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Optimization of water mist droplet size by using CFD modeling for fire suppressions

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ABSTRACT

With recent developments in sprinkler technology, water mist system is becoming more and more useful in fire suppressions. However, regulations on water mist system are inadequate, because most of them are based on experimental results. The computational method is an efficient way to make validations and optimize droplet size distribution of water mists. In this work, a computational fluid dynamics (CFD) model and a fire dynamics simulator (FDS) code were used to analyze effects of fire suppression using water mists with different droplet sizes. By using numerical methods, the interaction between water mist and fire could be better understood. The range of droplet size was determined based on the NFPA 750 standard. The fire extinguishing times of different droplet sizes were calculated by running the FDS code. After running the FDS code for different droplet size ranges, the optimal droplet size range was obtained. With the increase of droplet sizes, the fire extinguishing time first fluctuated and then increased. An optimal droplet size range was determined to have the best suppression effectiveness with the shortest fire extinguishing time and less water consumption. It should be noted that there are limitations for the CFD study since the real circumstance of fire is more complicated.

1. Introduction

The Montreal Protocol was enacted in 1987 which regulated Halon fire suppressants should be replaced by the start of the 21 century. Since then, water mist fire suppression system has been considered as one of the most effective candidates to replace Halon. According to the current NFPA 750 standard (National Fire Protection Association, 2015), 99% of the water mist droplet size should be less than 1000 μm. Although the standard gives designers a wide flexible range of droplet size, it is not beneficial in real fire scenes because the suppression time usually plays a vital role in eliminating of injury and property loss. In order to have better suppression effects, an optimal droplet size is essential to design a water mist fire protection system.

In order to determine the optimum water mist droplet size, experiments have been carried out by different researchers. Ultra-fine water mists (<10 μm) discharged with multiple floor outlets around a 120 kW gas fire in a 28 m^3 compartment have been studied (Adiga et al., 2007). The work indicated that the ultra-fine water mist behaved like a dense gas which could be used in the case of total flooding situation. A two dimensional methane diffusional flame was studied by using a modified Wolfhard-Parker burner along with the mist generation chamber (Ndubizu et al., 1998). The results showed that the gas-phase cooling is more dominant than oxygen dilution with a mean diameter of 60 μm. The size range between 100 and 1000 μm was regarded as the most effective size range for firefighting (Grant et al., 2000). However, the droplet size may be too small (<100 μm) with less weight that could easily spread out by flames and vapors. An advanced concept was suggested that the water droplet size distribution should have a mean diameter of 80–200 μm and 99% of the volume should be smaller than 500 μm (Ramsden, 1996). This definition is more suggestive for providing such a narrower range. Similarly, an optimal mean diameter of 350 μm was proposed theoretically by using the maximum heat transfer coefficient (Herterich, 1960). A summary of the optimum droplet sizes distribution was made which suggested most of the effective suppression droplet sizes are smaller than 500 μm (Andrews, 1992).

It is not always ideal to conduct field experiments of fire suppressions, not only because of a high cost and demand of man

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power for providing real scene situations, but also because of unrecoverable fire damages (Zhang et al., 2015; Gopalaswami et al., 2016). Computer modeling has been recognized as an alternative way in understanding and validating most of the engineering problems. This kind of cost effective and time efficient software could assist the fire protection system design and evaluation. The modeling can show a process in a visual way which could enhance the understanding of fire behaviors. The commonly used models for studying the interaction between water mist and fire are CFD based models. FDS and CFX are two main CFD based software that incorporated most of the necessary elements from thermodynamics and fluid dynamics (Hurley, 2015). As for the studying of some specific attributes of fire and water mist, FDS has been considered as the best simulation tool for fire research with some available built-in fire codes.

A lot of models have been set up by various researchers. A 4.0 m × 4.0 m × 2.3 m enclosed compartment with a fire source and water mist fire suppression system was simulated by using FDS (Kim and Ryou, 2003). The results indicated two kinds of regimes in the smoke layer: initial sudden cooling and gradual cooling. This model was further extended into a study of fire suppression mechanisms of different droplet size water mist (Ferng and Liu, 2010). The results showed that the fire extinguishing time first increased and then decreased with increase in droplet size. The interaction between a heat release rate of 6 MW fire plume and water mist in a 10 m × 10 m × 5 m brick-walled room was simulated by using FDS (Yang et al., 2010). Four water mist nozzles were placed at 4 m height from the floor with a mean diameter of 46 μm and a flue spray was placed 1 m above the floor. The performance between pool fire and water mist suppression inside a 4.3 m × 4.2 m × 3.05 m parallelepiped room was modeled (Jenft et al., 2014). Four water mist nozzles injected the droplets with a sauter mean diameter (SMD) of 112 μm. A hollow cone water mist nozzle on the top of a 2.92 m × 2.92 m × 2.20 m room was simulated by using FDS code (Husted, 2007).

This study will use fire dynamics simulator (FDS) to simulate the fire growth along with water mist in order to study the effects of droplet sizes. In water mist fire suppression system design, droplet size plays a vital role in determine the fire extinguishing time. By studying the effects of droplet size, it will be beneficial for the manufactures to produce the most efficient water mist nozzles for the industries.

2. CFD modeling

2.1. Heat release rate

The Heat Release Rate (HRR) is the single most important parameter to characterize a fire (Babrauskas and Peacook, 1992). Generally, HRR can be regarded as the driving force of a fire because most other variables always have some relations with it. Methane was selected as the burning fuel, because it is the major component of natural gas. The production of natural gas is abundant, which can be used as the fuel for cooking and for heating of homes and commercial buildings. In this work, 200 kW was used as the HRR of methane fire.

2.2. Parameter setup

The scale of the tested room was a compartment with dimensions of 4.0 m × 4.0 m × 3.0 m and four-sided solid concrete walls. The cell size was set up as 0.1 m hence it could be easier to calculate manually in the simulation process (Stroup and Lindeman, 2013). The final mesh was 40 × 40 × 30 with a total of 48,000 cells. A rectangular methane table (HRR of 200 kW) with an area of 1.0 m × 1.0 m was placed 0.5 m above the floor in the center of the room. The water mist nozzle was placed in the center of the ceiling with its cone angle of 60° and the droplet velocity of 5 m/s. It is not related to the flow rate as the flow rate only determines the droplet density at the time when water mist nozzle emits. The flow rates were set up as 5 L/min, 10 L/min and 15 L/min separately in three series of simulations. The droplet particles were defined as water vapor with reference temperature of 50 °C. The reference temperature is the mass fraction of the burning material decreased at its maximum rate. The sampling factor is used to reduce the size of the particle in the output simulation files, the value of which was one. The water mist nozzle started to emit water mist at the time after the fire lasts for 5 s. Three thermocouples were set up in the center of the room above the methane table with heights of 1.0 m, 1.5 m, and 2.0 m from the floor, respectively. A clock was set inside the system in order to make sure the nozzle would start on time after 5 s. The droplet diameter was changed in each of the simulation in order to investigate its influence on the suppression effectiveness. Fig. 1 shows the general schematic of the simulated room. For other parameters in the model, the default values were used as given in the FDS manual.

The limitations of this model are primarily due to the attribute of FDS as it only deals with low-speed, thermally-driven or buoyancy-driven flows. The real circumstance of fire is more complicated than the theoretical model with more uncontrollable variables, such as the destruction of the structure, influence caused by ventilation system, etc. However, by running the FDS code, it could provide some basic preliminary results with the fire scenarios. A typical size range of water mist droplet could be beneficial for the future experimental studies.

3. Results and discussion

3.1. Temperature distribution

In order to give a general understanding of the simulation in water mist fire suppression, some of the screen shots were captured from the FDS Smokeview. Fig. 2(a) is the temperature profile after the fire started. Fig. 2(b–f) show the interaction between water mist and fire after the water mist nozzle activated. All of these screen shots were taken at the plane of y = 2.0 m with a droplet size of 100 μm and a flow rate of 5 L/min.

As shown in Fig. 2(a) on the temperature reference column, the

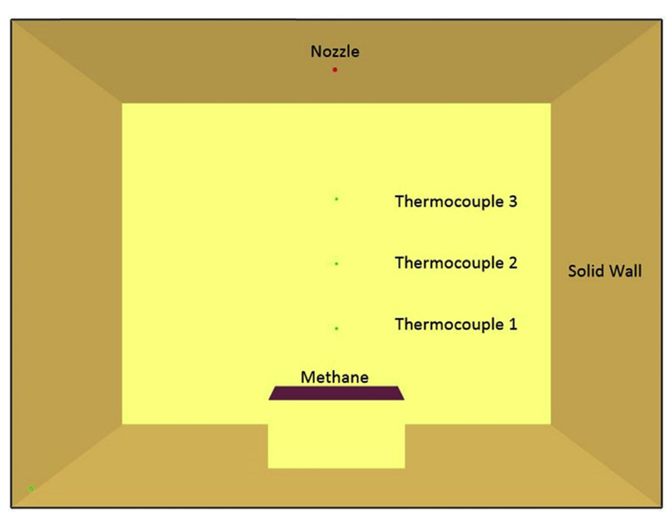

Fig. 1. Schematic of the simulated room.

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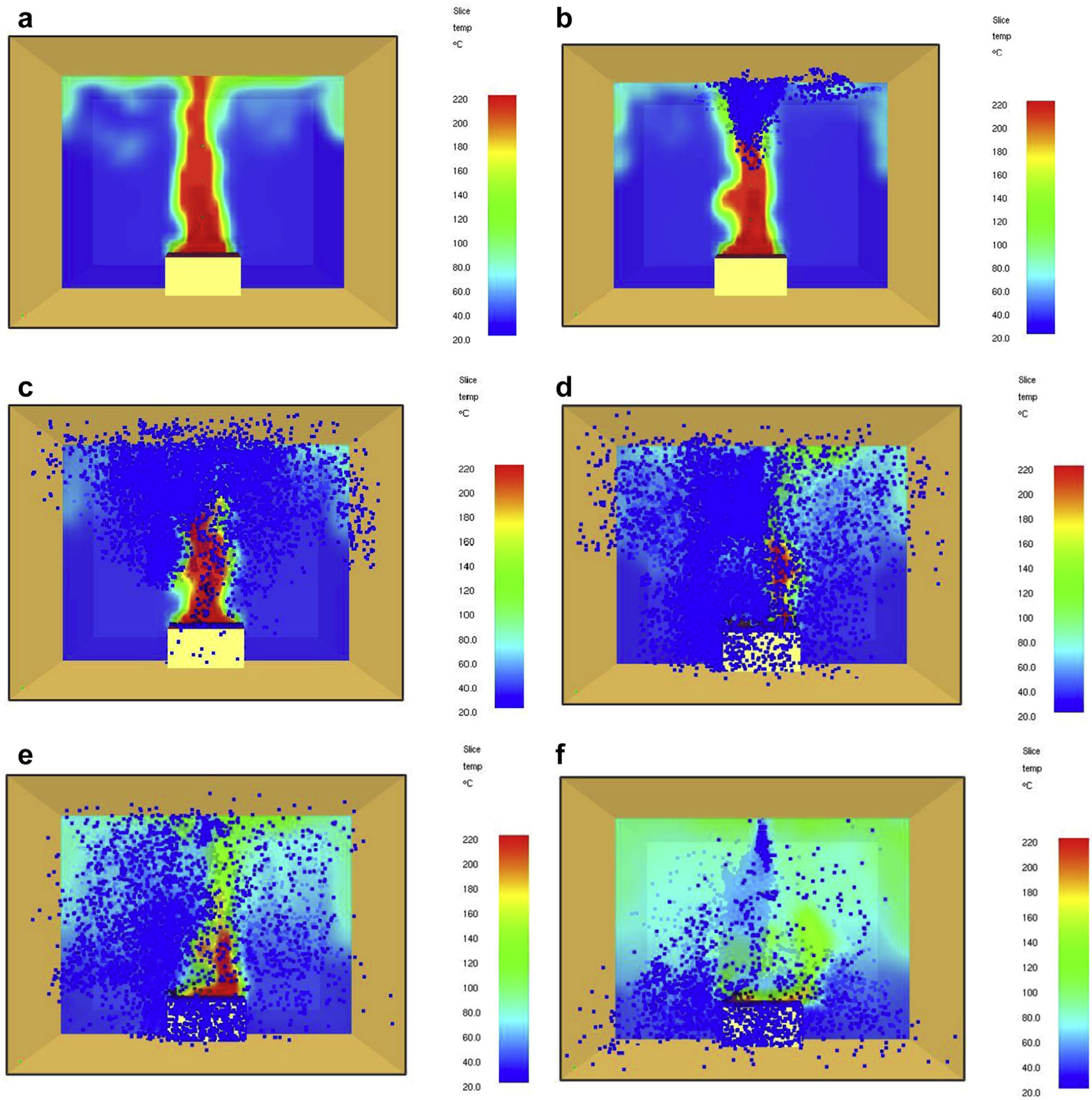

Fig. 2. (a) 5 s after the fire started. (b) 1 s after the activation of water mist nozzle. (c) 3 s after the activation of water mist nozzle. (d) 6 s after the activation of water mist nozzle. (e) 12 s after the activation of water mist nozzle. (f) 20 s after the activation of water mist nozzle.

cold-toned color such as blue and green represent lower temperature, and the warm-toned color such as orange and yellow represent higher temperature. The methane fire of 200 kW grew rapidly in 5 s with the plume temperature raised to over 220 °C, and the ceiling had a temperature over 100 °C. After the activation of water mist nozzle as shown in Fig. 2(b), the top of the plume temperature decreased first as it contacted with water mist. Fig. 2(c–f) showed that as the time went on, the water mist began to interact and absorb heat from the fire. The suppression process was quite effective because it only took about 12 s for the water mist to make half-height of the plume temperature decreased to lower than 180 °C. More significantly, the fire was about to extinguish in approximately 20 s after the activation started.

Three primary water mist suppression mechanisms are: radiation attenuation, oxygen displacement and heat extraction (Liu and Kim, 2000). The radiation attenuation and heat extraction could be directly reflected by the above temperature profiles. With the decrease of surrounding temperature, the radiation was decreased because of heat extraction from the hot body of fire by the water mist. Similar measurements have been performed for hydrogen fires (McCaffrey, 1989). It was concluded that the general trends of methane fires could be similar with hydrogen fires, and the reduction of radiation from flames had a direct relation to the water mist. The radiation transmission through water mists and the geometric spread were also studied by Thomas (Thomas, 1952). The results indicated that the suitable droplet sizes are most efficient in attenuating radiation. In order to investigate the suppression effectiveness, it was vital to relate these three mechanisms to the droplet size.

3.2. Droplet size comparison

The extinguishing time was defined from the activation of the water mist nozzle to a suitable fire temperature. Because there is a constant HRR at the methane table, the temperature of 100 °C was considered as the suitable extinguished fire temperature. The extinguishing times of droplet size from 100 μm to 1000 μm at different flow rates of 5 L/min, 10 L/min and 15 L/min were measured. After comparing the extinguishing time, a detailed range was selected to have better suppression effectiveness. Fig. 3 shows the general trend of temperature along with the time. The water mist nozzle was activated 5 s after the fire started.

From Fig. 3(a–d), it can be concluded that at the flow rate of 5 L/min, the extinguishing time of water mist increased a lot with the increase of droplet size. When droplet size was 100 μm, it only took about 25 s to suppress the fire. As the droplet size increased to 200 μm, the extinguishing time was nearly 45 s. Similarly, it took approximately 85 s at the droplet size of 300 μm. For the first three droplet sizes, the fire extinguishing time increased significantly. However, the extinguishing time would be much longer or not be able to converge for 400 μm droplet size as indicated by the graph. There is no reason to simulate it in a longer time span because it would be meaningless for fire suppression as well as much water consumption. This effect was also observed from the hydrogen fires that the degree of cooling was a direct function of droplet size. The higher cooling phenomenon had a direct relationship with the smaller droplet sizes (McCaffrey, 1989). Fig. 3(e) and (f) had the similar trend with Fig. 3(d), as the droplet size became larger than 400 μm, there was no suppression at the flow rate of 5 L/min because the temperature went up and down constantly and could not be stabilized.

Furthermore, the temperature decreased rapidly when applied with the 100 μm droplet size and there was only one small peak around 200 °C. With the increase of droplet size, there were more wave crests with relatively higher temperatures at the place where thermocouple 1 detected as over 400 °C. The reason for larger droplet size took longer time and even could not converge primarily because of the cooling regime of water mist. From the aspect of thermodynamics, water mist droplet evaporation removed energy due to latent heat. It not only transferred the heat to the droplet surface, but also transferred water liquid from the droplet surface. Because small droplets have less weight, when they emit from the nozzle they always have little momentum. This is beneficial for them to absorb heat and transfer it quickly at the top of the flame as the heat transfer was caused by conduction and controlled by diffusion of water vapor. The smaller droplet size contributes to higher evaporation rate, which led to a quicker heat transfer and evaporation. Another reason of the quick heat absorption is due to the quantity of droplets. With the same amount of flow rate in the simulation, the smaller diameter will have more droplets compare to the larger droplet size. Obviously, the bigger momentum for the large droplets did not have a significant impact compared to the smaller droplets with larger quantities. The large surface area to volume ratio made those smaller droplets a higher performance in fire suppression.

From the point of oxygen displacement, water mist created a cloud of water vapor that displaced the gases such as oxygen, which led to the decrease of oxygen concentration. When water mist penetrated into the plume and became vapor, the volume could be expanded to about 1700 times larger than the original water mist liquid (Liu and Kim, 2000). This volumetric expansion took place of oxygen that diluted the fuel-air mixture. As the fuel-air mixture below the lower flammable limit which is 5% by volume of air, the combustion process could not be sustained.

Since the droplet size of 100 μm indicated better suppression effectiveness, it was necessary to investigate the droplet size smaller than 100 μm. Due to some of the technical issues of the mist nozzle, it was not recommended to have droplet size too small. As mention earlier, some kind of ultra-fine (<10 μm) water mist would need special emitting tools which would increase the expense of installing nozzle. Therefore, only droplet sizes with 50 μm–90 μm were simulated.

From Fig. 4(a–e), the extinguishing times of different droplet sizes were around 30 s except for the droplet size of 70 μm. It only took about 10 s longer for 70 μm droplet size compare to the others, which was relatively acceptable compare to the much larger droplet size (>400 μm). The reason for the longer extinguishing time at 70 μm is probably because of the heat convection and thermal conduction processes were not in a good combination. It is a combined effect of the three water mist suppression mechanism that causes these phenomena. As the interaction of water mist and fire is a very complex process, it is necessary to use the FDS software in the real design of water mist fire suppression. According to the temperature shown in the above figures, droplet size of 60 μm and 80 μm only had one single peak temperature that was higher than 300 °C, the other three sizes had two wave crests. Compared to the droplet size of 100 μm, they have a very similar temperature profiles as well as the extinguishing time. From a heat release and absorb perspective, in order to minimize the high temperature caused by radiation, it was recommended to use 60 μm, 80 μm or 100 μm droplet sizes. However, from an environmental protective and water saving aspect, a droplet size of 60 μm is considered as the best choice at a flow rate of 5 L/min.

As the water mist suppression effectiveness is not only determined by the droplet size, but also based on the flow rate as well as other factors. It is essential to investigate the dependence of flow rates. Therefore, another two series of droplet sizes from 100 μm to 1000 μm at 10 L/min and 15 L/min were simulated by using the FDS software. For any other flow rate larger than 15 L/min, they were not considered due to the high water consumption.

Fig. 5(a) and (b) show the temperature profiles with the increase of time at droplet size of 100 μm and 200 μm at flow rate of 10 L/min respectively. The extinguishing times were approximate 15 s for droplet size of 100 μm and around 25 s for droplet size of 200 μm. Similar to the flow rate of 5 L/min, the latter extinguishing time was doubled of the former one with the increase of droplet size. Because of the longer time of fire suppression, the larger droplet sizes were not considered at the flow rate of 10 L/min. The curves did not converge as the droplet sizes larger than 800 μm which were similar with Fig. 2(d–f).

Similarly, simulations were performed for a flow rate of 15 L/min with different droplet sizes. The extinguishing time was relatively shorter than that at flow rates of 5 L/min and 10 L/min. The simulation images are not included as they have the similar trends with the previous two flow rates. With the increase in droplet size, the extinguishing time became longer. Fig. 6 and Table 1 show the comparison of the extinguishing times of different droplet sizes at different flow rates.

From Fig. 6, the extinguishing time increased with the increase of droplet size from 100 μm to 1000 μm. The extinguishing time became relatively shorter at the same flow rate, which is primarily because of the larger water consumption that absorbed most of the

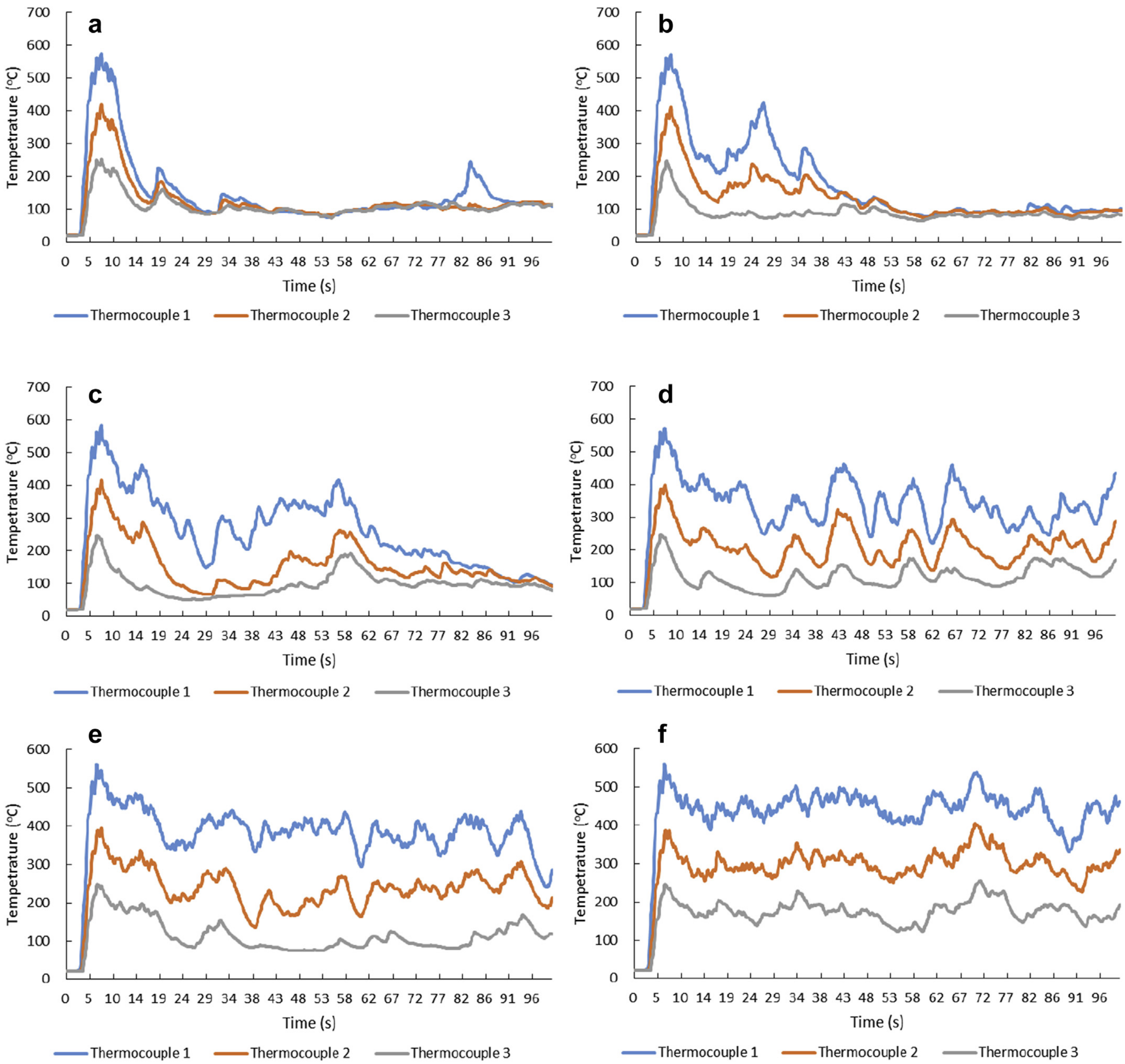

Fig. 3. (a) Temperature vs. Time at 100 μm with a flow rate of 5 L/min. (b) Temperature vs. Time at 200 μm with a flow rate of 5 L/min. (c) Temperature vs. Time at 300 μm with a flow rate of 5 L/min. (d) Temperature vs. Time at 400 μm with a flow rate of 5 L/min. (e) Temperature vs. Time at 500 μm with a flow rate of 5 L/min. (f) Temperature vs. Time at 600 μm with a flow rate of 5 L/min.

heat from the fire. Contrary to the flow rate of 5 L/min or 10 L/min, the extinguishing time at 15 L/min were continuously up and down with the increase of droplet size and finally increased very quickly at 900 μm. This non-linear trend started at 900 μm is mainly caused by the inadequate quantity of water mist droplet, they total surface area to volume ratio is not sufficient in providing continues amount of water in the conduction and convection process of heat that led to a much slower suppression. Although for the droplet size of 100 μm at a flow rate of 5 L/min, the time is only around 7 s and 9 s longer than that of 10 L/min and 15 L/min. This indicated that the droplet size of 100 μm with a flow rate of 5 L/min would be an ideal option for fire suppression design. For the same droplet size, the larger flow rate reflected the shorter extinguishing time. However, from the point of water saving and less water contamination to the surroundings, it would be more suitable to apply a smaller flow rate. The minimization of water consumption is essential because the water damage caused by fire suppression is usually a potential threat to the surrounding environment. This is extremely harmful to the rooms which are occupied with electrical appliances or books.

Generally, the water mist droplet size should not be exceeding 300 μm for all flow rates to have the best suppression effectiveness. Larger droplet sizes may not be able to extinguish a fire. From a water saving and less contamination comprehensive perspective, it is recommended that the optimum droplet size should be 60 μm at the flow rate of 5 L/min.

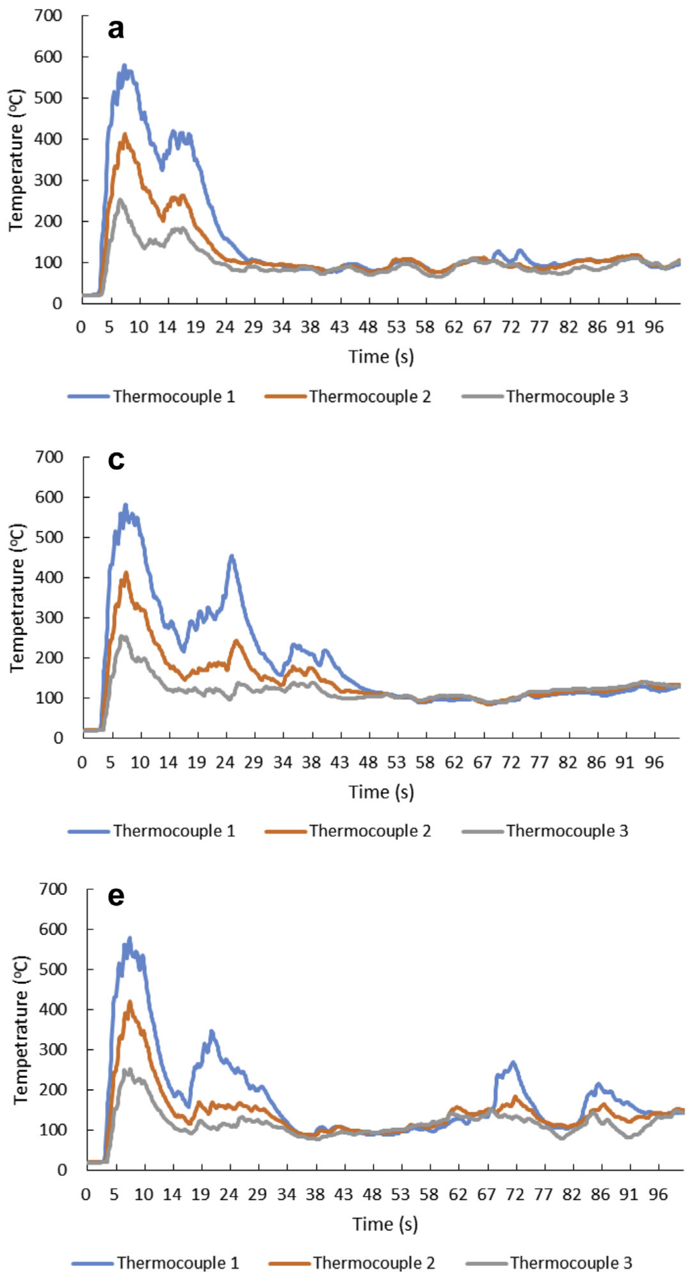

Fig. 4. (a) Temperature vs. Time at 50 μm with a flow rate of 5 L/min. (b) Temperature vs. Time at 60 μm with a flow rate of 5 L/min. (c) Temperature vs. Time at 70 μm with a flow rate of 5 L/min. (d) Temperature vs. Time at 80 μm with a flow rate of 5 L/min. (e) Temperature vs. Time at 90 μm with a flow rate of 5 L/min.

Experimental testing studies are underway. The proposed experimental testing method follows the set up process with the FDS software. By selecting the typical droplet size, such as 100 μm, 400 μm, 700 μm, and 1000 μm separately, a general trend of suppression effectiveness could be concluded in order to validating the simulation results. A series of thermocouples can be installed to measure temperatures for each test. The particle size can be measured by using the Phase Doppler Interferometer (PDI) which is available in the Department of Chemical Engineering. The PDI system simultaneously measures velocity, size, and concentration of liquid droplets in dense sprays. The system has the ability to characterize droplets over a wide range in droplet diameter (100 nm–2.8 mm).

4. Conclusions

The main objective of this study is to explore the suppression effectiveness of water mist with various droplet sizes by using CFD modeling through the FDS code. The water mist droplet size has an important role in determining the fire extinguishing time. Also the flow rate has an impact on the selection of suitable droplet size. In the suppression process, a large amount of water vapor is generated from the vaporization process displacing oxygen and thus dilutes the concentration of oxygen. More importantly, the smaller droplet size contributes to more quantity of droplets at the same flow rate, which can absorb more heat and attenuate the radiation from the fire as they have a suitable ratio of surface area to volume. From the analysis of suppression performance of different water mist droplet

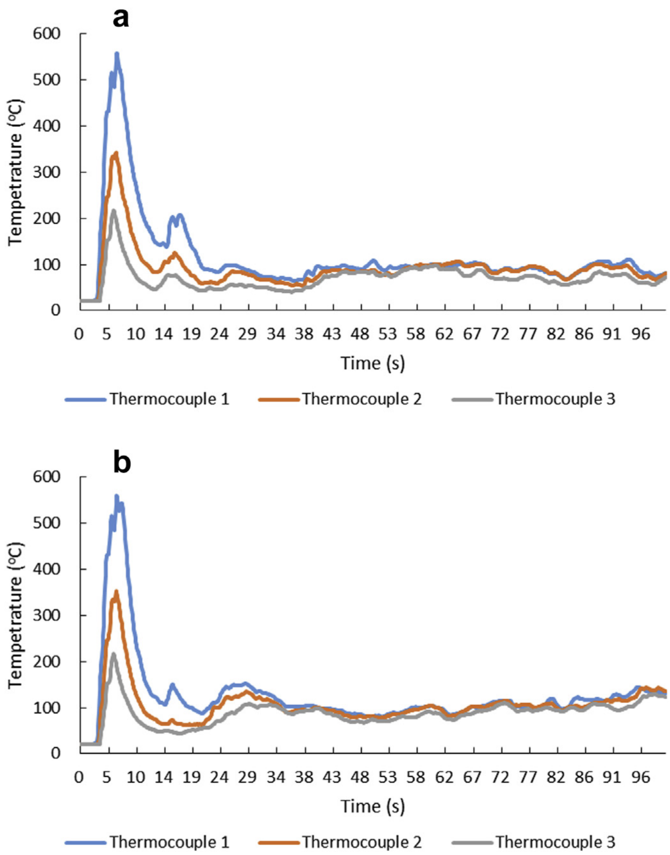

Fig. 5. (a) Temperature vs. Time at 100 μm with a flow rate of 10 L/min. (b) Temperature vs. Time at 200 μm with a flow rate of 10 L/min.

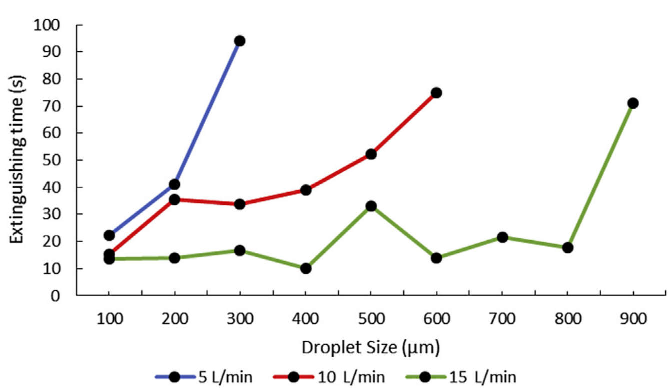

Fig. 6. Extinguishing time vs. droplet size at different flow rates.

size, it can be concluded that the droplet size ranging from 50 μm to 300 μm should be considered for water mist nozzles as an acceptable range in the design. The optimum droplet size is around 60 μm at the flow rate of 5 L/min. The results are obtained thorough the CFD modeling under certain assumptions and limitations. More cautions should be given for the practical industrial applications. The selection of the optimum droplet size is based on the compromise between extinguishing time and less water consumption. This work provides a good methodology to evaluate suppression effectiveness by using a computational tool, such as FDS.

Table 1
Extinguishing time vs. droplet size at different flow rates.

Flow Rate (L/min)	Size (μm)								
	100	200	300	400	500	600	700	800	900
5	22.3	41.2	94.1	–	–	–	–	–	–
10	15.5	35.5	33.9	39.0	52.4	74.8	–	–	–
15	13.5	13.8	16.9	10.2	33.0	14.0	21.6	17.8	71

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References

Adiga, K.C., Hatcher, R.F., Sheinson, R.S., Williams, F.W., Ayers, S., 2007. A computational and experimental study of ultra-fine water mist as a total flooding agent. Fire Saf. J. 42 (2), 150–160.
Andrews, S.P., 1992. Literature Review: Fire Extinguishing by Water Sprays. Building Research Establishment, UK (Internal Report).
Babrauskas, V., Peacook, R.D., 1992. Heat release rate: the single most important variable in fire hazard. Fire Saf. J. 18, 255–272.
Ferng, Y.M., Liu, C.H., 2010. Numerically investigating fire suppression mechanisms for the water mist with various droplet sizes through FDS code. Nucl. Eng. Des. 241, 3142–3148.
Grant, G., Brenton, J., Drysdale, D., 2000. Fire suppression by water sprays. Prog. Energy Combust. Sci. 26 (2), 79–130.
Gopalaswami, N., Liu, Y., Laboureur, D., Zhang, B., Mannan, M.S., 2016. Experimental study on propane jet fire hazards: comparison on geometrical features between experiments and empirical models. J. Loss Prev. Process Ind. 41, 365–375.
Herterich, O., 1960. Water as an Extinguishing Agent. Alfred Hüthig Publishing Company, Heidelberg.
Hurley, M., 2015. SFPE Handbook of Fire Protection Engineering, fifth ed. Springer, New York.
Husted, B.J., 2007. Experimental Measurements of Water Mist Systems and Implications for Modelling in CFD. Dissertation. Department of Fire Safety Engineering, Lund University.
Jenft, A., Collin, A., Boulet, P., Pianet, G., Breton, A., Muller, A., 2014. Experimental and numerical study of pool fire suppression using water mist. Fire Saf. J. 67, 1–12.
Kim, S.C., Ryou, H.S., 2003. An experimental and numerical study on fire suppression using a water mist in an enclosure. Build. Environ. 38, 1309–1316.
Liu, Z., Kim, A.K., 2000. A review of water mist fire suppression systems- fundamental studies. J. Fire Prot. Eng. 10 (3), 32–50.
McCaffrey, B.J., 1989. Momentum diffusion flame characteristics and the effects of water spray. Combust. Sci. Technol. 63, 315–335.
National Fire Protection Association, 2015. NFPA 750: Standard on Water Mist Fire Protection Systems. Retrieved from. http://codesonline.nfpa.org.
Ndubizu, C.C., Ananth, R., Tatem, P.A., Motevalli, V., 1998. On water mist fire suppression mechanisms in a gaseous diffusion flame. Fire Saf. J. 31, 253–276.
Ramsden, N., 1996. Water mist – a status update. Fire Prev. 287, 16–20.
Stroup, D., Lindeman, A., 2013. Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications. NUREG-1824, supplement 1. United States Nuclear Regulatory Commission, Washington.
Thomas, P.H., 1952. Absorption and scattering of radiation by water sprays of large drops. Br. J. Appl. Phys. 3, 385–393.
Yang, P., Liu, T., Qin, X., 2010. Experimental and numerical study on water mist suppression system on room fire. Build. Environ. 45 (10), 2309–2316.
Zhang, B., Liu, Y., Laboureur, D., Mannan, M.S., 2015. Experimental study on propane jet fire hazards: thermal radiation. Ind. Eng. Chem. Res. 54 (37), 9251–9256.