MODELING STUDY OF THE BEHAVIOR OF LIQUID FIRE SUPPRESSION AGENTS IN A SIMULATED ENGINE NACELLE

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INTRODUCTION

This paper is a status report for a modeling study to evaluate the fire suppression potential for compounds in protecting engine nacelles. The project, “Vapor Loading and Suppression Effectiveness of Two-Phase Fire Suppressant”, is part of the Strategic Environmental Research and Development Program (SERDP) funded DoD Next Generation Fire Protection Technology Program (NGP) [1]. The project seeks to assess the vapor concentration bounding conditions for condensed gases/liquids considering their physical properties and the intended application conditions.

There is a high probability that gases or liquids with high boiling points, likely higher than that of Halon 1301, will be required to provide fire protection in engine nacelles. For this application, agents will need to be effective both at normal air temperatures near 300 K and also at low temperatures present at high altitude. In such a cold, non-trivial flow environment, the performance of the suppression agent will depend on a number of parameters including physical properties of the agent (heat capacity, boiling point, and heat of vaporization), the application temperature, and the flow-imposed time constraints for liquid agent evaporation. There is a need to eliminate compounds from consideration that will never be suitable and to identify those favorable properties that the successful agents are likely to possess. It is expected that the pre-qualified list will then undergo further scrutiny, including detailed modeling and experimental investigation.

In this study, transport and evaporation of drops introduced into a simulated engine nacelle [2] are treated using the NIST Fire Dynamics Simulator (FDS) version 3 [3]. The computational matrix considers the incoming air and engine surface temperature and the quantity and physical properties of the suppression agents. A similar drop size distribution is assumed for all of the agents. The amount of liquid in this drop distribution will depend on the amount of liquid that flash vaporizes when introduced into the nacelle. Evaporation of agent remaining in the form of drops after flash vaporization will be evaluated as a function of position in the nacelle using FDS3. An estimated suppression effectiveness ranking can then be derived from the computational results and related to the physical properties of the compounds in the computational matrix.

A concern with any computational study, especially one that seeks a predictive capability, is validation. There is some limited experimental data applicable to the current study that can be used to get a general sense of the degree of validity. A small set of data has been obtained for CF_3I [4]. More experimental data for this and other agents would be valuable. In this paper, computational results for water are presented. In this set of simulation exercises, water was selected as a simulant for high boiling point agent. In addition, FDS (v.3) has the inherent capability to perform water spray calculations without modifying the code. The latest version of FDS (v.4) has the flexibility to change from water to other liquids, if desired. FDS (v.4) will be used to carry out calculations using CF_3I and CF_2Br_2.

FLASH VAPORIZATION VERSUS EVAPORATION

FLASH VAPORIZATION

When a liquid is released under pressure through an orifice, the pressurized liquid jet will experience mechanical breakup leading to the formation of drops and/or vapor. In general the release and formation of an aerosol from a pressurized discharge is a very complex process [5]. However, some generalizations can help to establish assumptions in order to form a basis for a valid comparison of agent performance in the nacelle environment.

The agent discharge process can be considered to occur in two stages: flash vaporization and subsequent evaporation of remaining liquid. Upon release, if the liquid boiling point is lower than the ambient temperature, the super-heated liquid agent can immediately change into its vapor state (flash vaporize) cooling the environment and leaving some liquid behind which can evaporate through thermal exchange with the surround air. Flash vaporization is essentially independent of the properties of the compressed liquid; evaporation, however, depends on the specifics of the liquid properties in addition to the application conditions, particularly ambient temperature and residence time in the nacelle.

The amount of superheated liquid (i.e., stored at temperature above the boiling point) flash vaporized versus the amount of liquid left behind can be estimated from the Jakob Number, *Ja*. *Ja* can be evaluated from the enthalpy change required to take the liquid from its normal boiling point to the ambient temperature (sensible enthalpy) and the heat of vaporization of the liquid, ΔH_{vap}. Expressed in terms of the heat capacity at constant pressure for the liquid, C_{pL}, the temperature change $\Delta T = T_{amb} - T_b$ between the ambient temperature, T_{amb} and the boiling point, T_b, *Ja* may be written as

$$Ja = \frac{C_{pL}\,\Delta T}{\Delta H_{vap}} \tag{1}$$

In general, C_{pL} will exhibit some dependence on temperature. In this case, the term $C_{pL}\Delta T$ in Equation 1 must be integrated from the boiling point temperature to the ambient temperature in order to determine the sensible enthalpy.

$$\int_{T_b}^{T_{amb}} C_{pL}(T)\, dT \tag{2}$$

Ja is thus not a constant but depends on the temperature of the air into which the agent is discharged. For those agents discharged into air that is at a higher temperature than the boiling point (at the ambient pressure), *Ja*, which represents the fraction of liquid flashed to vapor in an adiabatic expansion process, will be between 0 and 1. A *Ja* of one implies that the entire agent vaporized immediately upon discharge. The heat content in the superheated liquid vaporizes the liquid. A *Ja* of zero or less applies to compounds discharged into air at a temperature equal to or lower than their boiling point. For compounds and conditions where $Ja \leq 0$, all of the agent released into the nacelle will be in the liquid state. Liquid evaporation in this case must rely on the much slower process of extracting heat from the surrounding air. Examination of Equation 1 indicates that for a given ambient temperature, a higher fraction of the original liquid will be in the vapor phase for compounds with a lower boiling point, larger heat capacity, and a smaller heat of evaporation. However, compounds and conditions presenting a low Jakob number cannot necessarily be eliminated from consideration without further examination of the agent evaporation behavior.

EVAPORATION

The immediate vaporization of the super-heated liquid upon release, controlled by the Jakob number, occurs on a fast time scale for the adiabatic vaporization (~ 10^{-6} to 10^{-9} sec). Any liquid remaining that must subsequently evaporate to get into the vapor phase does so on a much slower time scale (~ 10^{-3} sec to several seconds depending on drop size and ambient conditions). For compounds with boiling points higher than the inlet air temperature ($Ja < 0$), the evaporation time scale will determine the agent vapor concentration in the nacelle. Evaporation of liquid agent will depend on the physical properties of the agent including heat capacity, boiling point temperature, enthalpy of vaporization, and transport properties (thermal conductivity and/or mass diffusivity).

Several models exist for describing the evaporation of drops. One model suitable for the conditions under consideration here is the *d*-square law [6]

$$D^2(t) = D_o^2 - K\,t \tag{3}$$

where *K*, the evaporation constant, is given by

$$K = \frac{8\lambda_g}{\rho C_{pg}} \ln(1 + B) \tag{4}$$

With the mass transfer number, *B*, expressed as

$$B_H = \frac{C_{pg}\,(T_{amb} - T_b)}{\Delta H_{vap}} \tag{5}$$

or

$$B_L = \frac{Y_s - Y_a}{1 - Y_s} \tag{6}$$

Equation 3 predicts the drop diameter, *D*, at time, *t*, in terms of the original drop diameter, D_o. B_H is normally used at ambient temperatures above the boiling point; B_L is used at ambient temperatures below the boiling point. The evaporation constant depends on the temperature, *T*; the thermal conductivity, λ_g, of the surrounding gas; mass fraction of agent in the ambient surrounding air, Y_a; mass fraction of the agent at the drop surface, Y_s (assessed from the temperature dependent vapor pressure of the liquid); the heat capacity of the gas at constant pressure, C_{pg}; the liquid density, ρ; the enthalpy of evaporation at its boiling point, ΔH_{vap}; and the boiling point, T_b. The time required for complete evaporation can be expressed as

$$t_{vap} = \frac{D_o^2}{K} \tag{7}$$

Higher agent mass will exist as vapor in the nacelle if t_{vap} is small compared to the residence time in the nacelle. In general, properties that lead to small t_{vap} or large *K* are low boiling point, small heat of vaporization for the liquid and **low** heat capacity. Recall that in general for the super-heated liquid, more of the agent will start out in the vapor phase (flash vaporize) for those compounds with **high** heat capacity relative to its heat of vaporization. As a final consideration, better thermal agent suppression performance will be exhibited for those compounds that contribute a larger thermal load per mass of agent (high sensible enthalpy, **high** heat capacity) to the air stream. The determination for compound effectiveness in suppressing engine nacelle fires obviously lies in a trade-off between the agent properties and the application conditions. A detailed treatment of the transport and evaporation behavior of the dispersed agent, considering the agent specific properties, is necessary in the nacelle environment.

FIRE DYNAMICS SIMULATOR

The Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) computer code developed by NIST to study fire dynamics, smoke movement, and sprinkler-fire interaction [3]. Other applications, including pool fires and tank farm fires, have also been modeled using FDS. Details of FDS, its theory and operation manual, can be downloaded from the NIST Building and Fire Research Laboratory website [7].

SIMULATED ENGINE NACELLE

The engine nacelle is the region of on an aircraft between the body of the engine and the housing. Fuel and hydraulic lines, pumps, and lubrication systems are located within the nacelle. Air is vented through the nacelle to prevent any build-up of combustible vapors, and underside drain holes are used to mitigate potential pooling of flammable fluids as a result of a leak.

For fire suppression performance evaluation in this environment, it is important that a sufficient representation of the relevant application conditions be included. The complex geometry within the nacelle permits many opportunities for unwanted fires. The convoluted flow pattern resulting as air passes through the nacelle favors those agents that do not persist too long in the liquid state after release into the nacelle area. Thus, an assessment of suppression performance must consider evaporation behavior in this type of flow field.

Features of a previously developed experimental nacelle [2,4] were used to develop the computational grid used in this study. The experimental nacelle simulator consists of two concentric cylinders with agent and air flowing through the annulus with baffles and ribs. Figure 1 is a schematic of the simulator. The annulus of the simulator has an inside diameter of 0.6 m and an outside diameter of 0.9 m. The length (2 m) of the simulator is comparable to the distance between the agent injection port and the downstream end of a typical small engine nacelle. The baffle height was 0.075 m. The baffles are used to mimic a complicated flow path for the agent as in the case of a real nacelle. Two longitudinal ribs with the same height as the baffles are placed on the outer surface of the inner core of the nacelle between the inner forward and aft baffles. The ribs are used as barriers to the agent flowing circumferentially. The agent is released through a vertical tee. Agent concentrations are measured at the two locations, termed here as front port and aft port. A frequency-controlled, variable-speed blower provided airflow through the nacelle simulator.

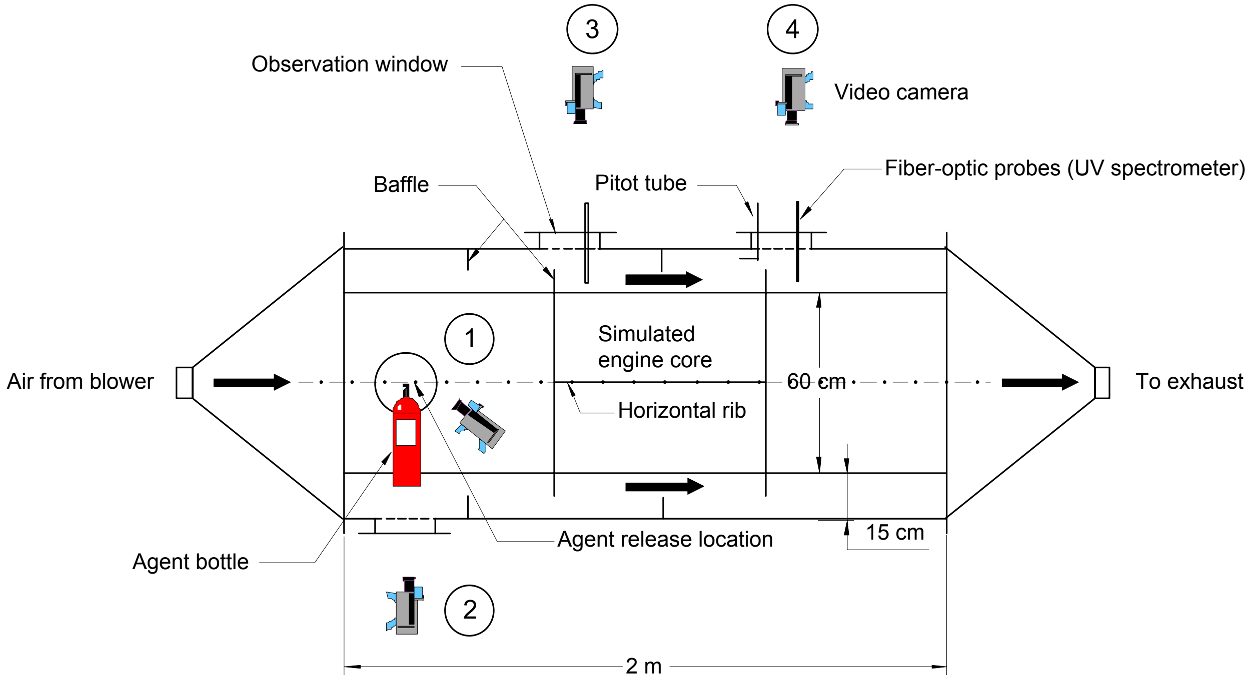

Figure 1. NIST nacelle simulator

The configuration used in the FDS simulation is shown in Figure 2. The grid model has geometrical dimensions commensurate with the experimental fixture. The computational grid model was previously developed in a separate NGP project [1]. The following conditions were used in the simulations. Air speed at the inlet of the nacelle was set at 4.25 m/s or 2.125 m/s and

22 °C. Two sprays, one pointing vertically upward and one vertically downward, were used to simulate the tee used for agent discharge. Water was discharged at a rate of 416 L/min, which was comparable to a high rate discharge used in nacelle fire suppression. The sprays were activated at 1.5 s from the start of FDS simulation and then de-activated at 1.8 s. The total activation time was 0.3 s. The dispersion process was simulated to 5 s with 50 × 200 × 50 grid cells. The drop size distribution used in the simulations was in the form of a Rosin-Rammler/log-normal distribution with a median volumetric diameter of 20 μm with the distribution parameter set at 2.4 (default value used in FDS). The minimum spray angle was set at 30°, the maximum at 75°, and the drop speed at 20 m/s. Water drop interaction with nacelle walls was handled in the way described in FDS. When a water drop impacts a solid horizontal surface, it is assigned a random horizontal direction and moves at a fixed horizontal velocity component until it reaches the edge, where it drops straight down at the same fixed velocity. When the water drop hits a solid surface vertically, it is removed from the computational domain.

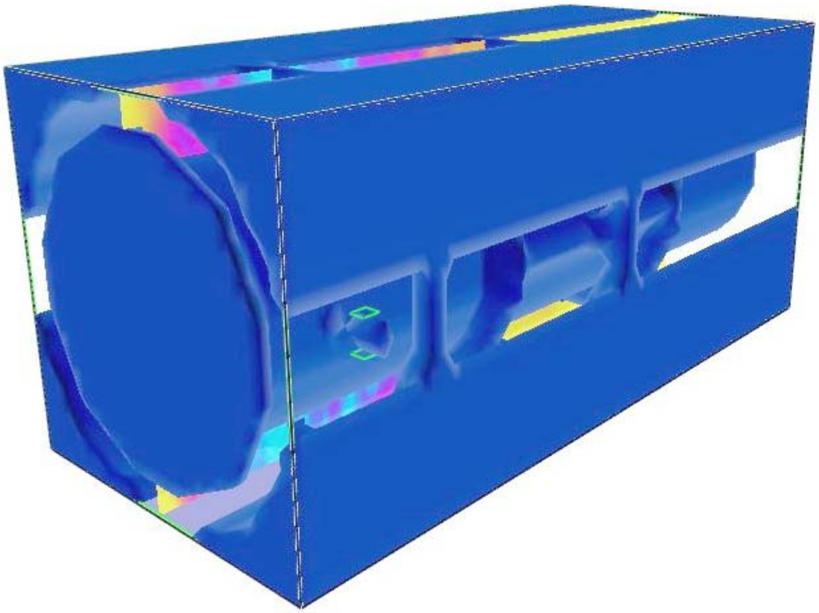

Figure2. Grid model of NIST nacelle simulator for FDS calculations.

Two nacelle conditions were examined. The nacelle walls were either at 22 °C or at 100 °C. Relative humidity was initially set at zero throughout the computational domain. The initial temperature in the annulus region was 22 °C. The dispersion effectiveness of water drops was assessed based upon water vapor concentration (mass fraction) measurements at the front and aft ports. The intent was to evaluate vapor loading that could be attained at these two locations.

Results and discussion

Figures 3 and 4 show the temporal variation of water vapor mass fraction at the two locations during the 5 s simulations when the nacelle walls were at 22 °C and 100 °C, respectively.

Several pertinent features are revealed in the two figures. There is a delay time (due to transport and evaporation) for water vapor to get to the two locations upon activation of the sprays (at *t* = 1.5 s). The time-averaged water vapor mass fraction at the front port is higher than that at the aft. The time-averaged concentrations at the two locations are higher when the nacelle walls are at higher temperature (100 °C vs. 22 °C). Higher nacelle wall temperature results in higher ambient temperature in the annulus region, which in turn causes water drops to evaporate faster.

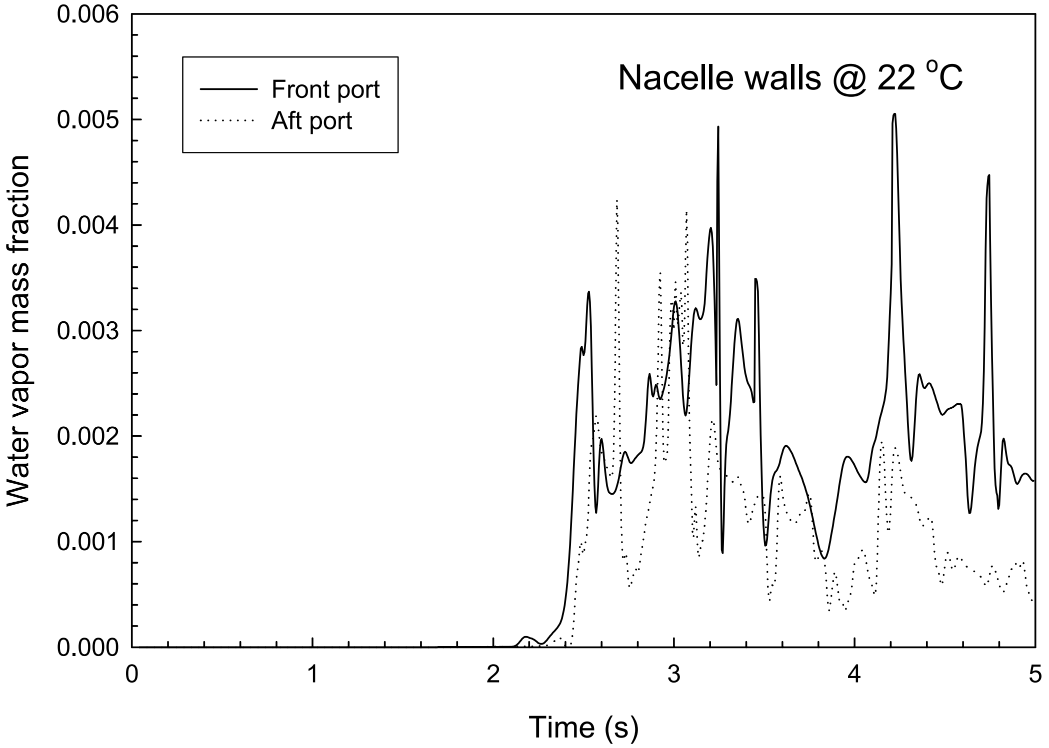

Figure 3. Temporal variation of water vapor at the two measurement locations resulting from the injection of 416 L/min of liquid water at 1.5 s into a 22 ^{o}C inlet air flow with a speed of 4.25 m/s. The nacelle walls were at 22 ^{o}C.

Figures 5 and 6 show the effect of nacelle airflow on the water vapor loading at the two measurement locations. The reduction in airflow increases the transport time of water vapor to the two measurement locations. The time-averaged concentrations do not appear to be significantly different under the two flow conditions at the same location. This could be attributed to the combined effect of dilution due to airflow and evaporation. Higher airflow results in faster evaporation but more dilution, and conversely for a lower flow.

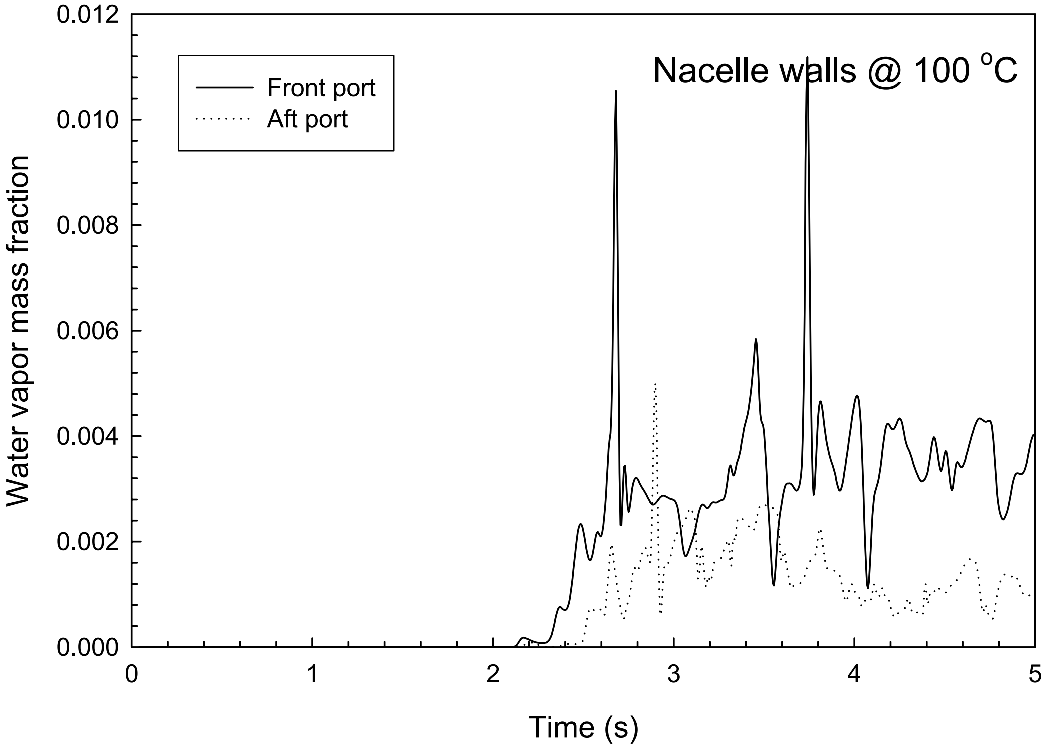

Figure 4. Temporal variation of water vapor concentration at the two measurement locations resulting from the injection of 416 L/min of liquid water at 1.5 s into a 22 °C inlet air flow with a speed of 4.25 m/s. The nacelle walls were at 100 °C.

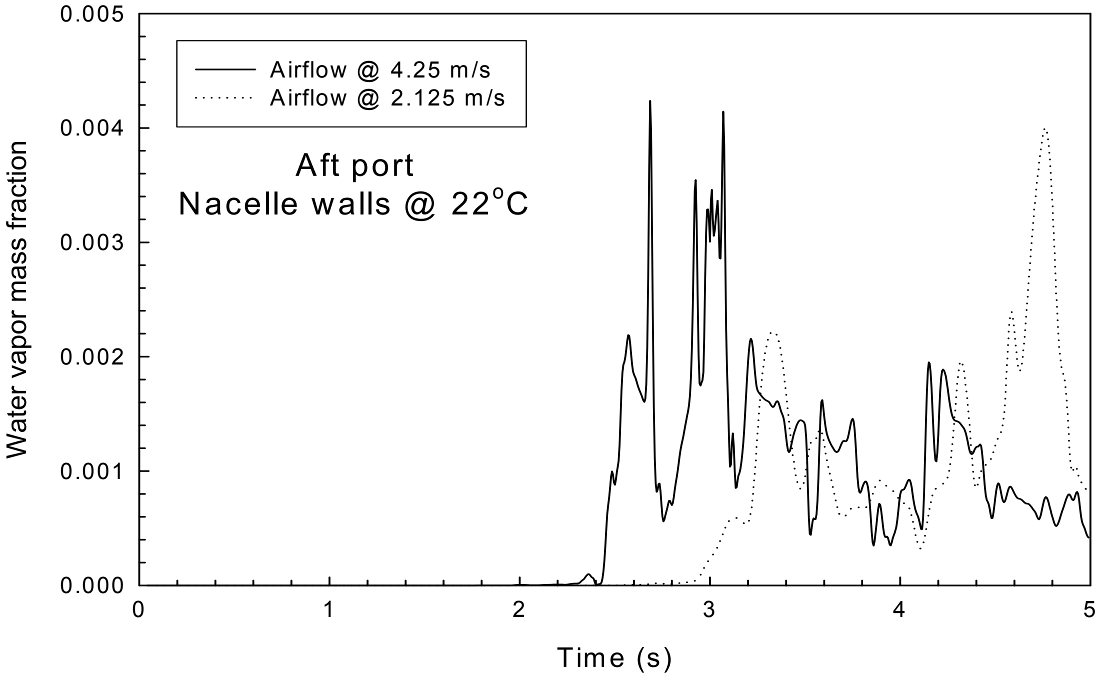

Figure 5. Effect of airflow at front port.

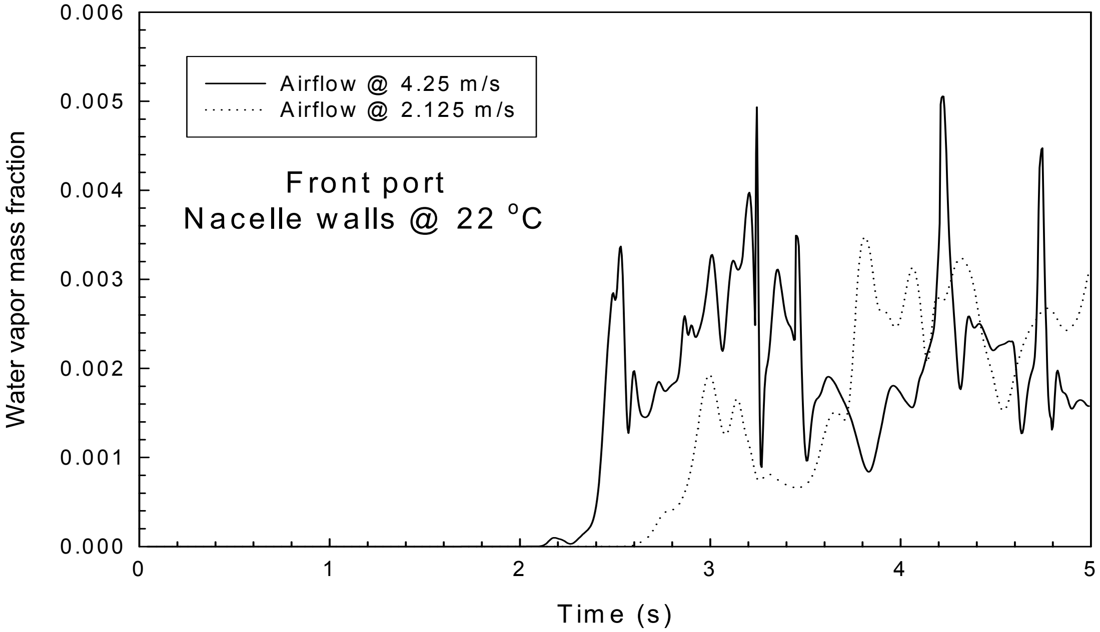

Figure 6. Effect of airflow at aft port.

CONCLUSIONS

This paper reports progress on a computational study to evaluate the fire suppression potential of compounds for engine nacelle fire protection. Drop transport and evaporation behavior of dispersed liquids (or gases under pressure dispersed as liquids) in a simulated engine nacelle is modeled using the NIST Fire Dynamics Simulator (version 3). Results for water, an example of a high boiling point liquid with excellent thermal properties, entrained in 22 ^{o}C air and interacting with cold (22 ^{o}C) and hot (100 ^{o}C) engine walls within the nacelle are presented. The results show the importance of the application conditions. Studies are underway to model the behavior of CF_3I at very low inlet air temperature conditions to simulate a low boiling, low temperature application. The ultimate goal of this project will be a determination of those compound properties and application conditions that should exhibit good fire suppression potential using the nacelle simulator as a test bed. This understanding will provide needed guidance for further development of two-phase fire suppression systems for engine nacelle applications.

ACKNOWLEDGMENTS

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