

FEASIBILITY STUDY OF WATER MIST FOR SPACECRAFT FIRE SUPPRESSION

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ABSTRACT

A combined experimental/numerical project recently initiated at the Colorado School of Mines to investigate the effectiveness of water mist as a fire-suppression agent in various fire scenarios and low-gravity conditions is outlined. Preliminary results obtained in the development of a polydispersed mist model are discussed. These results, while limited (one-way coupled), provide interesting insight regarding the mist evaporation dynamics that is directly relevant to the, issue of droplet penetration in the presence of obstacles.

INTRODUCTION

Having an effective strategy for spacecraft fire safety is of the utmost importance for NASA due to the enclosed environment and buoyancy-free conditions onboard. Currently the International Space Station (ISS) uses carbon dioxide (CO₂) for fire suppression and the Space Shuttle still relies on Halon 1301 fire extinguishers. While each of these technologies is effective, they also have serious drawbacks. It is therefore appropriate at this time to critically evaluate water mist as a possible fire suppression technology for future spacecraft and for planetary habitation modules, such as those planned for Mars and the Moon. On a per-unit-mass basis, water is as effective as Halon 1301. In addition, water is more effective for surface and deep-seated fires than CO₂. Water is also non-toxic, non-corrosive, readily available in spacecraft for multiple uses, and deionized water may be used for fighting electrical fires. Moreover, agent cleanup may be achieved with dehumidifiers in the ventilation system.

Consequently, a comprehensive study of the fire-suppressing properties of water mist in spacecraft and extraterrestrial habitats is being conducted at the Center for Commercial Applications of Combustion in Space at the Colorado School of Mines. The purpose of this project is to investigate the effectiveness of water mist in single or mixed-agent configurations on different fire scenarios, geometries, and low-gravity conditions evaluated numerically and experimentally and compared to other fire-fighting agents currently used in spacecraft fire-safety systems.

This is a combined experimental/numerical effort based on normal and reduced gravity experimentation coupled with numerical simulations. Three sub-models with limited coupling are being developed to simulate a fire source, suppression agent, and radiation effects for

selected extraterrestrial fire scenarios. These sub-models will then be integrated into a high-fidelity fire suppression model. The next step will be to reduce the order of the integrated model to the point that it can be used easily, with minimized computational requirements, while still retaining the most important components. The resulting modeling code will be intended as a tool for use in making design decisions for future extraterrestrial fire suppression systems.

Specific questions to be answered include:

- (1) What is the relative effectiveness of water mist and carbon dioxide (CO₂) as suppression agents?
- (2) What are the dominant fire-suppression mechanisms in reduced gravity and how is their relative importance different from that expected in ground-based fire-scenarios?
- (3) What is the relationship between the factors affecting water-mist performance in reduced gravity and the definition of optimum fire-suppression strategies in spacecrafts using water-mist?

EXPERIMENTAL STUDIES

The experimental effort is currently in development and the planned strategy is only outlined here to provide some perspective on the overall project direction. Experiments will be carried out to validate and provide feedback to the sub- and detailed models. The reduced gravity experiments will be conducted onboard the NASA KC-135 aircraft. Temperature, airflow, gas composition, and smoke and water-mist concentration will be measured during a typical test. The effects of water mist on the evolution and extinction of the type of fires most likely to occur onboard spacecraft will be assessed. Results will be compared to the suppression characteristics of carbon dioxide, the agent of choice onboard the ISS.

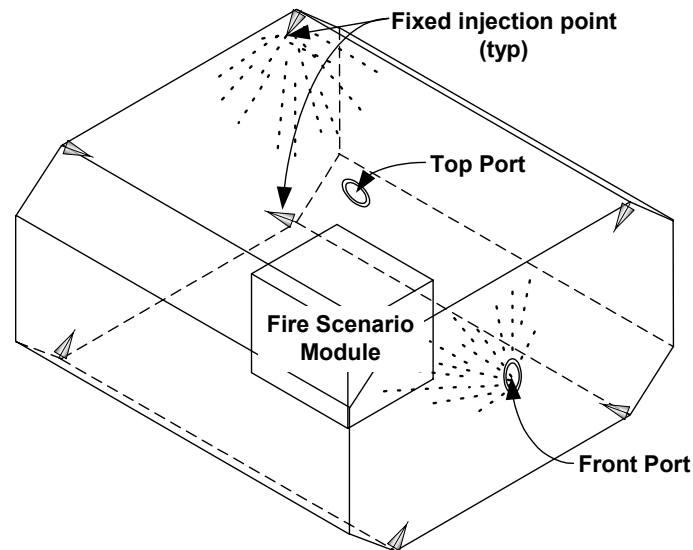


Figure 1 Experimental apparatus based on Space Shuttle middeck locker

A glovebox shell has been constructed that will enclose an experimental apparatus approximately the size of a Space Shuttle middeck locker (see Figure 1), within which all of the experimentation will be carried out. The top panel of the apparatus is transparent to allow video data collection and an adjustable ventilation system will be included for airflow and purging of

combustion gases. In this pseudo-locker we will test a variety of suppression methods, such as water-mist, carbon dioxide, and nitrogen with single and multiple injection points. These injection methods cover the current ISS fire suppression method of a portable hand-held fire extinguisher spraying through a port in a rack and also possible next-generation spacecraft components that may have a multi-point suppression delivery system built into the design. We will also test hybrid suppression methods such as water mist with a CO₂ or N₂ atomizing fluid.

At first, experiments will be done in our laboratory in normal gravity where we have the greatest access to instrumentation (e.g., gas chromatography) and the experiments can be carried out with greater repetition rates. The normal gravity experiments will provide preliminary heat release rate input for the fire source sub-model and will also be used to identify worst-case burning materials and fire configurations.

In addition to the normal gravity experiments, we plan to perform low gravity testing on NASA's KC-135 Reduced Gravity Aircraft. The KC-135 experiments will provide data for the fire source sub-model and the suppression agent sub-model as they apply to our idealized fire scenarios. Existing data indicates that fire behavior changes non-linearly with gravity; in fact, the worst-case fire growth conditions may occur at partial gravity levels near that of Mars [1,2].

The fire suppression methods mentioned above will be used to put out several fire scenarios that have been identified as the most relevant to spaceflight, such as overheated wires, cable bundles, and circuit boards, as well as burning cloth and paper. The four idealized scenarios we have chosen to study are:

- Scenario 1) Individual wires. This fire scenario would represent an overheated isolated single wire. The overheated condition is caused by the failure of an electrical component leading to excessive current draw and the failure or improper design of the circuit breaker. The threat of this scenario is both smoke and an ignition source. As we have shown previously, the smoke generated from space-rated wiring insulation can be extremely toxic [3].
- Scenario 2) Cable bundles. This fire scenario would also represent an overheated wire, in this case the innermost wire in a cable bundle. The cause and threat aspects of this scenario are very similar to scenario 1 above.
- Scenario 3) Elements on circuit boards. This fire scenario is related to the wiring scenario in that inherently fire safe materials are made to burn due to the application of an external heat source. As above, this fire scenario would be caused by the simultaneous failure (and/or improper design) of a component and the circuit breaker. While the cause and threats of this scenario are similar to wiring, the suppression characteristics are different because of the obstructions caused by the circuit board.
- Scenario 4) Cloth and paper. Friedman [4] has identified burning food, laundry and trash as an important fire threat, particularly on long-lasting missions. Assuming cloth and paper represent the worst-case flammability condition, these materials will be targeted in this project. In this case, the fire does not require an external energy source for propagation.

Tests will be conducted at the lowest gravity level possible in the KC-135 (milli-g), as well as at Lunar (1/6 g) and Martian (1/3 g) levels.

A module for each of the fire scenarios will be built to insert into the pseudo-locker. Data collection from these experiments will consist of multiple thermocouples, gas analysis, and extinction and video measurements for smoke and mist. The data will be recorded by an automated data acquisition system. The gas analysis will be done using either on-line gas chromatography or grab-samples depending upon the type of fire scenario and venue for the experiments. In addition, all experiments will be recorded on videotape.

To provide information to the Suppression Agent Distribution Sub-model, further testing will be conducted in which obstructions and ventilation will be added to represent possible spacecraft conditions (e.g., a series of cards in a card rack). We will measure the transport of mist using optical extinction measurements placed at various locations in the enclosure and determine the amount of water lost on surfaces using absorbent sheets placed on the surfaces and gravimetric analysis.

Initially, normal gravity experimentation will be used to perform a critical assessment of nozzle technologies. The characteristics of the selected sprays (droplet size distribution and number density, cone-angle, mass flow rates, velocity distribution) will be used to define the numerical simulations. Normal gravity testing will also provide guidance for determining the number and position of the multiple injection point suppression system and the position of the ports for portable fire extinguishers. We are also planning to test hybrid suppression methods such as water mist with CO₂ and nitrogen atomizing fluids in normal gravity as well. The most promising of these hybrid methods may be incorporated into the reduced gravity test matrix.

PRELIMINARY MODELING RESULTS

The long-term modeling effort consists of developing detailed sub-models of the fire source, the suppression agent generation and distribution, and the radiative shielding of the suppression agent. These sub-models will then be integrated into a high-fidelity, fire-suppression model. Finally, a reduced order model will be developed to minimize the computational requirements, yet retain the simulation capabilities of the original formulation. The following discussion is limited to preliminary results obtained in the development of a polydispersed mist model.

MODEL OUTLINE

Water mist injection characteristics include the number of injectors and their position in the domain considered, the mass flow rate injected (which may be time-dependent), the injection orifice size, the droplet size and velocity distribution, and the spray cone-angle.

The mist model used herein is based on a one-way coupled Lagrangian/Eulerian approach. The behavior of the mist is reconstructed from the calculated behavior of representative droplets. These representative droplets are selected using a Monte Carlo technique [5]. The distributions of the parameters that characterize the mist, droplet size, speed, and direction at “injection”, are assumed to be lognormal, Gaussian, and uniform respectively. The droplets have the same temperature at injection. The history of each representative droplet thus defined is then calculated as described below. Finally, overall mist behavior is reconstructed by integrating droplet histories in the Eulerian frame.

Evaluation of mist behavior requires a thorough understanding of in-flight droplet motion and evaporation. Droplet-gas relative velocity significantly influences the vaporization rate of the

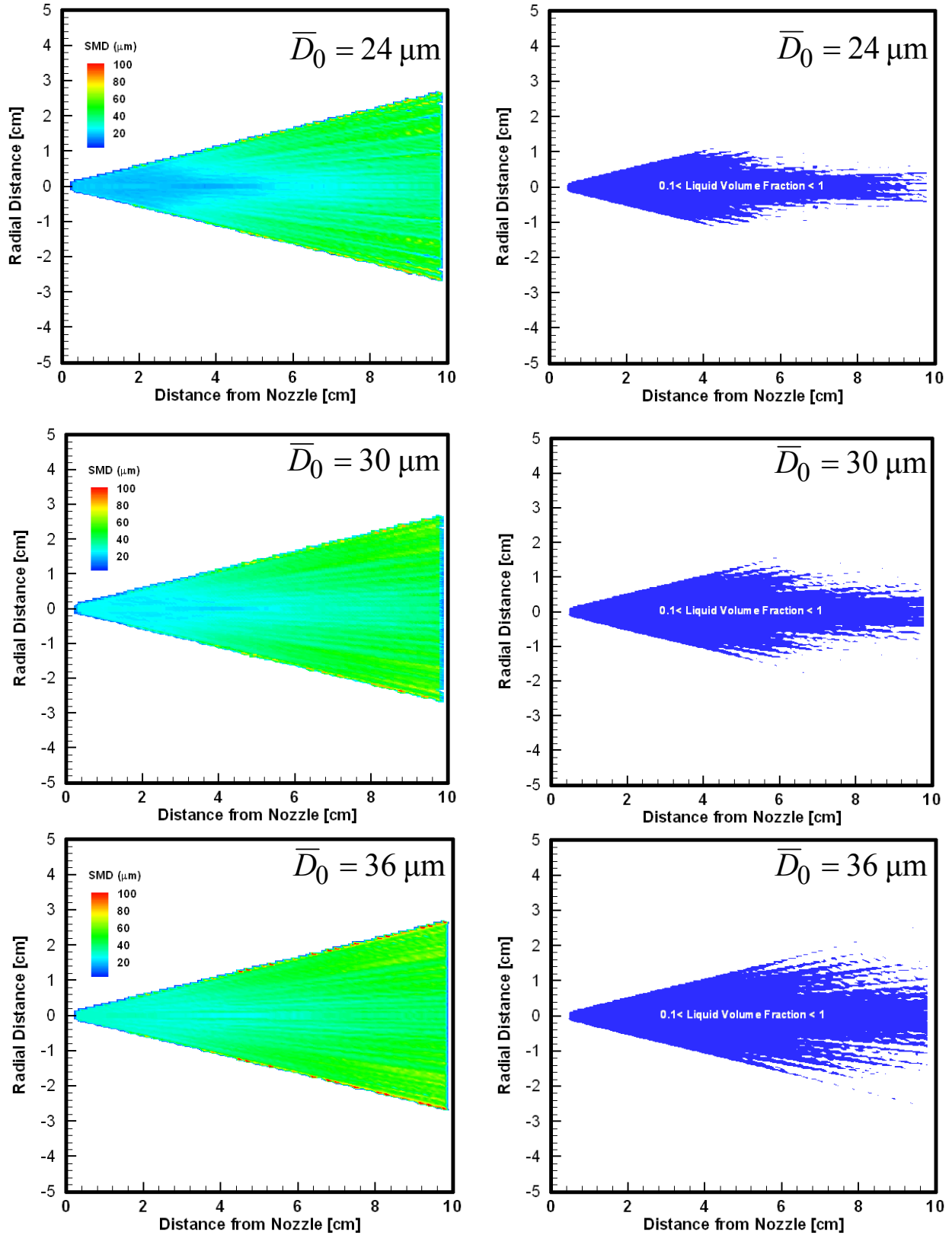


Figure 2: Predicted SMD (left) and liquid volume fraction (right) for $\bar{D}_0 = 24, 30, 36 \mu\text{m}$.

droplet in-flight, as well as its trajectory and, therefore, mist penetration. To represent this phenomena, a simplified version of the particle equation of motion is employed to track the droplets in a Lagrangian manner [5].

$$\frac{d\mathbf{V}_d}{dt} = \left(1 - \frac{\rho}{\rho_d}\right) \mathbf{g} + \frac{3}{4D} \frac{\rho}{\rho_d} \|\mathbf{V} - \mathbf{V}_d\| (\mathbf{V} - \mathbf{V}_d) C_D, \quad (1)$$

where \mathbf{V}_d is the droplet velocity, \mathbf{V} is the gas velocity, \mathbf{g} is gravitational acceleration, ρ_d is the droplet density, ρ is the gas density, and C_D is the drag coefficient. Droplet thermal energy conservation is evaluated using the spherically symmetric transient conduction equation:

$$\frac{\partial T}{\partial r} = \alpha \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right), \quad (2)$$

where a symmetry condition is enforced at the droplet center and convective heat transfer is applied at the droplet surface. Prior results [6] have shown that using a lump parameter approach results in a significant underestimation of the evaporation rate and, therefore, overestimation of the ability of the droplets to penetrate closer to a hot surface. As the droplet evaporates, the interface recedes and latent heat is absorbed [6]. The evaporation rate and the resulting droplet size are evaluated using Abramzon and Sirignano's extended film model [6,7].

RESULTS AND DISCUSSION

The base flow field considered here is that created by a jet ($V_{inj} = 15$ m/s) from a 50 mm nozzle impinging against a hot ($T_{wall} = 800$ K) flat plate 10 cm away. This is meant to simulate a fire suppression event for a smoldering surface. In the base case, the initial mean droplet diameter is set at $\bar{D}_0 = 30 \mu\text{m}$. Two other cases, $\bar{D}_0 = 24 \mu\text{m}$ and $\bar{D}_0 = 36 \mu\text{m}$ are also considered.

The predicted Sauter Mean Diameter (SMD) and liquid volume fraction distributions in the mist are shown in Figure 2 for these three cases. Note that the liquid volume fraction contour is a 0.1 isopleth. The influence of the initial mean diameter on mist penetration is evident. In the $\bar{D}_0 = 24 \mu\text{m}$ case, only the droplets that stay relatively close to the axis of injection can approach the hot plate before they disappear whereas in the $\bar{D}_0 = 36 \mu\text{m}$, the mist is able to retain most of its conical shape up to the plate. This is principally a result of the relatively cool fluid provided by the jet which, in effect, shields the droplets in that region. The

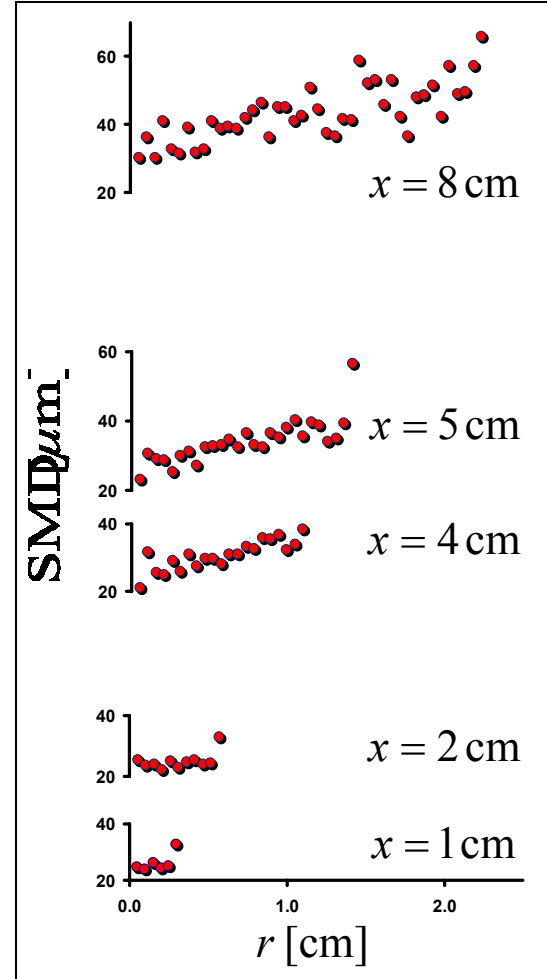


Figure 3: Computed SMD radial profiles at various axial location in the base case.

SMD plots (Figure 2) show two interesting features. In all cases, the smaller droplets tend to stay relatively close to the injection axis and the SMD increases as the mist approaches the hot plate. These features are seen more quantitatively in Figure 3 which shows the computed SMD profiles at various axial locations ($x = 1, 2, 4, 5, 8 \text{ cm}$) in the mist for the base case ($\bar{D}_0 = 30 \mu\text{m}$). The light scatter exhibited by these profiles is a reflection of the stochastic nature of the method used to discretize the mist. Near to the nozzle ($x = 1 \text{ cm}$), the SMD profile is relatively flat at about $25 \mu\text{m}$ except near the edge where it increase slightly to about $33 \mu\text{m}$. Moving along the mist axis, the profiles start exhibiting a slope that becomes more pronounced. At $x = 8 \text{ cm}$ the range of SMD (from the axis to the edge) is on the order of $30 \mu\text{m}$. Two mechanisms contribute to this behavior. Larger droplets have higher inertia, and are more likely to maintain the trajectory defined by their injection conditions. The slip velocity of smaller droplets vanishes much faster (they have a shorter momentum response time) and they are more likely to track the gas velocity field. Consequently, more large droplets are expected to be found near the edge of the mist. The second mechanism is related to the relative evaporation dynamics of small and larger droplets. Droplets near the edge of the mist experience larger temperatures ($\sim 800 \text{ K}$ vs. 300 K). Under these conditions small droplets ($\sim 30 \mu\text{m}$) will disappear even before the size of the larger droplet has been significantly affected by the evaporation process. Both mechanisms combine to increase the SMD at the edge of the mist.

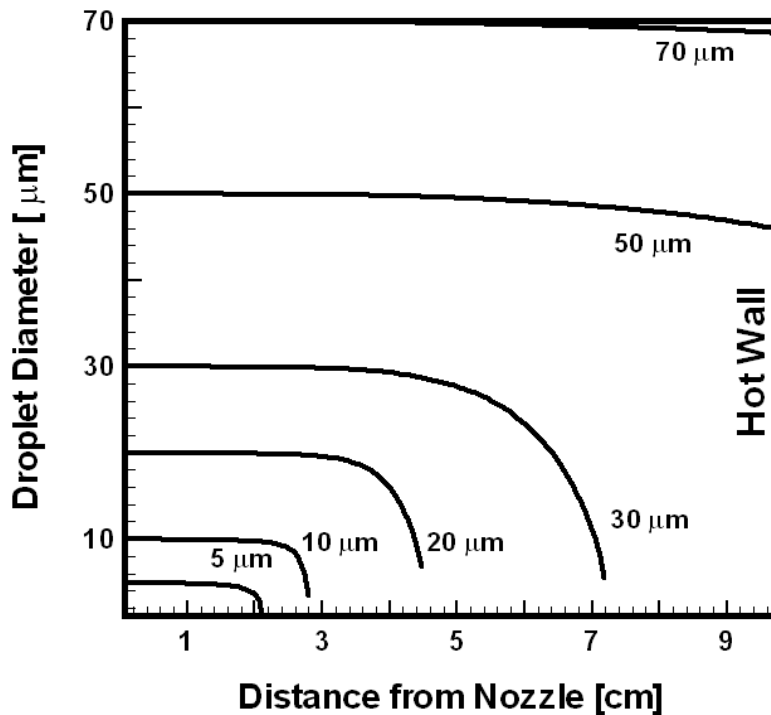


Figure 4: Calculated diameter histories for 5 to 70 μm droplets.

Figure 3 also shows that, on average, SMD's are higher as the mist approaches the hot plate. This may seem counter-intuitive since the evaporation process is enhanced by locally higher temperature as the hot plate is approached. However, this can be explained by the relative magnitude of heating and vaporization characteristic times for smaller and larger droplets. Figure

4 shows the calculated diameter histories for droplets ranging from 5 to 70 μm . All droplets exhibit a two-stage behavior. First, their size does not vary as they are first heating up with minimal to no evaporation (the local gas temperature is typically low near the nozzle). Then, as the local gas temperature increases and evaporation starts, the droplet size decrease abruptly and the droplet vanishes. Consequently, a size-segregated evaporation process occurs in which a smaller droplet will evaporate and disappear before the size of a larger droplet injected with the same condition has changed significantly. For example, for the case shown in Figure 4, a 30 μm droplet disappears at about 7 cm from the nozzle. At that point, a 50 μm droplet injected at otherwise identical conditions still has a diameter over 48 μm . This is similar to the mechanism described above for edge droplets.

SUMMARY

The overall goal of this fundamental study and the resulting numerical models is to evaluate the role of water mist in the next generation of fire-safety systems on spacecraft and habitation modules on the surface of other planets. It is expected that the knowledge gained from this research and the various models being developed to support it will also become useful tools for a variety of applications in fire science and fire modeling. For instance, the mist transport and evaporation model described above is currently being used to investigate droplet penetration for various fire-scenarios. In particular, the issue of droplet penetration in the presence of obstacles is being investigated.

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