

CFD MODELING OPTIONS FOR TOTAL FLOODING BEHAVIOR OF ULTRA FINE WATER MIST

K.C.Adiga and Robert F. Hatcher, Jr.
NanoMist Systems, LLC
151 Osigian Blvd, Suite 199, Warner Robins, GA 31088.
Voice: 478-953-2709 Email: kcadiga@nanomist.com

Ronald S. Sheinson, Frederick W. Williams and Scott Ayers^{a,b}
The Navy Technology Center for Safety and Survivability
Chemistry Division, Naval Research Laboratory
Washington D.C. 20375-5320

^a Geo-Centers, Inc., 5813 Bayside Rd Building 307, Chesapeake Beach, MD 20732

^b Kidde Aerospace, 4200 Airport Blvd NW, Wilson, NC 27896

ABSTRACT

Clean gaseous agents are very effective in extinguishing fires, but where the enclosure integrity cannot be assured, the effectiveness of gaseous agent systems is severely compromised. Commercial water mist systems (50-200 μm) are attractive from a volume-flooding point of view even with enclosure leaks; but lacking gas-like transport characteristics, traditional mist cannot easily overcome or go around obstacles in a cluttered space. Furthermore, these systems may cause collateral damage to equipment, particularly in electronics spaces or data center sub-floors.

The low-momentum, gas-like, ultra-fine mist (UFM) system behaves like a clean agent in certain total flooding fire suppression applications. Water mist droplets smaller than 10 microns in diameter appear to exhibit gas-like or *pseudo gas* behavior with a superior ability to diffuse around obstructions and rapidly suppress a fire.

In this work, two different modeling approaches are used to describe the behavior of ultra fine mist. The Discrete Phase Model (DPM) was used for two-phase flow behavior, while a dense gas model was used to approximate UFM as a dense gaseous species matching the bulk density of mist. NanoMist®, a proprietary ultra fine mist technology, was used for fire tests at the U.S. Naval Research Laboratory (NRL) facility.

The DPM model over predicted the mist transport timescales while the dense gas model gave timescales comparable to the total flooding experiments. Both modeling and observed behavior indicated the gas-like behavior of UFM in terms of dispersion and passing around complex obstacles in the path and reaching non-line-of-sight locations.

The dense gas model simulates the transport behavior of mist as a single-phase gas and provides a robust tool to predict mist distribution. For an understanding of mist-fire interaction and the vaporization behavior of mist, we need to use the computationally more complex Euler-Euler model.

INTRODUCTION

Research for the last 3-4 years indicated that ultra fine mist (UFM) with below 10 micron sized droplets dispersed in a carrier gas (microfluid) might be an attractive agent to replace current gaseous chemical agents with varying toxicity issues [1-11]. The ultra fine water mist with droplet diameter below 10-micron closely resembles clean gas agents in transport behavior in cluttered spaces with a superior ability to diffuse around obstructions without significant loss of mist due to plating and deposition [3-4]. Although commercial water mist is an efficient suppression agent, it has not been effective when applied to volumes with significant obstructions.

NanoMist® is a proprietary ultra fine mist (UFM) technology that uses patented techniques to generate, extract and deliver extremely fine water mist with average drop sizes smaller than 10 microns [8-9]. This drop size is significantly smaller than that generated in conventional water mist systems that utilize either high fluid pressure or shearing air flows to generate the water mist. NanoMist employs a carrier air stream to deliver the generated mist into the enclosure. By varying the carrier gas volumetric flow, the mass of water loading can be increased up to 45%. This mist behaves like a dense gas dispersing slowly from the discharge location.

The observation that the ultra fine mist behaves like a gas requires further work on modeling and understanding this new class of “microfluid” in a total flooding environment. The major question is whether UFM behaves like a two-phase spray-mist in terms of particle flow behavior having limitations going around objects and cluttered space with droplet fallout and plating on surface. Alternatively, does it behave like a dense gaseous species (CO₂, for example) in terms of convection and diffusion of mist filling the flooding volume and reaching the firebase and going around obstacles. Beyond its gas-like behavior, the entrainment of mist into the firebase and short extinction timescales have been confirmed by local flooding tests on large-scale cooking oil fires (300-500 kW).

OBJECTIVE

The objective of this work is to explore CFD modeling options for simulating the transport behavior of an ultra fine (UFM) mist in a volume-flooding situation. The motivation for this study is the observed *pseudo gas* (or a dense gas equivalent) behavior of UFM in earlier work and the ultimate need for predictive tools to aid in suppression system design. The UFM behavior differed from a typical two-phase system in passing over objects and baffles reaching the non-line-of-sight location.

APPROACH TO MODELING AND EXPERIMENTS

Specific approaches include:

- ◆ Simulate and estimate the time dependent concentration of water mass fraction transport of mist from the mist discharge location to the firebase or a target location using: 1) Discrete Phase Model (DPM) typically used for modeling two-phase

particle flows, and 2) the convection-diffusion species transport model approximating the mist as an equivalent dense gaseous species.

- ◆ Compare the concentrations of DPM and Dense Gas Model with the observed behavior.
- ◆ Explore the options of CFD modeling for describing mist transport in a total flooding scenario for UFM taking NanoMist® fine water mist technology.

MODELING AND TESTING METHODOLOGIES

CFD Modeling

The Fluent CFD program was used to model flow, turbulence, energy and species transport. The UFM transport and vaporization was modeled using the Discrete Phase Model of Fluent. The dense gas equivalent model was based on the species transport model of CFD. The details are reported earlier [1]. Beyond what was reported in previous publications, this work describes a detailed comparison of DPM and DGM models on relatively simple 3D flow channel and a sub-floor with complex obstructions.

Fire Testing and Mist Transport Measurement

The Navy's sub-floor test method was described in ref. 3, HOTWC 2005. The area of the sub-floor mockup was 25-m² and the height was 1.5 ft. The mist was discharged from several inlets with 4" diameter pipes. The mist had to pass the baffle before it reached the test telltale fire. Additional baffles were installed as required by the protocol. For simulating leaks, a selected number of tiles were removed from the floor. The electronic cabinet was placed on the floor by removing tiles. The UFM passed through the cabinet.

The cooking oil fire tests were conducted using a deep fat fryer with an approximate dimension of 19" x 23" fire area containing 75-80 lb of cooking oil. The tests closely followed the UL300 protocol established for cooking oil fires.

Ultra fine mist total flooding tests were conducted in a room mockup of 3 x 3 x 3 m size at the U.S. Naval Research Laboratory (NRL) facility. A heptane pool fire was located at the center of the floor. Eight mist discharge outlets were located around the fire. The details are reported in [6].

RESULTS AND DISCUSSION

First, the experimental work that motivated the investigation of gas-like transport behavior of ultra fine mist is reviewed and presented. This is followed by the current CFD work on two-phase flow and alternate dense gas modeling.

Previous Work Motivating the Current study

1. Transport of mist in sub-floor mockup with multiple obstructions [3] – the Naval Research Laboratory Evaluation study

Previous work on ultra fine mist showed considerable evidence of gas-like behavior in total flooding as well as local flooding scenarios. These results are summarized in order to describe this relatively new class of microfluid. UFM has undergone thorough testing for the last 3 years using NanoMist® technology developed by NanoMist Systems, LLC. The proprietary technology produces UFM with flow properties appearing to be very close to a gaseous agent. Considerable amounts of field and laboratory tests have shown UFM's ability to diffuse like a gas. Some of these are briefly described in the following paragraphs.

The US Naval Research Laboratory sponsored project at Hughes Associates, Inc. [3] evaluated UFM-NanoMist® flooding and fire extinction behavior in a sub-floor with baffles and additional obstructions via tube bundles. They provided flow obstructions as well as additional surfaces for droplet deposition and thus mist loss.



Figure 1: A) UFM-NanoMist® operation in 25 m² sub floor, B) tube bundles as obstructions additional to the main baffle, C) electronic cabinet exposed to NanoMist®, and D) NanoMist® leaking out of missing floor tiles.

Figures 1A, B, C and D show sub-floor test outlay and details. The mist distribution resembled clean gas agent dispersion. The mist transport was effective to four corners where telltales were located. An additional baffle was installed using tube bundles (Fig. 1A). The telltale fire behind the baffle and all the four corner telltale fires were extinguished in all tests. UFM also showed its ability to withstand reasonable leaks on the floor (Fig 1D). UFM did not short the modem card inside the cabinet (Fig 1C). The mist transport was not hampered by obstructions as evidenced from the extinction behavior with and without additional obstructions shown in Figure 2.

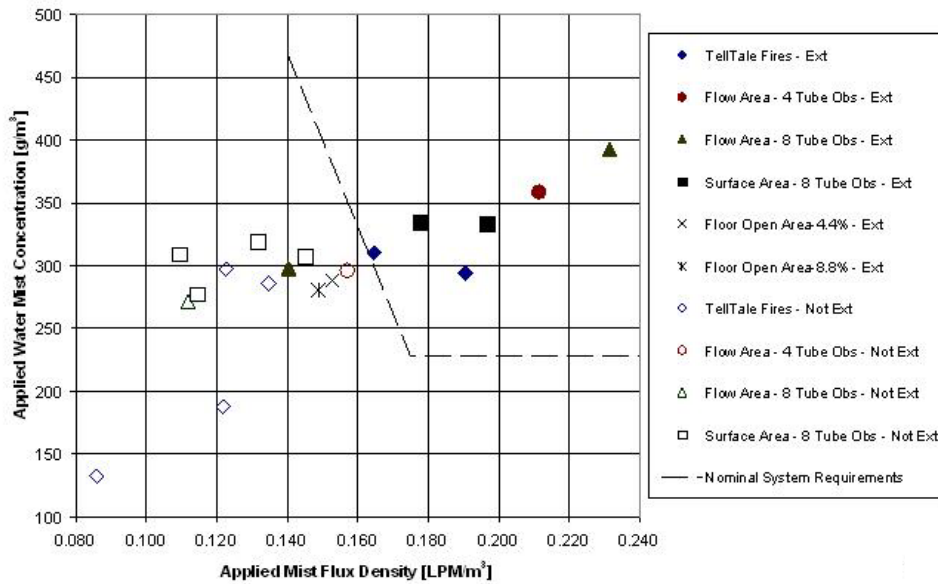


Figure 2: Total flooding in 25-m² sub-floors with and without additional obstructions and floor openings

2. Commercial Kitchen Cooking Oil Fire Scenario: Mist discharge at the base

The in-house work at NanoMist Systems, LLC on local flooding tests of UFM-NanoMist® on cooking oil fires on deep fat fryers showed very short extinction times. The amount of water required was very small, about 50-100 ml depending on the test configuration and fire size. The mist was deployed to the firebase locally. Once the mist concentration met the minimum flux requirement, the fire went out within 5-10 seconds like with wet chemical agents. The surrounding mist was entrained into the firebase as if it were a dense gas. Any attempt to push the mist with a high momentum resulted in mist sweeping across the flame surface without contributing to suppression. The dynamics of the suppression process are shown in Figure 3.



Figure 3: The gas-like UFM being entrained to the firebase of 300-400 kW cooking oil fires in deep fat fryer

The gas-like behavior of the mist was evident from its ability to stay in the air and be transported into the firebase along with the surrounding gas. Mist with droplets of larger size (25-50 micron) will fall out in a low velocity field.

3. Colorado School of Mines, the Center for Commercial Application of Combustion in Space (CCACS):

Abbud-Madrid et al. from Colorado School of Mines (CSM) carried out tests on cable fires inside the space shuttle mid-deck locker mockup box using UFM-NanoMist [13]. In their tests, they installed a baffle between the cable-fire and the mist discharge location. The regular water mist had difficulty reaching the non-line of site fire location behind the baffle. However, UFM-NanoMist extinguished fires by diffusing like a gaseous agent as shown in Figures 4 A and B.

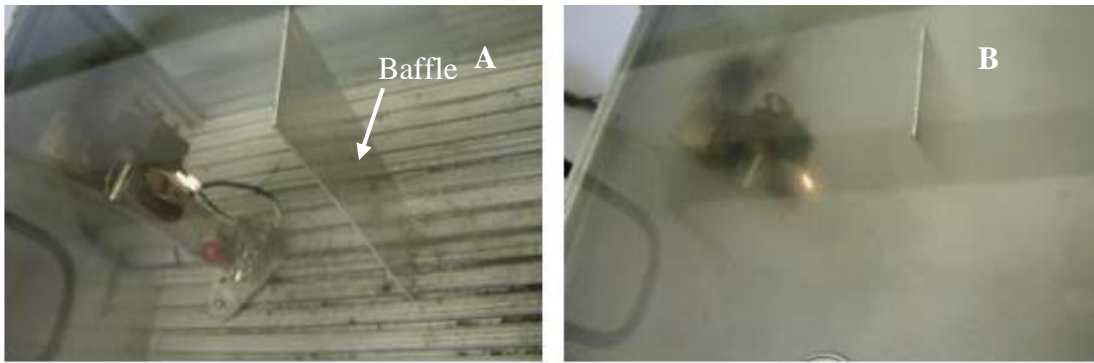


Figure 4: UFM-Nanomist application to Space Shuttle mid-deck locker box mockup fire suppression—courtesy Abbud-Madrid et al. [13]

4. The U. S. Naval Research Laboratory Work on Total Flooding [6]

Naval Research Laboratory (NRL), CBD compartment fire research on UFM-NanoMist [6] explored the ability of mist to extinguish liquid pool fires (heptane and methanol) in 27m³ volume. Figure 5 shows the geometry of the compartment used for CFD simulations.

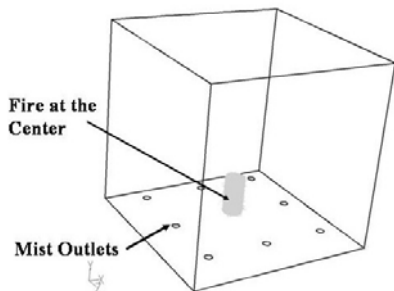
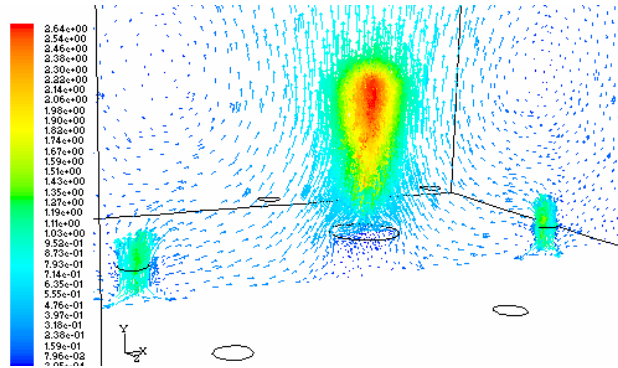


Figure 5: NanoMist flooding in 29-m³ compartments



Figure 6: A dense gas-like ultra fine water mist NanoMist® dispersion in a room

The compartment had eight mist outlets on the floor around the fire located at the center. The mist slowly rises up and builds from the bottom. A photograph of mist discharge is shown in Figure 6. The velocity profiles near the firebase are shown in Figure 7. If mist droplets are locally stable in this region surrounding the firebase, the mist will be entrained along with the surrounding air.



Velocity vectors colored by velocity magnitudes (m/s)

Figure 7: Velocity vectors near the firebase where stable UFM droplets may be can be entrained similar to air.

The experiments showed extinction of most fires tested. However, the fire extinction took several minutes.

Figures 8 A and B show the measured and calculated rates of mist transport inside the compartment.

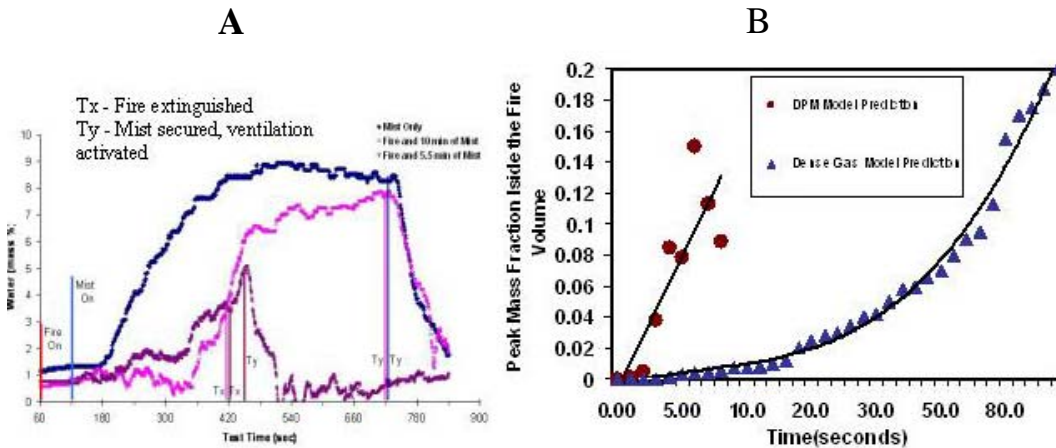


Figure 8: Comparison of A) measured water concentration history near the firebase with B) DPM and Dense Gas Model predictions and observed results in compartment fire tests.

The peak mist concentration was attained in approximately 7 minutes. Once the mist was available locally, the fire was extinguished quickly. This was similar to local flooding cooking oil fire tests shown in section 2. The DPM modeling of mist transport gave very short timescales of 5-10 seconds (Figure 8B) while experiments indicated 5-6 minutes (Figure 8A). In order to understand the observed longer timescales of mist transfer, the next modeling approach treated the mist as single-phase dense gas using the bulk density of the mist. As seen in Figure 8B, the dense gas model gives transport time in minutes.

The DGM predicted water concentration is shown as a function of time in Figure 9. The plots show the time-dependent concentration of water at the fire located at the center.

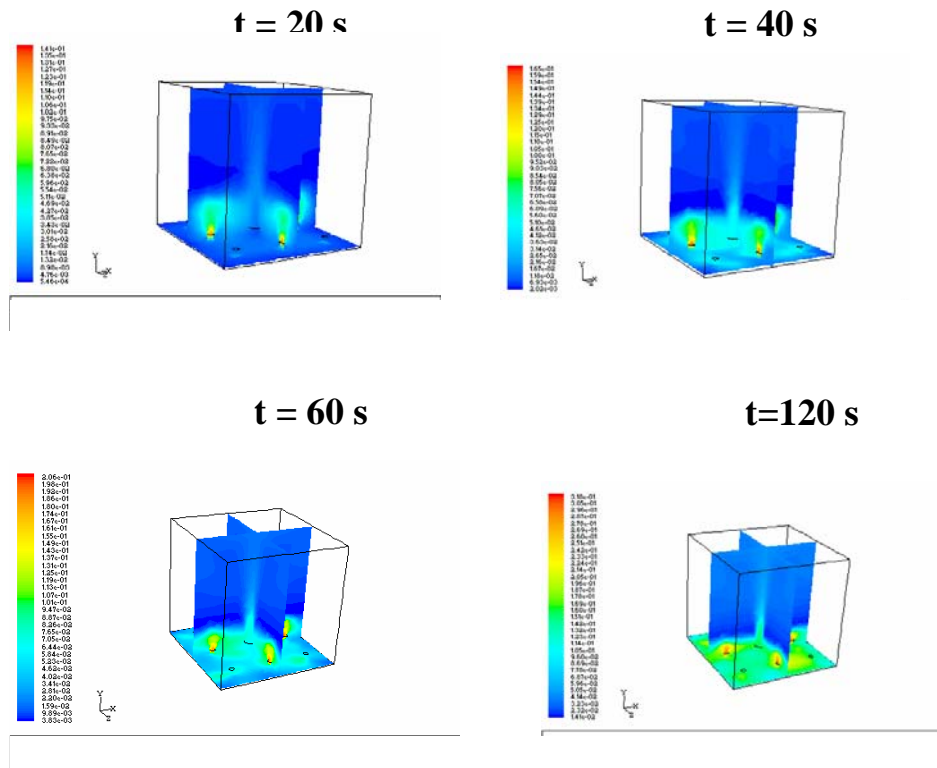


Figure 9: Predicted dense gas mass fraction contours of water concentration in the 27m³ compartment.

The dense gas model predictions in Figure 9 show a relatively slow buildup of water concentration. In fact, the compartment fire tests showed that mist transport was the limiting factor, which in turn was related to the rate of mist input through UFM-NanoMist inlets.

CURRENT WORK

The current work included estimation of timescales of mist transport in an obstruction-free flow channel by DPM and Dense Gas Model. Additional work included modeling and comparison of mist flow in a sub-floor mockup with multiple flow obstructions.

The flow channel of cross section 0.5 x 0.5 m and length 1.5 m was used in this study. The channel is free of any flow obstructions. The distributions of droplets as well as DPM concentration (kg/m³) are shown in Figures 10A and B respectively.

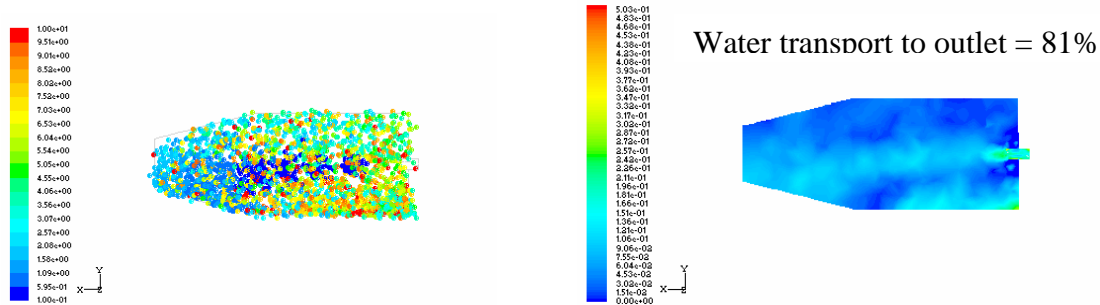


Figure 10 A: DPM droplet tracking colored by residence time (s). U= 5 m/s. The residence time=10 seconds

Figure 10B: DPM concentration (kg/m³); U=5 m/s, droplet diameter 5 micron; t=10 s.

The droplets travel with the free stream velocity because of low drag and relative velocities. The residence time matches the velocity field. Figure 10B shows droplet-tracking results in terms of concentration of water. The proportion of DPM water transported to the outlet within 10 seconds, W_{tr} , is calculated by:

$$W_{tr} = C_w (\text{outlet}) - C_w (\text{inlet}) \times 100; \text{ where } C_w \text{ is the DPM concentration in kg/m}^3.$$

Based on the inlet concentration (0.32 kg/m³) and outlet concentration of (0.26 kg/m³) at t=10 s, the proportion of water transported by DPM model, W_{tr} is = 81%. This timescale is short and does not scale with the previous compartment fire tests. In addition, this is relatively high compared to the dense gas model predictions shown next. The results of dense gas model are shown below in Figures 11A and B at t= 10 and 180 seconds respectively.

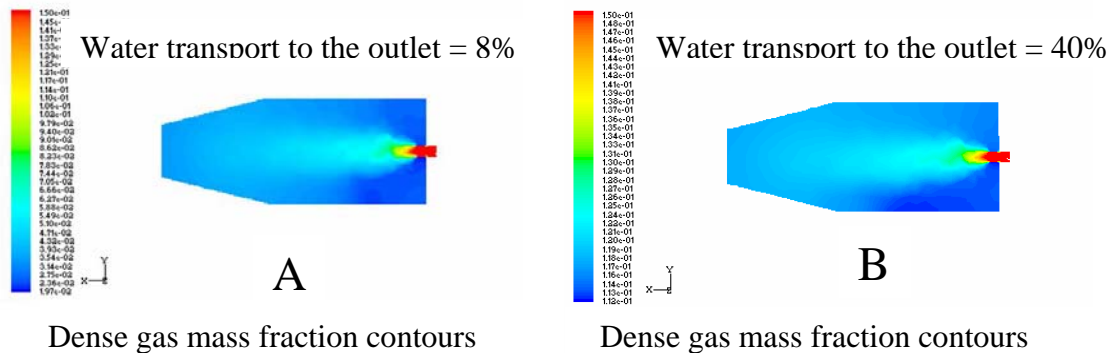
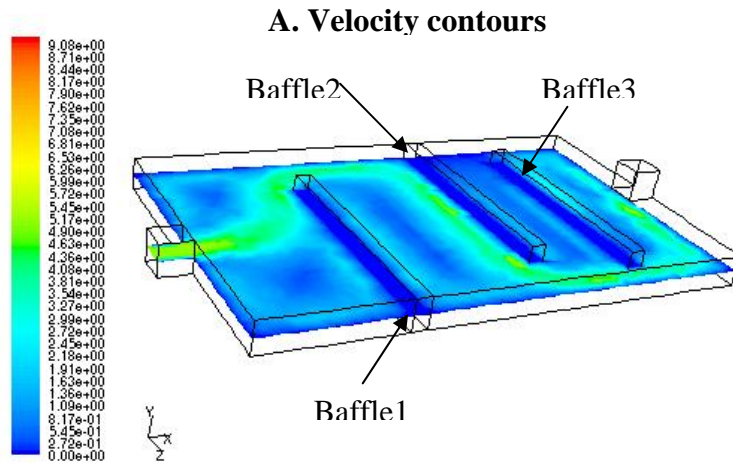


Figure 11: Dense gas prediction of mass fraction of water in the flow channel: A) t=10 s and B) t=180 seconds.

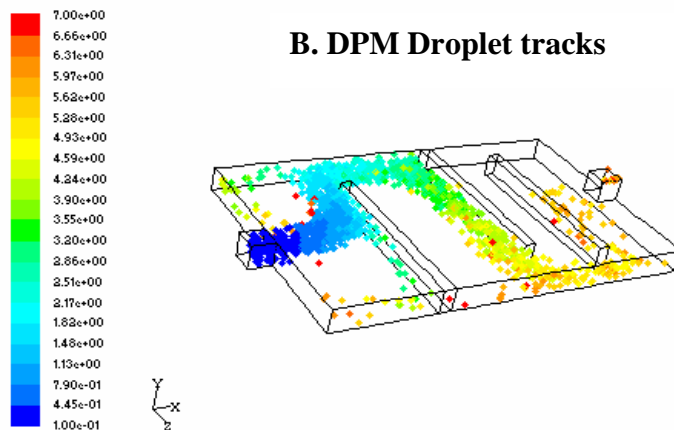
The dense gas model shows only 8% of water mass transfer (Fig.11A) to the outlet while DPM showed 81% at 10 seconds. However, the dense gas model shows about 40% at the end of 180 s (Fig.11B). This is a long transport time, but generally compares with experiments on this mist composition.

Multiple Flow Obstructions:

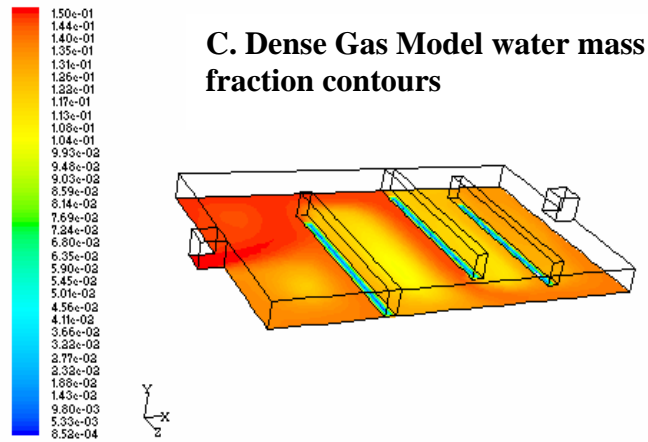
The flow of UFM mist inside a 16 x 10 x 1 ft sub-floor mockup with three baffles was simulated both by DPM and dense gas model. The outlay and test results are shown in Figures 12A, B and C. The two upstream baffles are staggered, with alternate baffles contacting the two opposite sides as seen in Figure 12A. The DPM particle tracks show a narrow distribution of droplets within the sub-floor (Figure 12B). The dense gas model simulates the transport behavior of mist as a single-phase gas. The concentration of water is relatively uniform in Figure 12C. The dense gas model results resemble the transport of a gaseous species such as CO₂. The baffle did not matter significantly. This supports the previous observation in NRL tests [3] on the 25-m² sub-floor. In those tests, the mist did reach the entire volume and put out all telltale fires in spite of added obstructions.



Contours of velocity magnitudes (m/s)



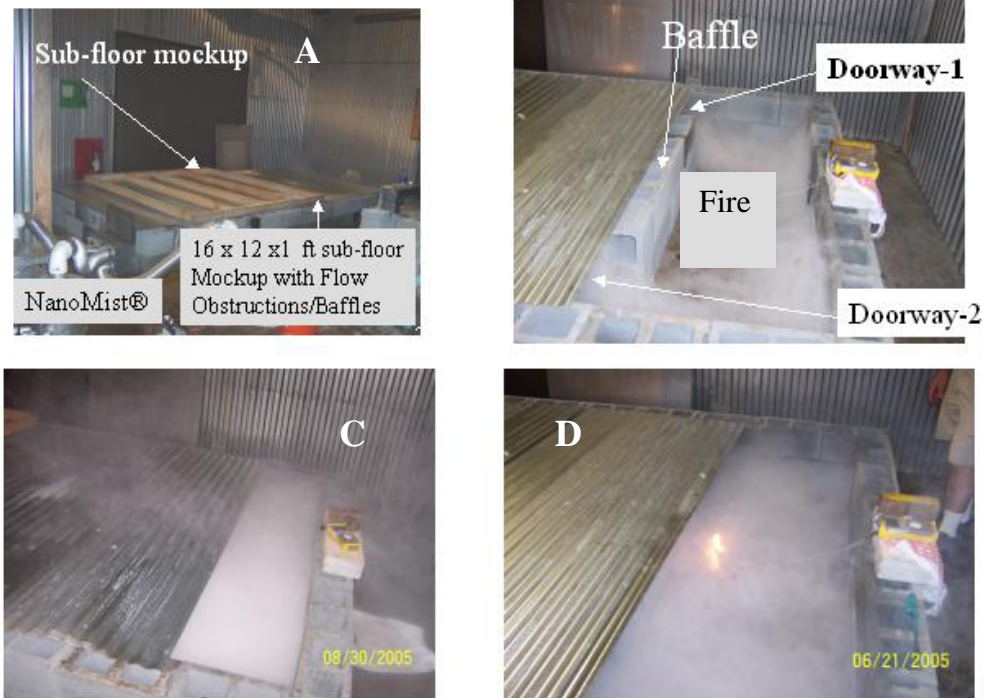
DPM droplet tracks colored by residence time (s)



Dense gas model water mass fraction contours

Figure 12: A) velocity magnitude, B) droplet track colored by residence time, and C) dense gas model water mass fraction.

Figure 13 A, B, C, and D show-sub floor test details. The photograph in Fig. 13A shows the sub-floor mockup outlay. In 13B, the mist passes through the baffle and reaches the fire area slowly. In 13C, the mist fills the fire area completely. The time to reach this stage is about 1-2 minutes depending on the inlet flow field. The mist distribution in 13C and D resemble the dense gas simulation shown in Figure 12 C.



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Figure 13: Mist transport in a sub-floor with multiple baffles.

CONCLUSIONS

A brief review of the past work on ultra fine mist (UFM) strongly suggests its gaseous nature. The mist showed its ability to diffuse around obstacles and extinguish fires in sub floor mock-ups with multiple flow blockers and leaks. The gas-like behavior of mist in terms of surrounding the fire and fire extinction by being entrained into the firebase was observed in large-scale cooking oil fires and was similar to chemical agent behavior. The UFM fire suppression tests in Space Shuttle mid-deck locker box mockup demonstrated UFM's ability to extinguish cable fires located in non-line of sight behind the baffle. The UFM in 27-m³-compartment fire test exhibited its ability to be entrained into the firebase like a dense gas and extinguish fires.

The modeling of UFM as a true two-phase system using a Discrete Phase model (DPM) showed relatively short timescales of water concentration buildup, typically 5-10 seconds. The dense gas model on the other hand predicted timescales in 1-2 minutes, which were close to experiments. The ability of the gas-phase model (dense gas) to reproduce the mist behavior in these scenarios suggests the gas-like behavior of UFM.

The study showed that the dense gas model (DGM) could reproduce UFM transport behavior very closely. As such, the dense gas model can be a robust tool for engineering and integrating the UFM-NanoMist technology into fire protection systems. For an understanding of mist-fire interaction and vaporization behavior of mist, we need to use the computationally more complex Euler-Euler model.

ACKNOWLEDGEMENT

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