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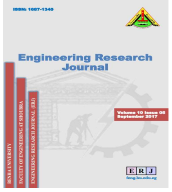

FIRE SUPPRESSION ANALYSIS FOR INDUSTRIAL BUILDINGS USING HYBRID SYSTEM

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Abstract

The present work has employed the Fire Dynamics Simulator "FDS – PyroSim program" to analyze the computational design, the spread of fire and distribution of particles. The FDS is used in modeling the present standard hanger building, through studying the effectiveness of using different ratios of Nitrogen gas flow rate injection compared with water mist flow rate amount at various water mist particles size and different fire source positions such as center and corner on fire extinguishing time, that shows a pronounced optimum ratio results of 1:1. The results showed that time of fire suppression is decreasing with decreasing the droplet size and increasing the water mist flow rate. The best mixing ratio of Nitrogen gas with water mist is found to be 1.1 for minimum suppression time 175 second .and the total optimum Nitrogen flow rate is 60 l/min and the diameter of the water droplet is 50 µm; and of total flow rate 60 l/min. The FDS is also used for the smoke flow modeling in different ventilation conditions, tunnel fires and multi-floors buildings.

Introduction

The fire suppression researches (fire safety) have captured more and more worldwide attentions, this is because of the heavy losses of people and property as a result of these fires. Fire suppression by using water mist is considered widely an alternative of the gaseous fire suppression methods. A lot of commercial activities have been occurred in the last years to develop the technology of the fire suppression systems based on water mist, besides various auxiliary factors; such as Nitrogen gas in this case [1]. Although the researchers in the 1950's have recognized the dominant mechanisms of fire extinguishing, recent experimental work has a specially fire scenario and is important for the algorithms development of the computer models which using water mist on fire suppression systems.

Fire safety regulations can have a major impact on different aspects of the buildings overall design, 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. The physical size of buildings is increasing casually, also there is a tendency to build a shopping complexes, warehouses and large car parks underground. The interior design of many buildings with large light shafts, patios, and covered atriums within buildings connected to horizontal corridors or malls introduces new risk factors concerning spread of smoke and fire [2], [3] and [4].

Statistics from the National Fire Protection Association NFPA help support the fact that the high-rise buildings are generally among the safest structures' types [5] and [6]. 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 the high-rise buildings [7]. 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 [8] constructed a full-scale industrial building and studied the fire growth over wall lining for different materials, also Motavalli, Ricciuti [9], and Motavalli and Marks [10] studied the characteristics of ceiling jets in fires for both confined and unconfined enclosures, Arnaud Trouvé, [11].

The dimensions of the fire dynamic simulator "FDS" model standard hanger are based on a 1/5 scale of typical industrial building model (hanger) of a gypsum board triangle polygon ceiling, and a rectangular base of dimensions (6.0m x 2.0m and a height of 2.5m) with an opening door dimensions of (0.6m x 0.5m), and 6 opening 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 along with using nitrogen gas. 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. All results are based on above scaled described standard model simulation for various water mist characteristics in addition to different proportions of nitrogen gas along with fire source position. The model is subjected to study different cases.

The nozzles inject a mixture of different proportions, changing the ratio of nitrogen gas to water mist from (1:6, 1:3, 1:2, 2:3, 1:1, 2:1), along with a tiny droplets of water mist that is also varies from 50 µm to 30 µm, after the nitrogen gas has enters the injection area, it quickly combines with the room air and reducing the oxygen volume fraction, thereby absorbs heat in the area, trying to suppress the flame. In addition, the evaporation of these tiny droplets of water mist can reduce quickly the fire temperature, meanwhile the water mist effect is like the physical effect of using a gas on fire extinguishment that could reduce the concentration of oxygen, 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 combination of Nitrogen gas and water mist as a fire suppression system is presented and analyzed in this paper, investigating the effect of using the mixture on the fire spread in industrial buildings such as a hanger, through using same heat release with different amounts of Nitrogen gas, water mist flow rate, and water mist droplet size.

Model Formulation

The specifications of the (FDS) model that presented in this paper, which consists of simulation of a hanger with inclined ceiling, fixed nozzles configuration, and various ratio of water mist to Nitrogen gas, along with droplet size, which plays a vital role to suppress the fire in different positions (center and corner) [12]. Also, a comparison between the present FDS simulated model and the experimental results of NFPA 750 [13] is done. The used model has more venation in walls and ceiling as per the guidelines of NFPA 204 [14] and [15].

The simulated fire is produced through a cubic burner that located within the compartment, also in the presence of Nitrogen gas and water mist nozzles. The input of the model, the output and the solution of the governing equations are presented.

Tested Building Configuration

The dimensions of the FDS hanger model 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 simulated FDS fire is produced by a cubic burner of 0.2 m side length located within the compartment in the presence of water mist nozzles and N2 gas nozzles.

A six nozzles are used in this model (three for water mist and other three for N_2 gas). Nylon is used as a fuel in the simulation.

Figure 1. "Elevation and Side View of hanger model"

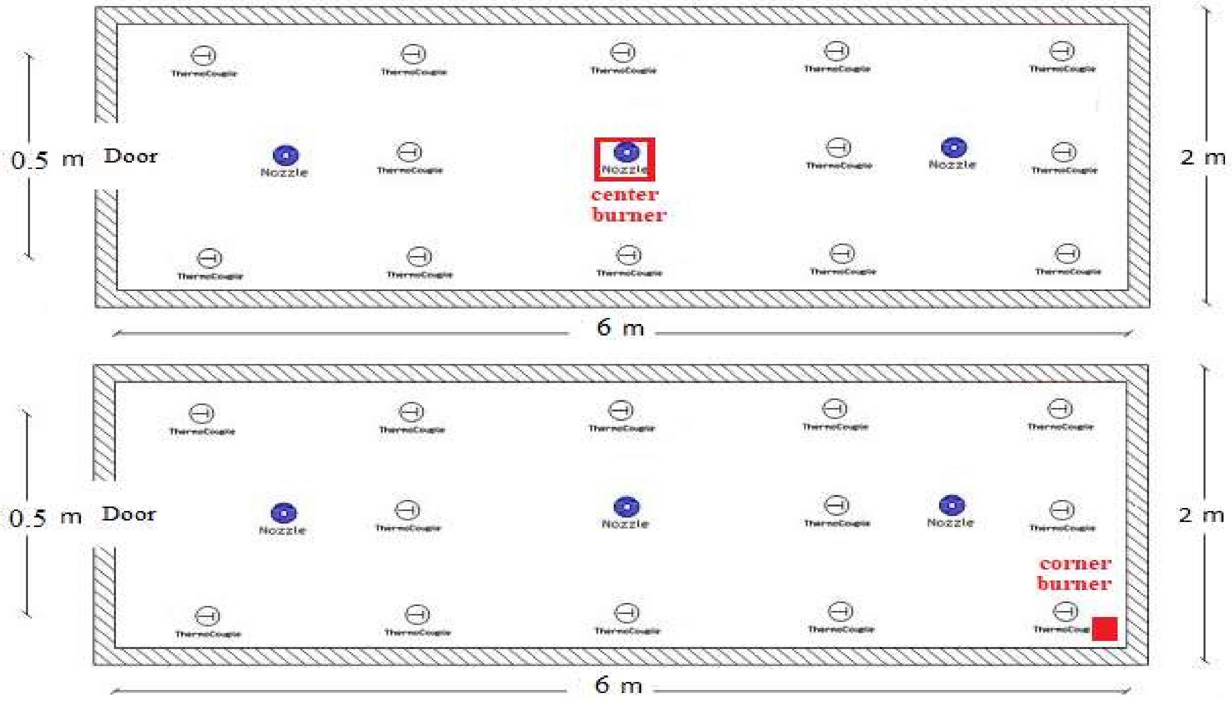


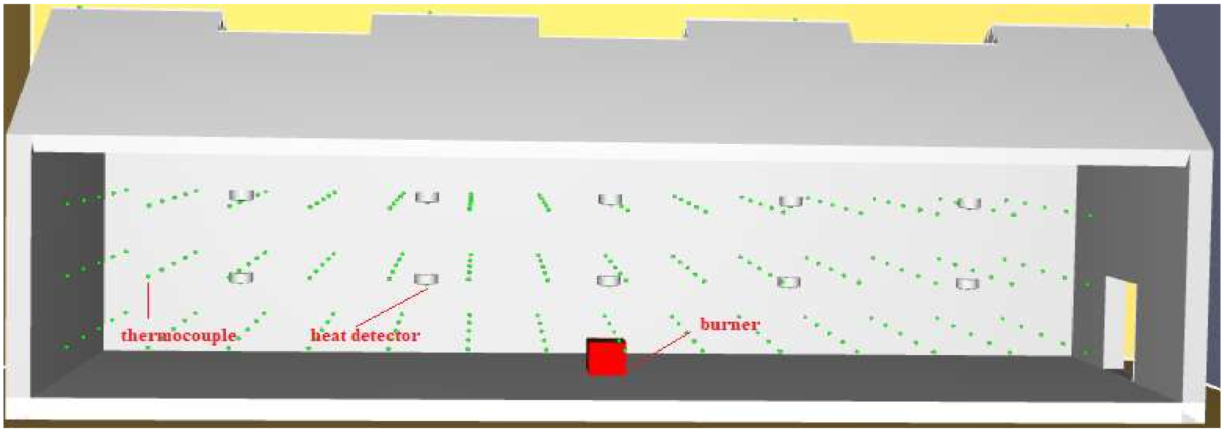
Figure 2. “Plan of hanger model”

Grid Resolution

A 0.09 m grid are specified for the modeled hanger, with total cells of 73,689. This simulation took around 48 hours each to run. The selection of mesh size is taken from FDS User Guide [16], it states to use a D*/dx ratio between 4 and 16 in order to determine the appropriate mesh size. In that ratio, dx is the nominal size of a mesh cell, and D* is a characteristic fire diameter defined in the equation:

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

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



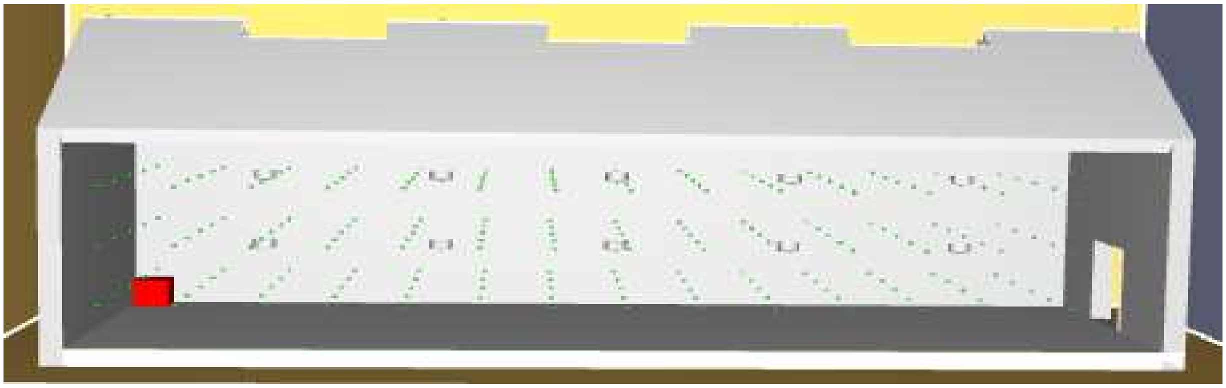


Figure 3. “Schematic 3D view of hanger model (FDS)”

Governing Equations

A set of partial differently equations consisting of six equations for six unknowns, all functions of three spatial dimensions and time: the density ρ, the three components of velocity U = [u; v; w], the temperature T, and the pressure p.

Continuity Equation

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

Navier-Stoke Equation

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

Energy Equation

Results and Discussion

The effect of using a combination of Nitrogen gas and water mist on fire spread in hanger through different fire suppression scenarios “as shown in Figs. 1, 2 and 3, is presented through using different proportions of Nitrogen gas injection against water mist amount, various water mist particles size and different fire source positions (center and corner) at constant heat release amount on fire extinguishing, the phenomena is studied and investigated by building and design a full-scale water mist system and Nitrogen gas injection system throughout FDS model.

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

The thermocouple temperature lags the true gas temperature by an amount determined mainly by its bead size. It is found by solving the following equation for the thermocouple temperature, 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 heat release rate equation

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

NFPA 750 experimental Verification Model is performed in ref. no. [17]

- **Brief discussion of the effect on extinguishing time while using water mist only [**ref. no. **17]:**

❖ Scenario I:

In this combined case (Fig. no. 4), the heat release amount is kept constant at (500 kW/m²), droplet size is various from (50 µm to 30 µm), while the flow rate is also various from (20 l/min to 40 l/min). Firstly, after reducing the water mist droplet size at same flow rate, the extinguishing time has been enhanced by more than (40 sec). Then, after that the flow rate amount become double to be (40 l/min) at same droplet size of (30 µm), as a result of this the extinguishing time has been reduced by around (50 sec).

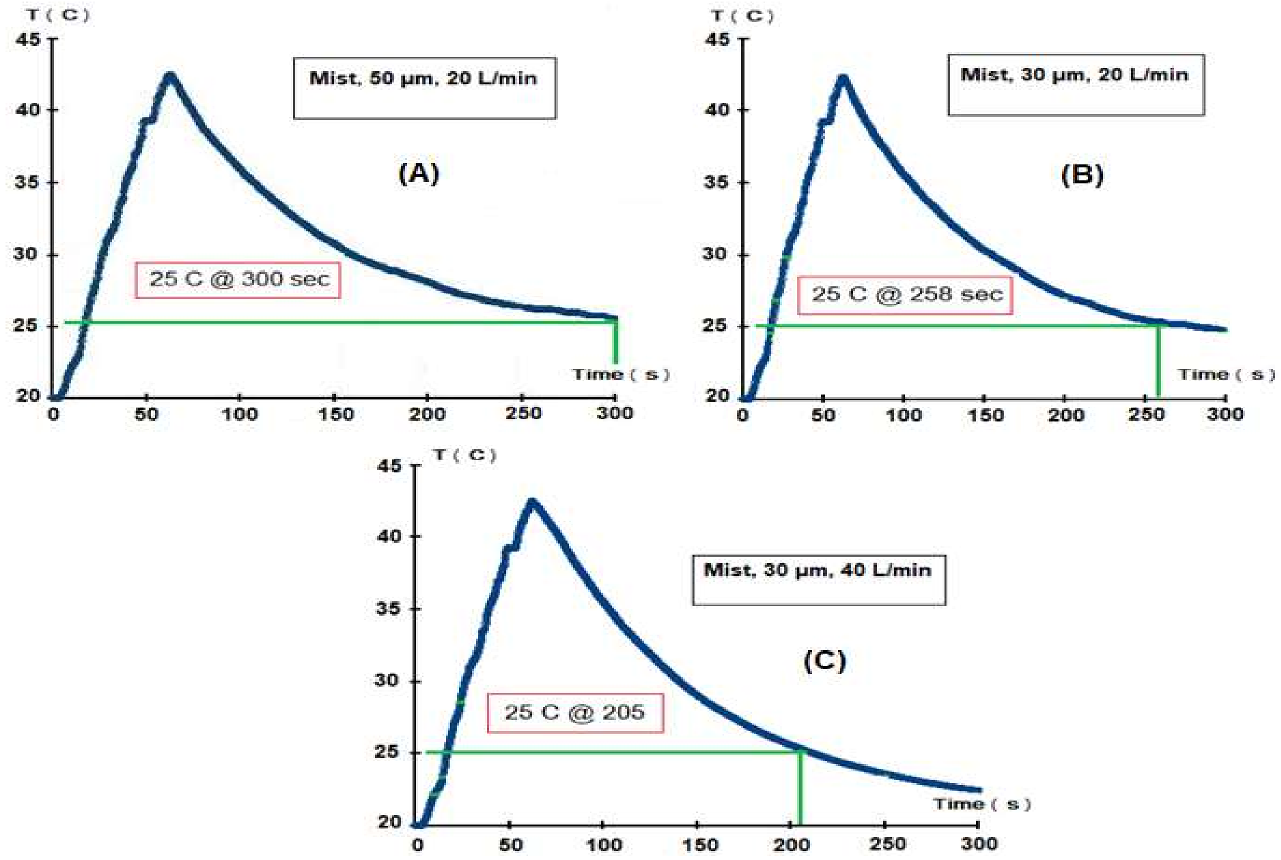


Figure 4. “Average Temperature of using Mist only for different 3 cases (Q= 500 kW/m², q= 20 - 40 l/min (per nozzle of 3), Di= 50 - 30 µm)”

- **Another scenario after injection of Nitrogen gas as an effective aid is presented:**

❖ ***Scenario II:***

➢ ***Case (A) - (N₂ Gas Only):***

In this case, a Nitrogen gas has been used alone to overcome the fire. It is noticed that after the Nitrogen gas has enters the injection area, it quickly combines with the room air and reducing the oxygen volume fraction, thereby absorbs heat in the area, trying to suppress the flame.

Comparing this case (Fig. 5) with the curve of (nylon combustion - fully opened model), which the max temp. @ 300 sec = 170 ºC, while after using Nitrogen gas injection it has been reduced by more than 100 ºC to be = 67.5 ºC @ 300 sec. But finally, the flame cannot be completely extinguished.

After many trials of increasing the Nitrogen gas flow rate quantity, that is varies from (10, 20, 40 to 60 l / m), the final conclusion can be said that Nitrogen gas can only keep the temperature and the heat flux in a low range, but using it alone is not sufficient to overcome the fire, as it would take too much time without reaching the required lower range of heat flux and temperature, which is not effective on fire suppression during a real accident.

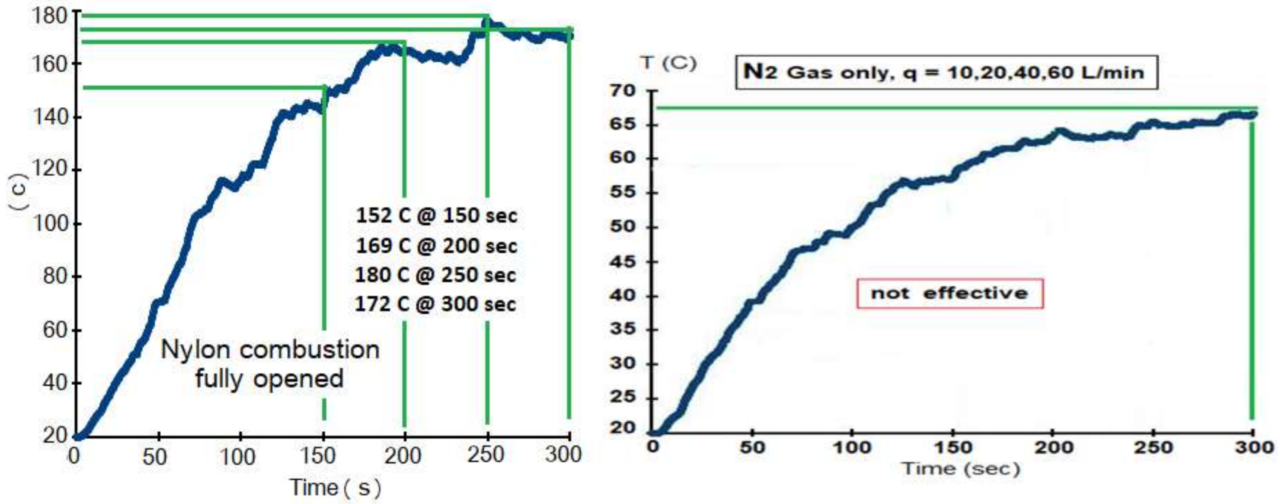


Figure 5. Average Temperature of Nylon combustion corresponding to average temp. of using N_2 Gas only for different flow rates
(Q= 500 kW/m^2, q= 10 - 20 – 40 - 60 l/min, per nozzle)

- ***<u>Case (B) - (N$_2$ Gas and Water Mist):</u>***

Another scenario of simulation for same hanger model through hereunder figures (6,7,8,9 and 10), at same heat release with water mist droplet size of (50 µm) and flow rate of (20 l/min), while changing the proportions of Nitrogen gas injection against the constant water mist flow rate amount.

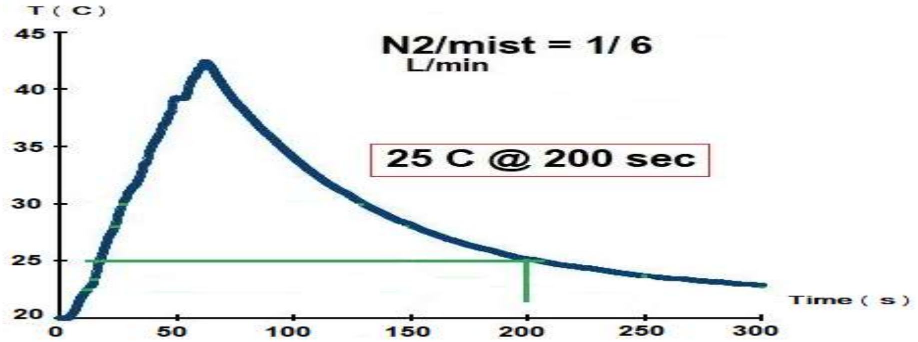


Figure 6. “Average Temperature of using a mixture of N_2 gas and water mist (1/6)
(Q= 500 kW/m^2, q N_2 = 10 l/min (per nozzle), q mist = 20 l/min (per nozzle of 3), Di= 50 µm)”

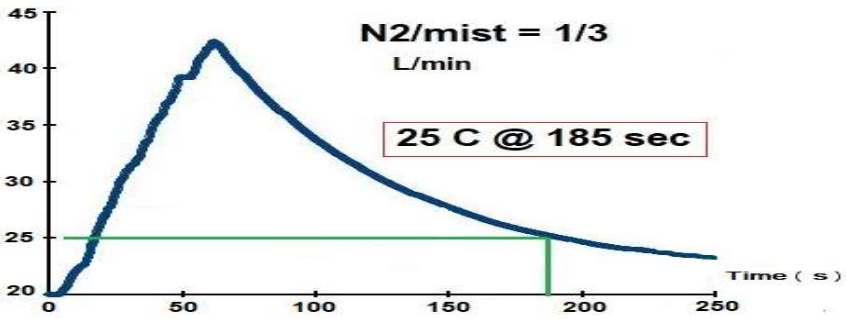


Figure 7. “Average Temperature of using a mixture of N_2 gas and water mist (1/3)
(Q= 500 kW/m^2, q N_2 = 20 l/min (per nozzle), q mist= 20 l/min (per nozzle of 3), Di= 50 µm)”

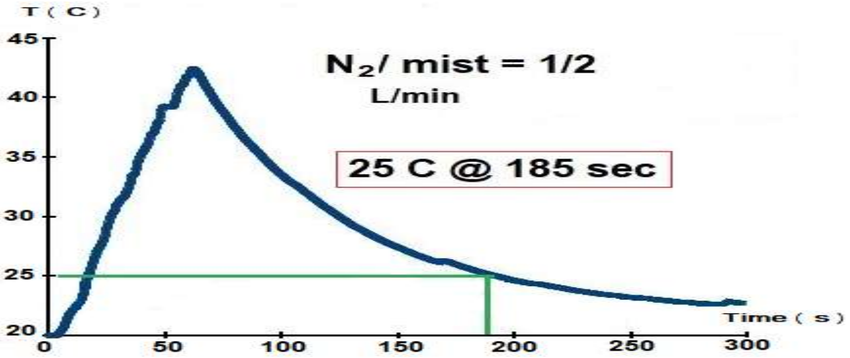


Figure 8. “Average

Temperature of using a mixture of N_2 gas and water mist (1/2)
(Q= 500 kW/m^2, q N_2 = 30 l/min nozzle of 3), Di= 50 µm)” (per nozzle), q mist= 20 l/min (per

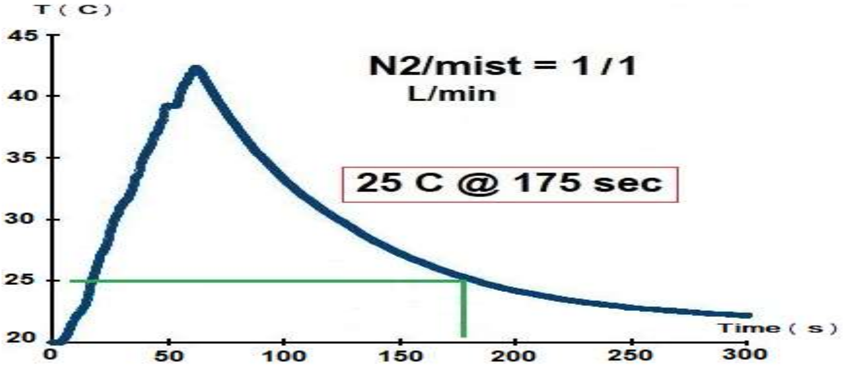
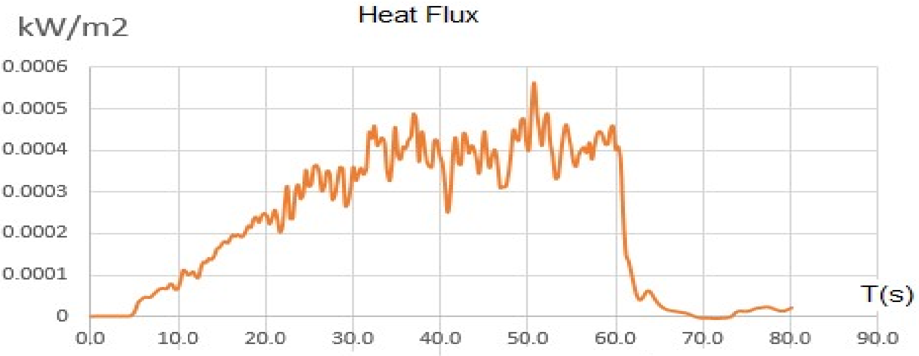


Figure 9. “Average

Temperature of using a mixture of N_2 gas and water mist (1/1)
(Q= 500 kW/m^2, q N_2 = 60 l/min (per nozzle), q mist= 20 l/min (per nozzle of 3), Di= 50 µm)”



Figure

9.a. “Average Heat Flux of using a mixture of N_2 gas and water mist (1/1)
(Q= 500 kW/m^2, q N_2 = 60 l/min (per nozzle), q mist= 20 l/min (per nozzle of 3), Di= 50 µm)”

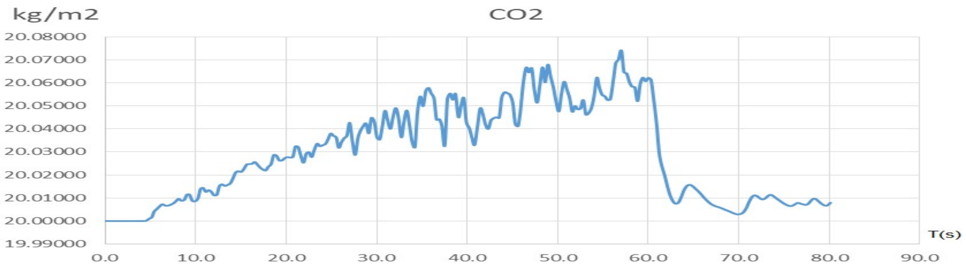


Figure 9.b. “Average CO_2 concenteration of using a mixture of N_2 gas and water mist (1/1)
(Q= 500 kW/m^2, q N_2 = 60 l/min (per nozzle), q mist= 20 l/min (per nozzle of 3), Di= 50 µm)”

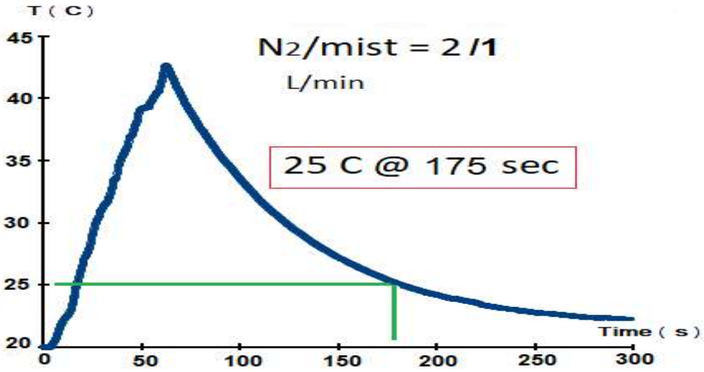


Figure 10. “Average Temperature of using a mixture of N_2 gas and water mist (2/1)
(Q= 500 kW/m^2, q N_2 = 120 l/min (per nozzle), q mist= 20 l/min (per nozzle of 3), Di= 50 µm)”

Now the effect of using Nitrogen gas injection has a pronounced effect while comparing the above presented results to the results of the first presented combined case scenario which the water mist was only been used [17].

Let’s discuss the comparison case by case, after injecting the Nitrogen gas by only 1:6 of water mist flow rate amount as shown in (Fig. no. 6), the extinguishing time has been reduced by 100 sec if compared to same case which water mist only was used at same conditions. And this result has more enhancement than the case of scenario I (Fig. no. 5.C), which the water mist flow rate is doubled amount (40 l/min per nozzle of 3) with smaller droplet size of (30 µm) which is presented in same combined case before Nitrogen gas injection [17].

Then by increasing the proportions of Nitrogen gas as per (Figs. 7, 8 and 9) it is noticed that a good enhancement in extinguishing time has been occurred along the presented curves to be reached 175 sec (best simulated case scenario, while using same flow rate amount of injected Nitrogen gas against same flow rate amount of water mist “N_2/mist =1:1”), which leads to a total decreased of 125 seconds (from 300 sec to 175 sec) in extinguishing time if compared to (Fig. 5.A) at the same conditions.

Also, (Figs 9.a and 9.b) show the positive effect on prevent heat flux spread and the CO_2 reduction.

Concerning (Fig. 10), it shows a conclusion called (saturation state – no pronounced enhancement in extinguishing time), that when Nitrogen gas flow rate is increased beyond a certain limit, it will be useless, as no development or effect shall be sensed beyond this limit even if a slight change maybe occurred but will not be effective.

- ***Scenario III:***

  - *Corner (A)- __(Water Mist Only):__*

The case scenario is performed and discussed in ref. no. [17]

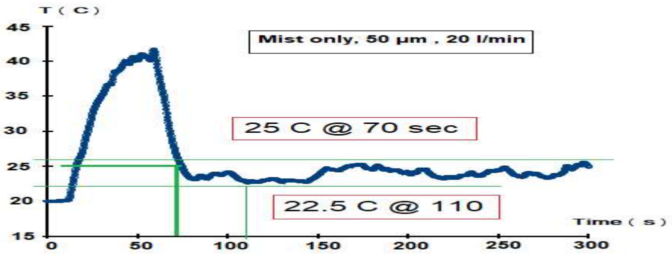


Figure 11. “Average Temperature of using water mist only
(Q= 500 kW/m^2, q mist= 20 l/min, Di= 50 µm)”

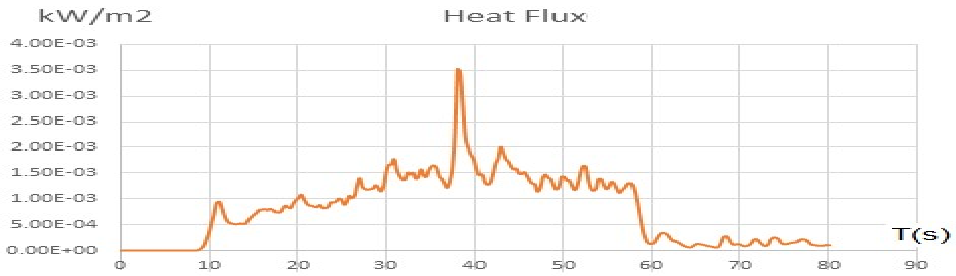


Figure 11.a. “Average Heat Flux of using water mist only
(Q= 500 kW/m^2, q mist= 20 l/min, Di= 50 µm)”

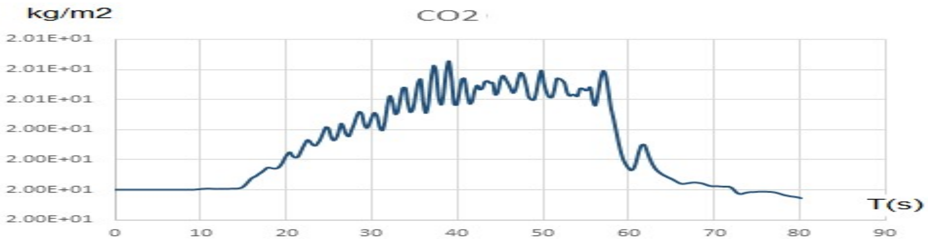


Figure 11.b. “Average CO_2 concenteration of using water mist only
(Q= 500 kW/m^2, q mist= 20 l/min, Di= 50 µm)”

- ***Corner (B) - (<u>Mix of using N_2 Gas and Water Mist):</u>***

Another scenario has been simulated for the same model of fire at the corner, the heat release still kept at (500 kW/m^2), and also the water mist flow rate still maintained at (20 l/min, per nozzle) with a droplet size of (50 µm), but a Nitrogen gas injection has been happened with an equal flow rate to water mist (20 l/min, per nozzle of 3), (one-one) case.

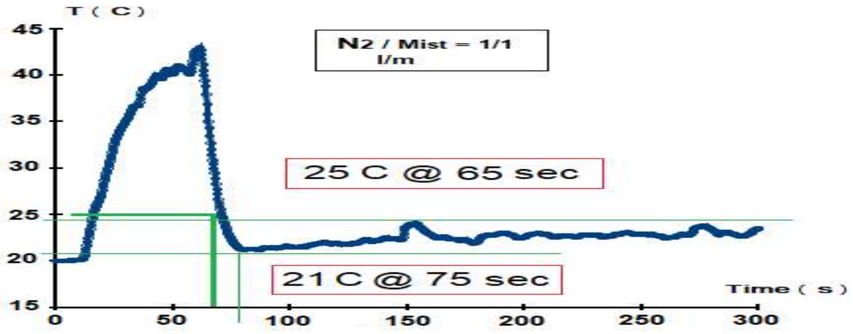


Figure 12. “Average Temperature of using a mixture of N2 gas and water mist (1/1)

(Q= 500 kW/m^2, q N_2 = 20 l/min (per nozzle of 3), q mist= 20 l/min (per nozzle of 3), Di= 50 µm)”

An enhancement has been noticed along the curve concerning both of temperature and extinguishing time, and also the fluctuation along the curve has been enhanced as a result of Nitrogen gas injection intervention in comparison with above previous curve (Fig. 11).

Let’s illustrate the curves of the Heat Flux and the CO_2, to show the other effects on different aspects:

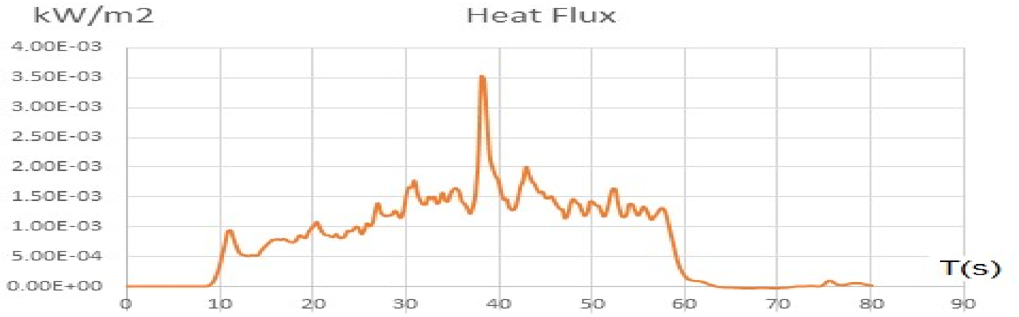


Figure 12.a. “Average Heat Flux of using a mixture of N_2 gas and water mist (1/1)

(Q= 500 kW/m², q N_2 = 20 l/min (per nozzle of 3), q mist= 20 l/min (per nozzle of 3), Di= 50 μm)”

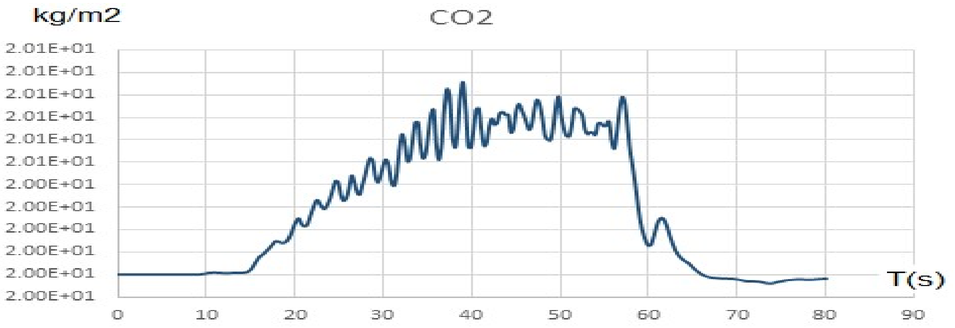
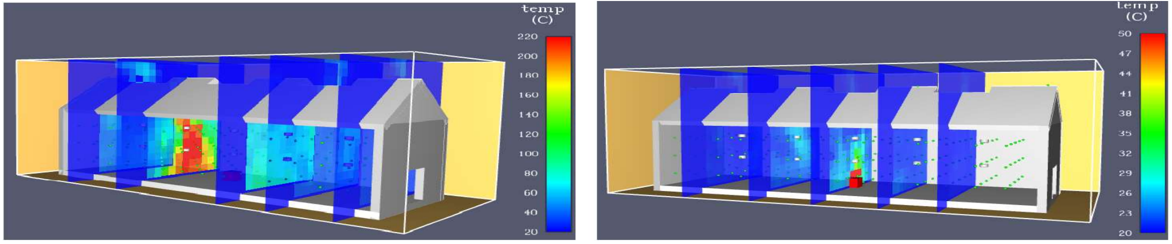


Figure 12.b. “Average CO_2 concenteration of using a mixture of N_2 gas and water mist (1/1)
(Q= 500 kW/m², q N_2 = 20 l/min (per nozzle of 3), q mist= 20 l/min (per nozzle of 3), Di= 50 μm)”

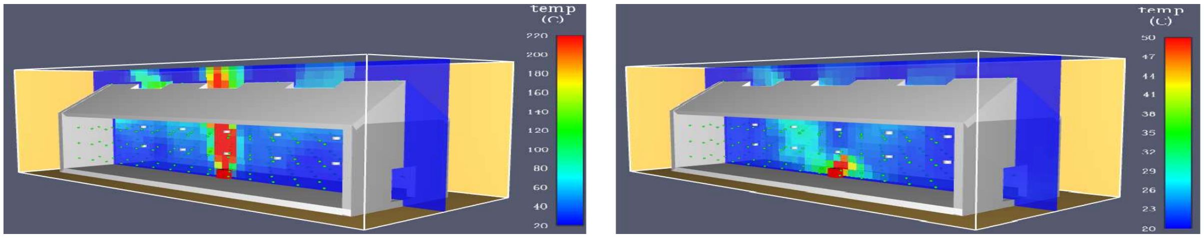
Injection of the mixture of the Nitrogen gas and water mist affect positively on both of heat flux and carbon dioxide concentration concerning the fluctuation enhancement along the curve if compared to figures no. (11.a and 11.b).

A temperature contours at different locations of hanger is presented hereunder through (Figs. 13, 14 and 15) to show that the closer slice has a highest temperature than other farther slices:



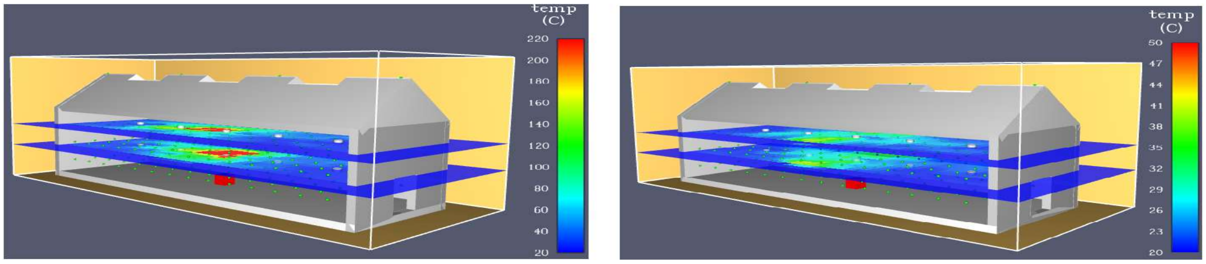
Before combination of mist and N2 injection After combination of mist and N_2 injection

Figure 13. “Temperature contours at different locations of hanger (in Y axis)”



Before combination of mist and N2 injection After combination of mist and N2 injection

Figure 14. “Temperature contours at different locations of hanger (in X axis)”



Before combination of mist and N2 injection After combination of mist and N2 injection

Figure 15. “Temperature Contours at Different Locations of Hanger (in Z axis)”

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

Table 1 Cases Classifications

Cases / **Ser.**	**Fire Source Location - Heat Release (500 kW/m2)**	**N2 Gas Flow Rate (L/min)/ Per Nozzle**	**No. of activated Nozzles of N2 Gas**	**Water Mist Droplet Size (µm), Flow Rate (L/min)/ Per Nozzle**	**No. of activated Nozzles of Water Mist**	**Ratio of N2: Mist**	**Extinguishing Time (Sec) @ 25 °C**	**Results Summary**
1,2,3,4	**Center**	**10,20, 40,60 L/min**	**1,3**	**-**	**-**	**-**	**67.5 °C @ 300**	Using N2 only is not sufficient to overcome the fire. (fig. no. 4.10)
5		**-**	**-**	**Water only**	**3** **Sprinklers**	**-**	**35 °C @ 300** **38 °C @ 600**	Using water only is not sufficient to overcome the fire. (fig. no. 4.5)
6		**-**	**-**	**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**
7		**-**	**-**	**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**

8	**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**
9		**10 L/min**	**1**	**50 µm, 20 L/min**	**3**	**1:6**	**200**	The extinguishing time has been enhanced after N2 gas injection influence. (fig. no. 4.12) – **paper, scenario II**
10		**20 L/min**	**1**	**50 µm, 20 L/min**	**3**	**1:3**	**185**	After increasing the N2 gas flow rate amount, the extinguishing time has been enhanced. (fig. no. 4.13) – **paper, scenario II**
11		**30 L/min**	**1**	**50 µm, 20 L/min**	**3**	**1:2**	**185**	Additional amount of N2 gas has been injected, no enhancement happened to fire extinguishing time. (fig. no. 4.14) –**paper, scenario II**
12		**60 L/min**	**1**	**50 µm, 20 L/min**	**3**	**1:1**	**175**	Another additional amount of N2 gas has been injected, an enhancement by 10 sec to extinguishing time has been occurred. (fig. no. 4.15) –**paper, scenario II**
13		**120 L/min**	**1**	**50 µm, 20 L/min**	**3**	**2:1**	**175**	After injecting double amount on N2 gas, nothing has been changed compared to previous case (a saturation state). (fig. no. 4.16) –**paper, scenario II**
14	**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 III**
15		**20 L/min**	**1**	**50 µm, 20 L/min**	**1**	**1:1**	**65**	A slight enhancement has been noticed along the curve, with a somewhat similar readings of previous case. (fig. no. 4.26) – **paper, scenario III**

Conclusions

A FDS program (PYROSIM) is used to simulate the fire compartment and show output results of temperatures, firefighting time, blockage of heat flux, and concentration of fire exhaust gases due to the effectiveness of different proportions of Nitrogen gas and water mist, droplet diameter and water mist flow rate 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 [14] and [17].

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

- The time of firefighting is reduced with decreasing the droplet size of water mist (up to 30 µm), Table no. 1 (case no. 7).
- The fire suppression time decreases as a result of increasing water mist flow rate injection, Table no. 1 (case no. 8).
- Detecting the suitable appropriate mixture ratio for Nitrogen gas and water mist leads to reduce the time of fire extinguishing, Table no. 1 (case no. 12).
- When Nitrogen gas flow rate is increased beyond a certain limit, it will be useless, as no development or effect shall be sensed beyond this limit, or maybe a slight change occurred but not effective (a saturation state), Table no. 1 (case no. 13).
- Changing the size of water mist droplet shall cause an effect, but during using Nitrogen gas as an aid, it maybe not sensed a lot especially beyond a certain limit, while injecting different flow rates amount of the Nitrogen gas has the main sensed effect.
- Reducing water mist droplets size beyond a certain limit, it may cause a negative effect during using Nitrogen gas as an aid, as this too much tiny size of water mist droplet forms a curtain of mist which prevent and block the Nitrogen gas atoms from entering the empty spaces between the other air mixture components, and thus doesn't have the ability to replace the oxygen gas atoms.

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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