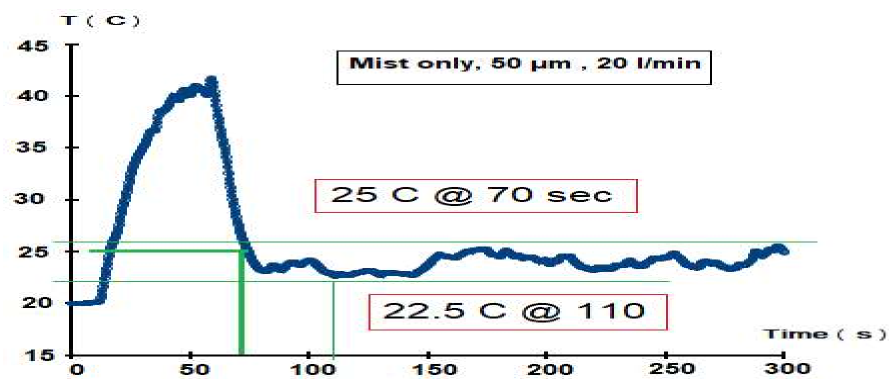


Figure 9. "Average Temperature of using water mist only (Q= 500 kW/m², q mist= 20 l/min, Di= 50 µm)"

Extinguishing a fire in corner has a good result in temperature control, as the fire has been suppressed in a short time, that's a sign of good control on fire extinguishing in case the fire accident has been occurred at the corner of the room. A slight fluctuation along the curve has been noticed.

Let's illustrate the curves of the Heat Flux and the CO2, to show the other effects on different aspects:

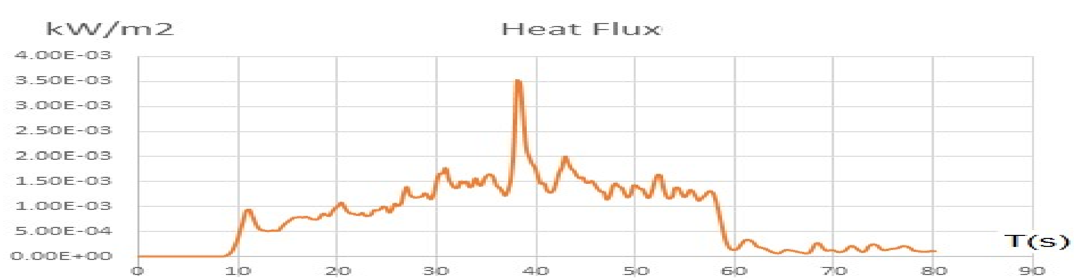
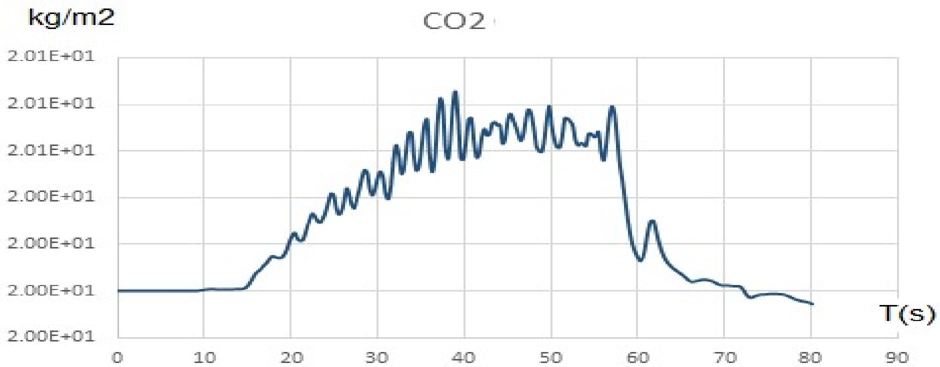


Figure 9.a. “Average Heat Flux of using water mist only (Q= 500 kW/m2, q mist= 20 l/min, Di= 50 µm)”



Water mist nozzles activations affect extremely positively on both of carbon dioxide concentration and the heat flux.

Figure 9.b. “Average CO^2 concenterationof using water mist only (Q= 500 kW/m^2, q mist= 20 l/min, Di= 50 µm)”

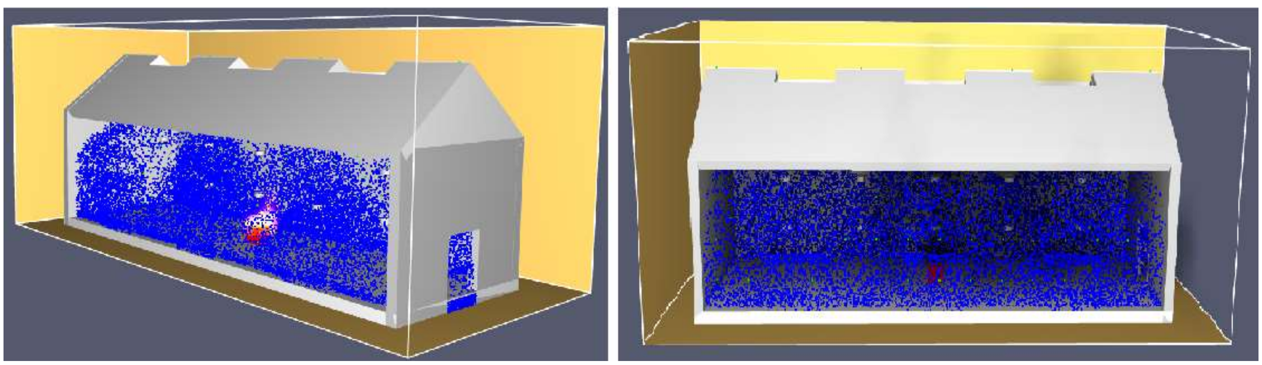


Figure 10. “Activation of water mist on fire at center “

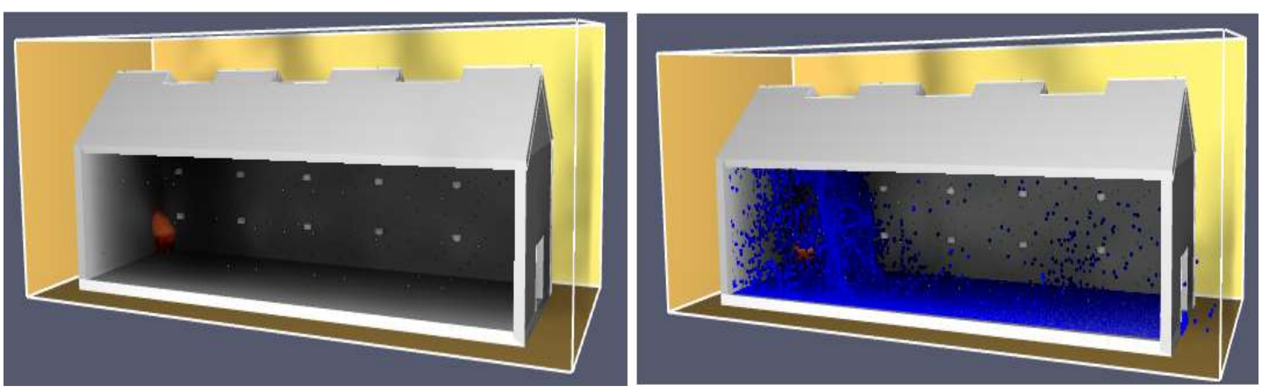


Figure 11. “Activation of water mist on fire at corner “

The summary of results analysis for all simulated cases are shown in hereunder table:

Table 2. “Cases Classifications”

Cases / Ser.	Fire Source Location - Heat Release (500 kW/m2)	Water Mist Droplet Size (µm)and Flow Rate (L/min) - (per Nozzle)	No. of activated Nozzles of Water Mist	Extinguishing Time (Sec) @ 25 ºC	Results Summary
1		**Water only**	**3 Sprinkler s**	**35 ºC @ 300** **38 ºC @ 600**	Using water only is not sufficient to overcome the fire. (fig. no. 4.5)
2	**Center**	**50 µm, 20 L/min**	**3**	**300**	After using the water mist, the fire has been extinguished but it still could be enhanced. (fig. no. 4.7) – **paper, scenario I**
3		**30 µm, 20 L/min**	**3**	**258**	Then after reducing the water mist droplet size, the extinguishing time has been enhanced. (fig. no. 4.7) – **paper, scenario I**
4	**Center**	**30 µm, 40 L/min**	**3**	**205**	In addition, after increasing the water mist flow rate quantity, the extinguishing time has been enhanced. (fig. no. 4.7) – **paper, scenario I**
5	**Corner**	**50 µm, 20 L/min**	**1**	**70**	A good result in temperature control as the fire has been suppressed in a short time. (fig. no. 4.25) –**paper, scenario II**

Conclusions

A CFD program (FDS-PYROSIM) is used to simulate the compartment of fire and illustrate temperatures output results, firefighting time, blockage of heat flux, and concentration of fire exhaust gases due to the effectiveness of using different water mist droplet diameter sizes and different flow rates of water mist on fire suppression through several scenarios of same hanger at constant heat release.

The output results of the FDS simulated model are verified through a comparison with the results of NFPA 750 experimental Verification Model [13].

After running the computer simulations at same heat release amount for different proportions of nitrogen gas and water mist flow rates amounts, and various droplets sizes of water mist, the following conclusions are estimated:

- The firefighting time is reduced with decreasing the water mist droplet size (up to 30 µm), table no. 2 (case no. 3).
- The fire suppression time decreases as a result of increasing the flow rate of water mist spraying, table no. 2 (case no. 4).

NOMENCLATURE

A_d	Area of droplet exposed to drag forces, m^2
A_o	Orifice area, m^2
B	Mass transport number
C_d	Drag coefficient
C_g	Specific heat of gas, J/kg.K
C_l	Specific heat of liquid water, J/kg.K
C_p	Specific heat (kJ/kg.K)
C_o	Nozzle discharge coefficient
D_F	Diffusion coefficient
D_i	Droplet diameter, µm
D_o	Initial droplet diameter, µm
$D_{V0.5}$	Volume Mean Diameter
d_o	Orifice diameter, mm
D*	A characteristic fire diameter (m)
dx	The nominal size of a mesh cell(m)
F_d	Forces on the droplet, N
G	Gravitational force, N
g	The gravitational acceleration (9.81 m/s^2)
H	Pressure at nozzle, meter water
h	Height of opening (m)
h_c	The heat transfer coefficient($W/m^2.K$)
l	Distance from nozzle, m
l_o	Distance from nozzle where droplets starts to fall out, m
k	Conductivity(W/m.K)
L	Latent heat of vaporization of water, J/kg
M_d	Mass of droplet, kg
Nu	Nusselt number
p	Pressure, Pa
Pr	Prandtl number
Q	Specific heat, J/kg
$\dot{Q}$	The heat release rate (kW)
$\dot{q}_c''$	Convective heat flux (kW/m^2)
$\dot{q}_r''$	Radiative heat flux(kW/m^2)
R	Radius of droplet, m
R_n	Reaction force of nozzle, N
r	Radius of spray, m
Re	Reynolds number
SMD	Sauter Mean Diameter
T	Temperature
T_d	Droplet temperature, K
T_g	Gas temperature, K
T_R	Temperature inside droplet, K
T_r	Adjusted reference temperature, K
T_W	Droplet wall temperature, K
T_∞	Temperature far away from droplet, K
T_{TC}	The thermocouple temperature(K)
T_∞	The ambient temperature(293 K)
U	The integrated radiative intensity

$\dot{V}$	Volume flow rate, m^3/s
V_d	Velocity of spray, m/s
V_c	Velocity of combustion products, m/s
V_{dtol}	Total water droplet velocity with respect to gas flow, m/s
V_h	Relative horizontal water droplet velocity with respect to gas flow, m/s
V_n	Mean velocity after the nozzle, m/s
V_r	The velocity in the pipe before the nozzle, m/s
V_v	Vertical water droplet velocity with respect to gas flow, m/s
V_y	Water droplets velocity in y direction in fixed coordinate system, m/s
V_x	Water droplets velocity in X direction in fixed coordinate system, m/s
V_z	Water droplets velocity in z direction in fixed coordinate system, m/s
VMD	Volume Mean Diameter
X_i	number of droplets
Y	Mass fraction
Y_R	Mass fraction inside droplet
Y_∞	Mass fraction far away from the droplet
Θ	Angle between droplets trajectory and horizontal plane
α_g	Thermal diffusivity, m^2/s
β	Angle between droplets trajectory and gas flow in the horizontal plane
ρ	Density (kg/m3)
ρ_∞	The density of air (1.204 kg/m^3)
ρ_d	Density of droplet, kg/m^3
μ	Dynamic viscosity , N.s / m^2
ε	The emissivity
ε_{TC}	The emissivity of the thermocouple
σ	Stefan Boltzman constant ($W/m^2 K^4$)
υ	Viscosity, m^2/s
Θ	Cone angle , degree

Abbreviations

APV	Adaptive phase Doppler velocimetry
CFAST	Consolidated model of Fire growth and Smoke Transport
CFD	Computational Fluid Dynamics
FDS	Fire Dynamic Simulator; the CFD model used in this research
HRR	Heat Release Rate
HRRPUA	Heat Release Rate Per Unit Area
LES	Large Eddy Simulation
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
WMFSS	Water Mist Fire Suppression System
UL	Underwriters Laboratories

EN European Notification

BS British Standard

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