ULTRA-FINE WATER MIST AS A TOTAL FLOODING AGENT: A FEASIBILITY STUDY

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ABSTRACT

The overall objective of this area is to evaluate and understand the fire suppression behavior of a patented ultra-fine water mist technology with the tradename NanoMist™. NanoMist is a dense gas-like, ultra-fine (<10 μm) water mist produced at ambient pressure. The mist exhibits superior ability to readily diffuse around obstructions and has a potential to be a total flooding agent. However, the technology needs research into key issues such as the mist deployment design, the transport behavior of mist within the flooding volume, the optimum conditions for the mist entrainment into the firebase, and the interaction of mist with laminar and turbulent fires.

The specific objective of this work is to develop experimental design factors for testing NanoMist total flooding in a 27-m^3 compartment using CFD simulations. The mist is deployed through multiple outlets located on the compartment floor. The number of outlets, their location are determined from the CFD results in order to produce the desired mist flux density. The mist spreads laterally across the compartment floor and rises to fill the compartment volume. The design factors including mist outlet locations, the outlet velocity, and the mist throughput were evaluated for extinction of a turbulent pool-like gas fire located at the center of floor.

In the CFD calculations, 120 kW pool-like gas fires were extinguished with a mist throughput of 1 Lpm, which corresponds to a mist flux density of 0.11 Lpm/m^2. Significant cooling was observed even at lower flux densities. The fire entrains the nearly stagnant mist into its base as seen from stochastic droplet trajectories, and cools before the chamber reaches the total-flooding condition. The time to extinguishment is <10 seconds, which includes mist filling time as well. The mist filling behavior is similar to low momentum dense gas dispersion inside a chamber. Under weak flow conditions, the dispersion time scale is in minutes, while typical flame extinction is in seconds. Additional computations were conducted to understand the transport behavior of dense gas-like mist and its implications on fire suppression times.

Using the predicted design factors as guidelines, total flooding fire tests were conducted at the Naval Research Laboratory (NRL) fire test facility at the Chesapeake Bay Detachment (CBD), MD. The tests results are reported in a companion paper presented in this conference.

INTRODUCTION

The low-momentum gas-like ultra fine water mist (< 10 μm) system embodied in NanoMist™ technology [1,2] may be a potential alternative to clean agents in certain selected fire suppression applications. Droplets smaller than 10 microns begin to exhibit gas-like behavior with a superior ability to diffuse around obstructions without significant loss of mist due to plating and deposition. A recent study by Forssell et al. [3] demonstrated the ability of NanoMist to overcome obstructions in a sub-floor mockup. The ultra-fine mist disperses like a dense gas or as a total flooding agent unlike standard (or commercial) water mist systems (50-100 micron) and rapidly absorbs heat because of the huge surface area and the large vaporization rate of micron-sized mist droplets. NanoMist droplets generated at ambient pressure have a relatively narrow droplet-size distribution [3] whereas conventional pressure atomization generally yields broad droplet-size distributions. Because the mist is not generated using traditional nozzle technology, it presents a different challenge in meeting target fire suppression technology applications.

Figure 1 shows NanoMist flow from a side outlet into the room. The mist behaves like a dense gas dispersing slowly from the discharge location. If the mist were deployed from the base upwards, it would start to fill the volume like a liquid, the extent of lateral dispersion depending on the flux density. The extent of vertical dispersion depends on outlet discharge velocity.

Figure 1: A dense gas-like NanoMist water mist dispersion inside a room

The following factors distinguish NanoMist from regular or commercial mist:

<u>Mist Delivery</u>: NanoMist behaves like a dense gas unlike streaming regular nozzle-based pressure atomized mist [4-9]. Proper engineering of the mist discharge and transport into the reaction zone is critical to the success of NanoMist technology.
<u>Coupled Processes</u>: For gas-like NanoMist, the extent of mist entrainment into the firebase depends on the coupled behaviors of the fire induced flow-field and the mist flow. This is unlike

traditional commercial spray mist, which involves nearly one-way streaming flow optimized through nozzle locations, droplet size, spray angles, and injection velocity.

Cooling Process: Rapid cooling of the fire reaction zone occurs due to the large surface area presented by the NanoMist. This ultra-fine droplet mist uses a remarkably small quantity of water. The rate and amount of mist entering the firebase are key factors in suppression behavior of NanoMist.

Flooding Behavior: Because of the large surface area combined with the extremely low droplet mass, NanoMist tends to show localized flooding behavior within the compartment.

Self-Entraining Behavior: Studies to date show showed indications of self-entrainment behavior of NanoMist under a suitable set of flow conditions [10-12].

The following technical challenges remain to be addressed:

- ◊ Effective ways to deploy and disperse such a fine mist efficiently into the firebase without being swept away by the fire flow field.

- ◊ Determine required NanoMist mass concentration to overcome fractional loss of ultra fine mist by premature vaporization before reaching the fire.

Designing and creating a suitable flow environment for the NanoMist is the key to success in exploiting this technology in specific fire scenarios. Research into these and other closely related areas are necessary to qualify the NanoMist for immediate applications. Both CFD modeling and field-testing form the central theme of NanoMist fire suppression technology advancement.

CFD studies in the past have been focused on the interaction of water mist with fires [13, 14]. The emphasis of the present study, however, is on evaluating test design parameters to evaluate the performance of NanoMist. FLUENT, a commercial CFD program was used [15] with relatively simple sub-model elements. A pool-like hot gas fire [16.17] without combustion chemistry and radiation was considered. There is a need for radiation modeling in order to account for the possible premature vaporization loss of mist using approaches described in prior studies [18-21]. The Discrete Phase Model (DPM) of CFD was utilized to treat the mist transport and entrainment into the firebase, and the cooling of the fire by droplet vaporization. In order to estimate the transport time of mist and its implications on the overall fire extinction time scales, additional simulations have been carried out treating the NanoMist as a dense gas.

The test parameters evaluated by CFD simulations were used as guidelines for field-testing at the Chesapeake Bay Detachment (CBD) facility, the Navy Technology Center for Safety and Survivability (NTCSS), the Naval Research Laboratory (NRL). The results are reported in a companion paper by Sheinson et al. [22].

RESULTS AND DISCUSSION

Modeling and Mist Discharge Configuration

Fluent CFD [15] with a κ-ε turbulence model was used to simulate a compartment fire with a set of NanoMist deployment configurations. The Fluent Discrete Phase Model (DPM) was used to simulate the distribution of ultra fine mist, the mist entrainment into the fire, and the subsequent droplet vaporization resulting in the fire-cooling process. A pool-like gas fire [16, 17] model without fire chemistry kinetics and radiation was used to generate fire test data.

Mist Outlets: the floor area of 3 x 3 m was divided into 9 equal zones of 1 m^2. The center zone contained a 0.3-m diameter pool-like gas fire. Eight mist outlets were installed at the center of each of the eight surrounding zones. This layout is shown Figure 2. The total mass flow was divided amongst these outlets. The flux density is calculated by dividing throughput by the floor area of 9 m^2. The outlets are connected to the NanoMist generators.

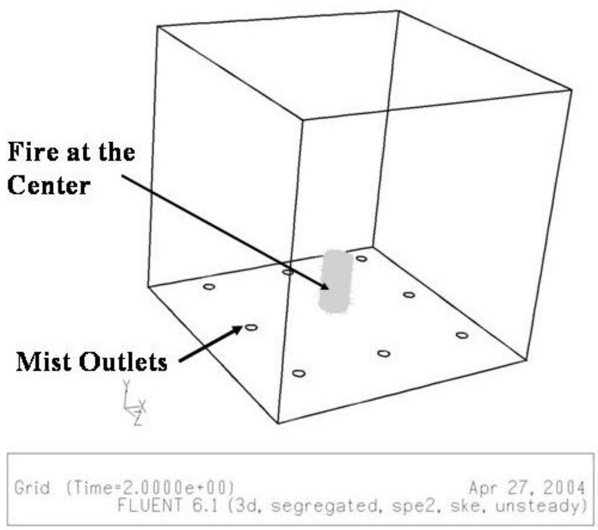

Figure 2: Configuration of NanoMist discharge outlets on the floor of test compartment

Upon discharging through these outlets, the mist disperses laterally while filling the compartment upwards. The NanoMist device provides outlet velocity < 1.5 m/s at the mist outlets.

Fire Simulation

The fire was simulated by a volumetric heat release source within a cylindrical gas volume of 0.3 m diameter and 0.6 m high as shown in Figure 2. The input heat release rate was varied to give a 120 kW fire with fire peak temperatures 900-1000^{0}C. This peak temperature compares well with the experimental turbulent heptane pool fires [4]. Figure 3 shows the pool-like fire located at the center of the compartment floor at time 2 seconds. The maximum fire temperature is 984 ^{0}C. The time-dependent fire simulations were carried out to 20 s in order to capture the unsteady behavior of the fire temperature. The transient trend observed provides a calibration curve for the fire behavior before the mist is deployed into the room.

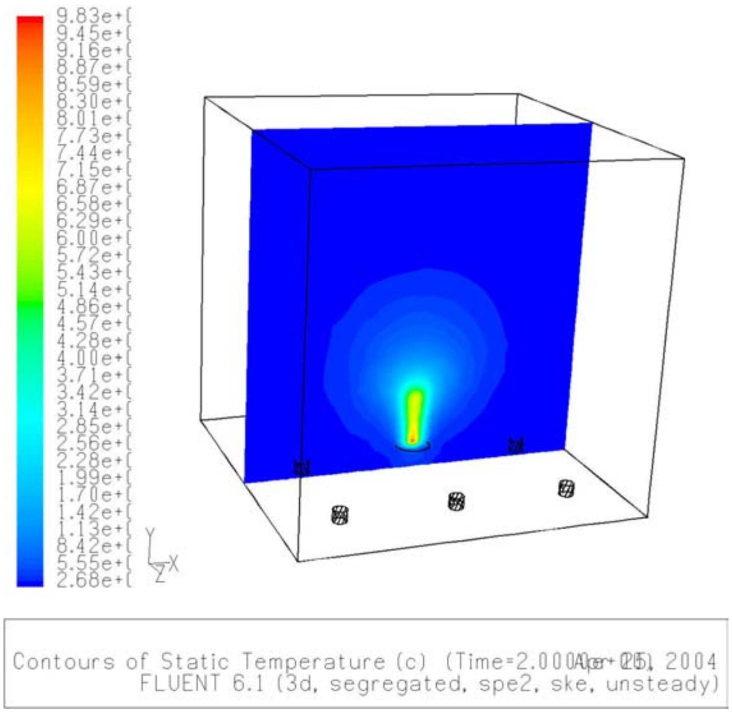

Figure 3: Temperature (^{O} C) contours of fire at t= 2 s. The peak temperature is 984 ^{O}C

Mist Deployment and Mist-Fire Interaction

Monodisperse droplets of 10 micron diameter were introduced at the mist outlets with mist loading of 30% wt of water in air (number density = 2 x 10^{14} drops/m^3). The throughput of mist was varied from 0.5 to 2.0 Lpm. The injection of NanoMist was initiated after a pre-burn period of 2 seconds. Figure 4A shows the velocity vectors inside the compartment with the fire located at the center. The flow close to the firebase is relatively weak except at mist outlets. This is an important computational result to notice because the dispersion and the fill rate of mist at the base of the compartment will be limited to this transport velocity. If a dense gas were to be discharged at these outlets, the dispersion time for the gas to reach the fire location will be a function of this background flow-field.

At the base of compartment, the fire pulls the air into the base as shown by a close-up view in Figure 4B. If mist is positioned at these locations with a suitable flow condition, it will be pulled into the firebase; otherwise, mist falls out or sweeps across the firesides downstream. This observation is supported by the entrainment of inert droplets into the firebase as shown by the calculated inert droplet trajectories in Figure 5A. Figure 5B shows trajectories of droplets with vaporization. The numerical simulation supports the concept of self-entrainment of mist into the firebase as shown by experiments in earlier work [10-12].

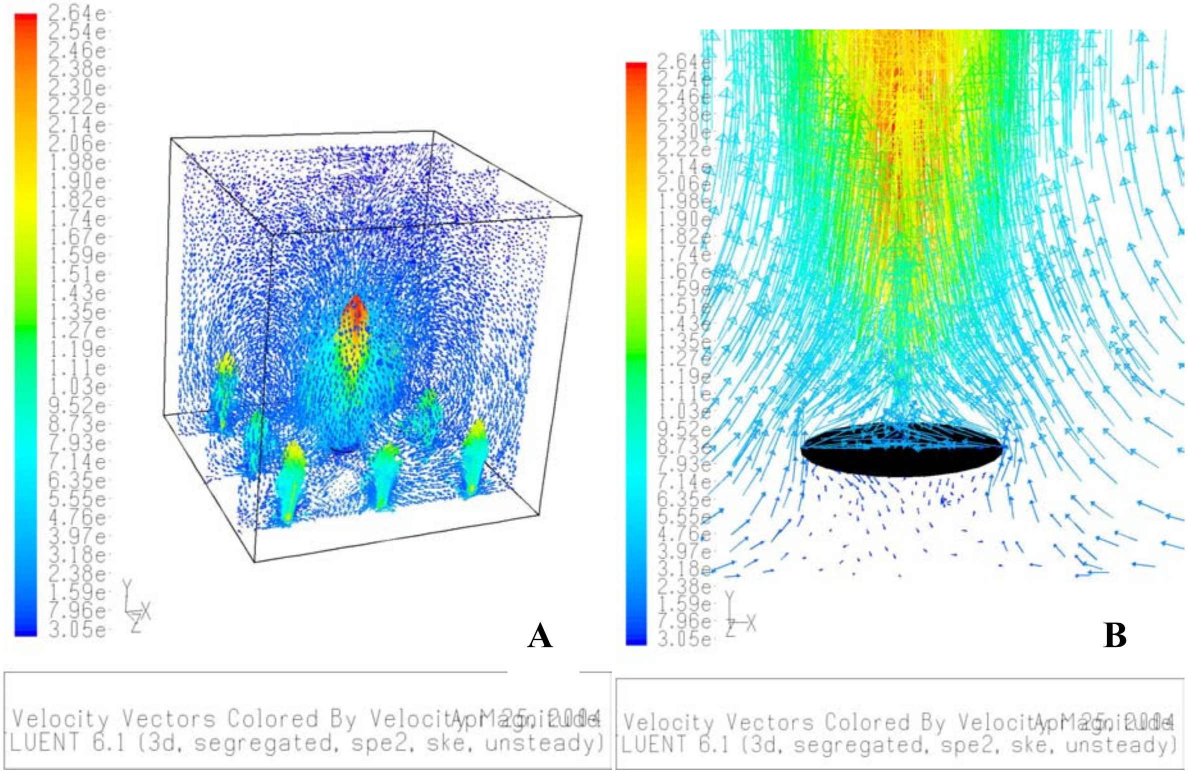

Figure 4: A) Velocity vectors (m/s) inside the compartment and B) velocity vectors (m/s) near the firebase, a close-up view

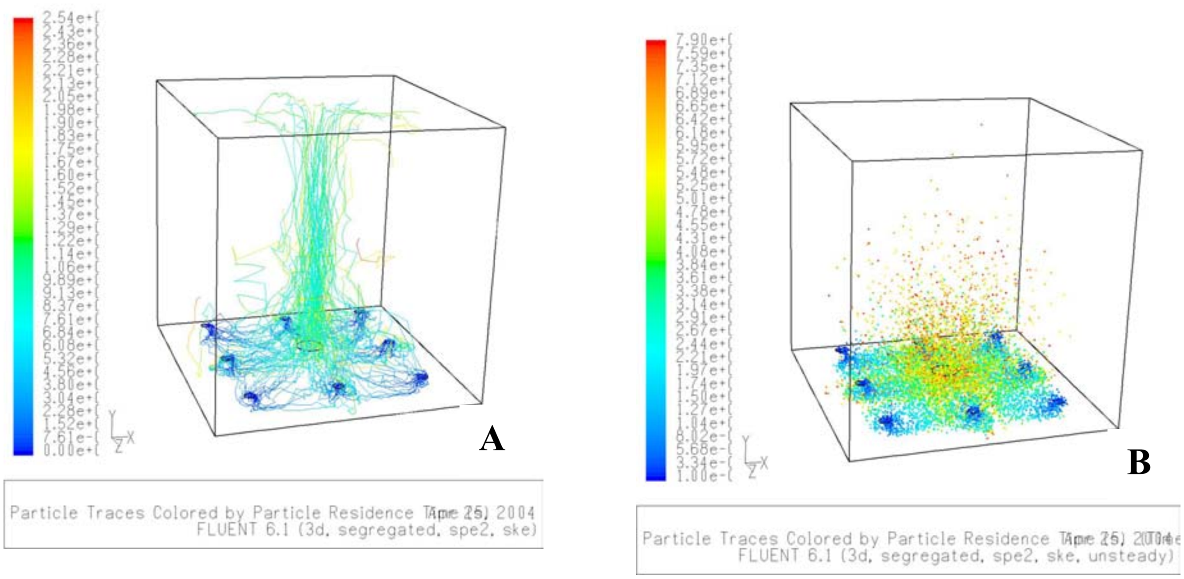

Figure 5: A) Stochastic droplet trajectories of inert droplets, and B) droplet trajectories with vaporization.

Local flooding experiments on a 0.3 m heptane pool fire showed self-entrainment behavior as shown in Figure 6, when the fire is surrounded by the mist cloud. The mist surrounding the firebase has extremely low momentum. The fire is seen as submerged in a pool of mist cloud. The mist is quickly pulled into the firebase. The fire goes out within 10 seconds.

Figure 6: Heptane pool fire (0.3 m) surrounded by NanoMist.

The extent of entrainment of mist into the firebase in the present simulation can be inferred from the vaporized mass fraction of water inside the fire geometry. Figure 7 shows the water vapor mass fraction contour at time t=10 s. The maximum vapor mass fraction of 0.19 is seen at the firebase. Based upon the latent heat absorption by the mist, this region of the fire shows a considerable temperature drop. The time dependent cooling of fire upon the injection of mist is shown in Figure 8 by centerline peak temperatures. Within about 6 seconds, the fire peak temperature cools from 984 to about 900 ^{O}C. The fire cooling continues indicating the tendency to go out. These results were obtained at a water mist flow of one liter per minute.

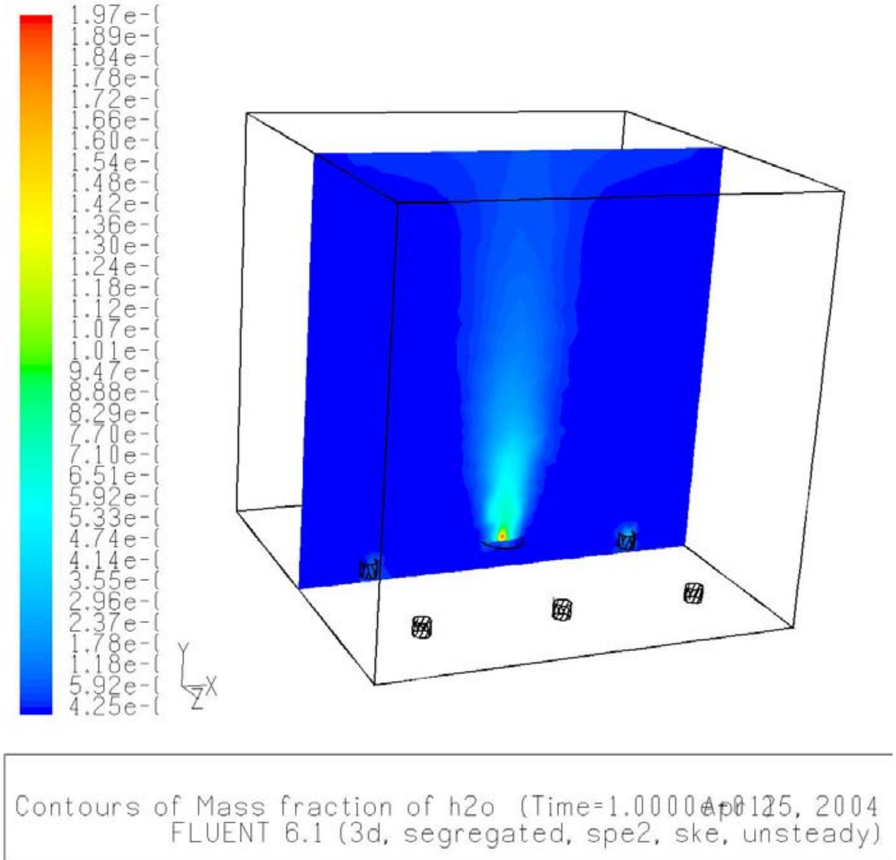

Figure 7: Water vapor mass fraction at t=10 s. The peak value of mass fraction is 0.19

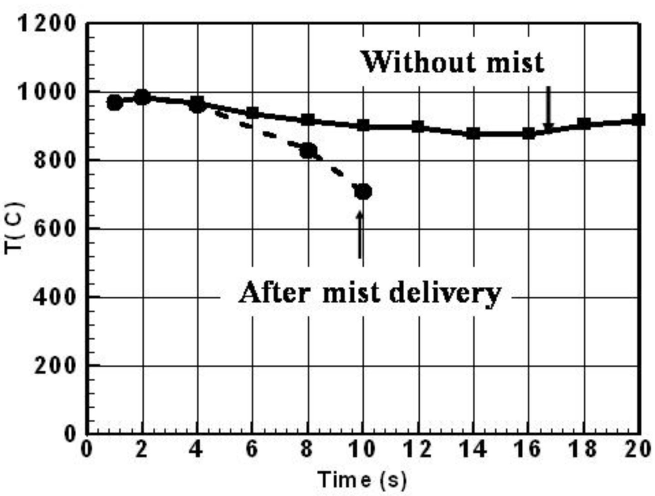

Figure 8: Centerline peak temperature of reference fire and fire with NanoMist injection

The fire extinction criterion was qualitatively determined by pre-determined peak temperature drops of 100 ^{O}C or more. When temperature drops below this limit, the fires were assumed to go out. However, the situation will be different with a combustion model that incorporates chemical kinetics. The gas temperature will be closely coupled to the combustion rate and will be self-decelerating once the cooling process starts. The extinguishment time of 5-8 seconds seems reasonable when compared with local flooding tests conducted on heptane pool fires as shown before in Figure 6. However, in the context of total flooding in a room, the situation may be different. The filling time for mist plays a key factor in limiting the mist concentration at and near the firebase, unlike in local application. Additional CFD simulations were carried out treating the mist as a dense gas in order to understand and estimate the time scales of mist transport to the firebase. The approach and results are described in the following section

Dense Gas (DG) Model Approach for NanoMist Dispersion

In this treatment, NanoMist is regarded as a dense gas (DG). The bulk density of the model DG mist with a water mass fraction of 0.3 (30% wt) is about 1.7 kg/m^3. The species DG has the transport properties of water vapor except for density. DG was injected at the mist outlets with an identical carrier gas velocity as in the case of mist. The mass fraction of DG was monitored at the fire location as a function of time with the identical pool-like gas fire at the center.

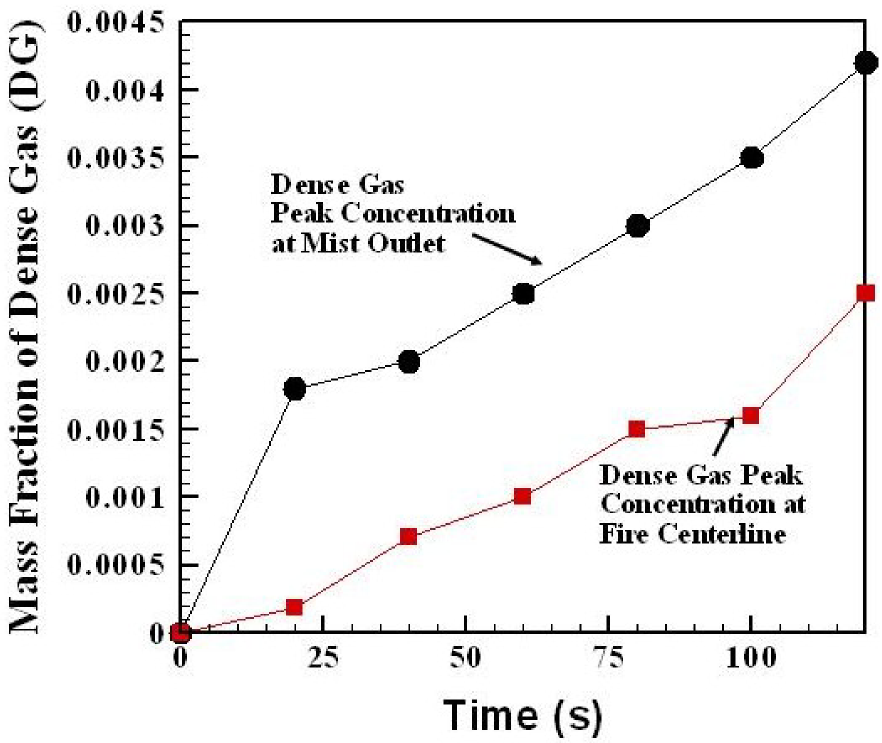

Figure 9: Comparison of Dense Gas (DG) concentration at the mist discharge location and at the fire centerline. The concentration of dense gas is about 50% at 2 minutes.

Similar to entrainment of mist, the dense gas is entrained into the firebase. In order to understand and estimate the time scales of DG transport to fire, the peak concentrations of DG at the mist outlet and centerline of fire are plotted as function time in Figure 9. As seen, the time scales are in minutes, as opposed to extinction times of seconds reported for a local flooding fire scenario (Fig.6). In order to reach about 50% dense gas concentration at the fire centerline, the time take is about 2 minutes. The slow dispersion of DG demonstrates the vastly differing time scales of mist transport and flame extinction time, particularly under weak convective flow at the firebase. Figure 10 shows the dense gas mass fraction contours at various time intervals. The gas concentration at the central fire location increases with time as seen at the center of the floor where the fire is located.

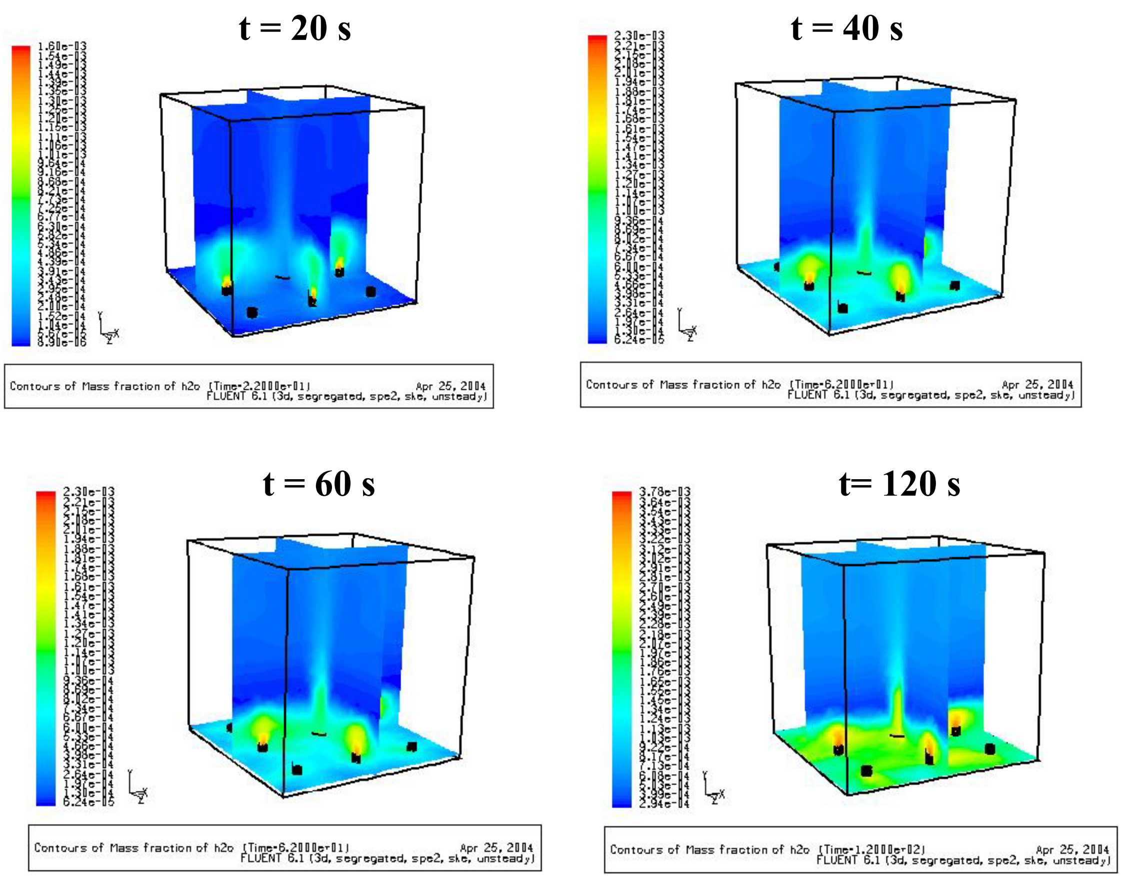

Figure 10: Mass fraction contours of dense gas (DG) at various time intervals.

Mist Dispersion and Fire Suppression Time Scales

The desired mist concentration around the firebase for shorter extinction times can be achieved by accelerating the convective flow field supporting the mist discharge, and/or increasing the mist throughput. Additionally, for large-scale turbulent pool fires, the strong convective flow at the firebase entrains even the low momentum mist.

SUMMARY

The CFD study provided guidelines for experimental tests in a 27-m^3 compartment. Test design is described below.

The 9 x 9 m area floor area was zoned into nine 1-m^2 zone. Eight mist discharge outlets were installed. The individual mist outlet was located at the center of each 1-m^2 zone. A 0.3 m diameter pool-like gas fire was located at the central 1-m^2 zone. A flux density of 0.11 Lpm/m^2 gave a reasonable cooling effect. The mist fills the compartment from the floor up and builds up in layers with a lateral dispersion determined by the input mist flux density. The time-scales of flooding combined with the flame extinction time observed was <10 s.

The mist filling behavior is similar to a low momentum dense gas dispersion inside a chamber. Under low velocity mist discharge conditions, the dispersion time scales are in minutes, rather than seconds. Additional study was conducted to understand and estimate the NanoMist transport behavior on possible fire suppression time scales, and to device ways to shorten it.

Using these test parameters as guidelines, compartment fire test were completed at the NRL's CBD facility. Fire tests also included obstructions to mist flow by installing baffles. A methanol fires was also tested. These results are reported in a companion paper by Sheinson et al. [22].

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