Effectiveness of Water Mist Droplet Size on Fire suppression in Air Craft Cabin and Cargo Compartment

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Motivation

• Water mist has been identified as a potential alternative to Halons
• Smaller than 150 μm water mist droplets have been shown to be effective in fire suppression
• The physics of droplet size effects in terms of thermodynamic cooling vs. oxygen displacement need to be better understood
• Other applications of mist (other than water)

Advantages of water mist over sprinkler systems

• Water damage reduction
• Retrofit applications
• Weight considerations, aircraft applications
• Facilities where water vapor or run-off could cause higher damage

Applications include:

• Aircraft Cargo Compartments and Cabins
• Engine nacelle
• Hidden spaces
Relevant Previous Research


• Spray as a fire suppression agent for aircraft cargo compartment fires, Marker et al. (2001)

• One zone model of water mist fire suppression systems, Li, Y. F. et al. (2004)
Relevant Previous Research

• Full-scale test effectiveness of water spray systems for improved aircraft fire safety, Sarkos et al. (1995)

• Cargo compartment fire protection in large commercial transport aircraft, Blake et al. (1998)


• Small-scale and large-scale experimental research and testing at NRL
Competition between Oxygen Displacement and Thermodynamic Cooling

- **Thermodynamic Cooling** - Water mist droplet evaporation removes energy due to latent heat.

- **Oxygen Displacement** – Water mist droplet evaporation creates a cloud of water vapor around each droplet that displaces the rest of gases including oxygen, thus causing a drop in oxygen concentration.
Water Mist Interaction in Flame Zone

\[ n_d V_{d,w} \rho_w (Y_{vap} L_v + c_{p,w} \Delta T_w) + m_f h_c (\eta_c - \eta_{c,w}) = \]

\[ [(m_{in} + m_{ent}) c_p \Delta T]_{out} - [(m_{in} + m_{ent,m} + Y_{vap} n_d V_{d,w} \rho_w) c_p \Delta T]_{out,m} + (m_{en} - m_{ent,m}) c_{p,air} \Delta T_{air} \]

Issues:

• Mist droplet penetration into the flame zone, \( f_n \) (droplet size, velocity, flame intensity)

• Evaporation rate and efficiency of oxygen displacement is a function of surface area \( (d^2) \)

• Modeling the chemistry to account for oxygen displacement
Theoretical Overview

- Conservation equations with and without mist

\[ \int\int \rho u_c p dT dA + \dot{Q}_c = \int\int \rho u_c p dT dA + \int\int \rho v_c p dT dA_x \]

\[ \int\int \rho u_c p dT dA + (\dot{Q}_{c,m} - \dot{Q}_{\text{latent}}) = \int\int \rho u_c p dT dA + \int\int \rho v_c p dT dA_x + (mc_p \Delta T)_w \]

\[ (\dot{Q}_c - \dot{Q}_{c,m}) + \dot{Q}_{\text{latent}} = (mc_p \Delta T)_{\text{out}} - (mc_p \Delta T)_{\text{out,m}} + (mc_p \Delta T)_{\text{ent}} - (mc_p \Delta T)_{\text{ent,m}} - (mc_p \Delta T)_w \]

\[ (\dot{Q}_c - \dot{Q}_{c,m}) = \dot{Q}_{O2,\text{Displ.}} = (m_f \Delta h_c \eta_c - (m_f \Delta h_c \eta_{c,m}) = m_f \Delta h_c (\eta_c - \eta_{c,m}) \]
A multi-zone model has been developed using conservation of mass and energy equations.

Four Distinct Zones

1. Upper layer
2. Plume
3. Flame
4. Ambient zone

Uniform temperature in each zone
Conservation of mass and energy with water mist interaction for the upper layer zone leads to the following equation:

\[
\frac{dT_u}{dt} = \frac{\dot{Q}_{\text{fire}} - \dot{Q}_{\text{water}}}{(m_u + m_{\text{evaporated}})c_p}
\]

\[
\dot{Q}_{\text{water}} = \dot{m}_w c_{p,w} (T_b - T_0) + \dot{m}_w Y_e \left( L + c_{\text{vap}} (T_u - T_b) \right)
\]

\( Y_e \), Evaporation Rate

\( L \), Latent heat of evaporation

\[
m_u = \rho A Z_u \quad m_{\text{evaporated}} = \dot{m}_w dt Y_e
\]
Using the conservation of mass and energy equation for non-flaming zones

\[
\frac{dZ_u}{dt} = - \frac{\dot{m}_e}{\rho_a A} - \frac{\dot{Q}}{c_p \rho_a T_a A}
\]

\[
\frac{dT_u}{dt} = \frac{\dot{Q} - \dot{m}_e c_p (T_u - T_a)}{m_u c_p}
\]

Applying forward difference discretization

\[
Z_{u_{i+1}} = \left( - \frac{\dot{m}_{e_i}}{\rho_a A} - \frac{\dot{Q}_i}{c_p \rho_a T_a A} \right) \Delta t + Z_{u_i}
\]

\[
T_{u_{i+1}} = \left( \frac{\dot{Q}_i - \dot{m}_{e_i} c_p (T_u - T_a)}{m_u c_p} \right) \Delta t + T_{u_i}
\]

\[
m_u = \rho_a A Z_{u_i}
\]
Water Droplet Evaporation Rate

According to D² Law for droplet evaporation:

\[ D^2(t) = D_0^2 - Kt \]

D (t): diameter of droplet as a function of time
D₀: initial diameter of the droplet
K: Evaporation constant

\[ m_w = m_{in} \frac{Kt}{\rho D_0^2} \]

This relation would allow calculation of oxygen concentration diluted by water vapor
Evaporation Rate Formulation

\[ K = \frac{8k_g}{\rho_l c_{pg}} \ln(B_q + 1) \]

\[ B_q = \frac{c_{pg}(T_\infty - T_{boil})}{h_{fg}} \]

Using formulation by Turns, S. R., Kg, the mean thermal conductivity of gas is calculated

\[ k_g = 0.4k_F(\overline{T}) + 0.6k_\infty(\overline{T}) \]

\[ \overline{T} = \frac{T_{boil} + T_\infty}{2} \]

\( T_{boil} \), the boiling temperature of the droplet (water droplet)

\( k_\infty \), thermal conductivity of gas
Evaporation constant for $290 \leq T(k) \leq 2037$

$$y = -3E-17x^3 + 1E-13x^2 - 2E-11x - 5E-09$$

$R^2 = 0.9998$
Evaporation Rate for Different Droplet Sizes

- $d = 20$ microns
- $d = 40$ Microns
- $d = 60$ microns
- $d = 80$ microns
- $d = 100$ microns

$\Delta t$ (s) vs. $Y_{vap}$
Evaporation Rate for Different Droplet Sizes, Different Ambient Temperature

![Graph showing evaporation rate for different droplet sizes and ambient temperatures. The x-axis represents diameter (μm), and the y-axis represents Y_{evap}. The graph includes lines for different temperatures: T=900K (blue), T=1000K (magenta), T=1100K (red), and T=1200K (brown).]
Results for Upper Layer Temperature
Dimensions of Enclosure: Area: 12 m², Height: 3 m
Time Step (Δt=0.15 seconds)
Slow Fire Growth

Graph showing the change in upper layer temperature (ΔT_u) and upper layer height over time (t(s)) for different scenarios.
Results for Upper Layer Temperature
Dimensions of Enclosure: Area: 12 m², Height: 3 m
Time Step (Δt=0.15 seconds)
Fast Fire Growth

![Graph showing the relationship between time (t(s)) and upper layer temperature (ΔTu (K)) for Upper Layer Temperature, FirmMB, and Upper layer Height.]
Fire Scenario: **Fast Fire Growth**
Water Flow rate: **0.5 kg/s**, Droplet size: **150 μm, 100 μm, 50 mm**
Total water used: **13.5 kg**
Average rate of change for upper layer temperature: **-1.102 °/s, -7.342 °/s, -21.08 °/s**

- **Upper Layer Temperature, Without Water Mist**
- **Upper Layer Temperature, Droplet Size= 150 microns**
- **Upper Layer Temperature, Droplet Size= 100 microns**
- **Upper Layer Temperature, Droplet Size=50 microns**
Fire Scenario: **Fast Fire Growth**

Water Flow rate: **0.35 kg/s**, Droplet size: **100 \( \mu m \)**, Total water used: **0.5775 kg**

Average rate of change for Plume zone temperature, **-8.115 \( ^\circ C / s \)**

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**Graph:**
- **Plume Zone Temperature, With Water Mist**
- **Plume Zone Temperature, Without Water Mist**

**Axes:**
- \( \Delta T_u \) (K) on the y-axis
- \( t(s) \) on the x-axis

**Legend:**
- Blue line: Plume Zone Temperature, With Water Mist
- Pink line: Plume Zone Temperature, Without Water Mist
Water Droplet Size Effect in The Flame Zone
Thermodynamic Effect Only

\[ \Delta T_{\text{out}} \]

- 5 gr/s
- 6 gr/s
Proposed Experimental Approach

**MEASUREMENTS**
- Monodisperse mist
- Droplet size analyzer
- Temperature Measurement (TC)
- Thermal Mapping (IR Camera)
- Oxygen Concentration
- Mist evaporation Rate

**Experiment Characteristics**
- Wolfhard-Parker burner with co-flow
- 2-D flame, 10x1 cm, Up to 5 kW
- Premixed and Diffusion Flames
- Laminar flow in the burner
Conclusions

• Simpler mathematical models, as opposed to CFD, can be used to track mono-disperse droplets and examine flame-mist interaction.
• Smaller droplets are more effectiveness in thermodynamic cooling, because of the surface area per unit mass, but suffers with lower mass per droplet.
• Oxygen displacement is a function of droplet surface area but is only important in the flame zone.
• A carefully designed experiment proposed here can be used to resolve the question of oxygen displacement effect vs. thermodynamic cooling.
• Quantity of water used can be reduced for several suppression applications, such as air cabin and cargo compartment.