Factors Affecting Efficiency of Water Mist Suppression of Solid Combustible Fires in Open Environment

Hong-Zeng (Bert) Yu
FM Global

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Background

• FM Global tested combined sprinkler-fine water spray protection in the 1960s for wood pallet fires in a 2300-m³ building.
  – 4.2-mm nozzles operating at 69 bar to supplement sprinkler protection

• FM Global tested fine water sprays for the protection of light hazard, residential fires in 1970s and early 1980s.
  – 5.6-mm nozzle had the best suppression result for nozzles from 4.1 to 11.2 mm at the same application density
Background

• Water mist was applied to other light hazard occupancies in 1990s and 2000s, mainly for marine and some land-based applications.

• Standard bodies recently expanded water mist applications to higher solid combustible fire hazards with limited or no fire test data:


    OH-1: Storage heights up to 2.4 m for commodities with moderate fire heat release rate.

    OH-2: Storage heights up to 3.7 m for moderate heat release rate, or up to 2.4 m high for high fire heat release rate.
Current Needs

• Identify the key factors for suppressing solid combustible fires in open environment

• Expand the database for water mist suppression of solid combustible fires
Outline

• Test commodities and fuel array configurations
• Assessment of droplet size’s impact on fire plume penetration and propensity of droplet deposition on fuel surface
• Water mist operating conditions
• Fire tests and results
• Conclusions
Test Commodities

Class 2 Commodity (EUR Commodity Category I)
- 1.06 x 1.06 x 1.19 m high per pallet load
- Cartons: 35.8 kg
- Metal liner: 20.7 kg
- Hardwood pallet: 23.0 kg

Cartonized Expanded Plastic (CEP) (EUR Commodity Category IV)
- 1.07 x 1.07 x 1.20 m high per pallet load
- Cartons: 20.3 kg
- PS meat trays: 24.3 kg
- Hardwood pallet: 23.0 kg
Test Fuel Array and Nozzle Arrangement

Class 2 Commodity

Cartoned Expanded Plastic (CEP)

Application density: 6.1 mm/min

8.1 mm/min
## Water Mist Nozzle Operating Conditions

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Operating Pressure (bar)</th>
<th>Downward Spray Thrust Force per Nozzle (newton)</th>
<th>Spray Angle (degrees)</th>
<th>Nozzle Spacing (m x m)</th>
<th>Median Droplet Diameter (µm)</th>
<th>Application Density (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100</td>
<td>71.0</td>
<td>110</td>
<td>2.6 x 2.6</td>
<td>75</td>
<td>6.1</td>
</tr>
<tr>
<td>B</td>
<td>16.5</td>
<td>40.0</td>
<td>110</td>
<td>3 x 3</td>
<td>218</td>
<td>8.1</td>
</tr>
<tr>
<td>C</td>
<td>20</td>
<td>18.3</td>
<td>110</td>
<td>3 x 3</td>
<td>345</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>44.8</td>
<td>41.0</td>
<td></td>
<td></td>
<td>265</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>79.3</td>
<td>72.5</td>
<td></td>
<td></td>
<td>220</td>
<td>8.1</td>
</tr>
</tbody>
</table>
### Sprinkler Operating Conditions

<table>
<thead>
<tr>
<th>Operating Pressure (bar)</th>
<th>Downward Thrust Force per Sprinkler (newton)</th>
<th>Median Droplet Diameter (µm)</th>
<th>Spray Angle (degrees)</th>
<th>Nozzle Spacing (m x m)</th>
<th>Nominal Density (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>6.9</td>
<td>1400</td>
<td>115</td>
<td>3 x 3</td>
<td>6.1</td>
</tr>
<tr>
<td>0.9</td>
<td>12.4</td>
<td>1200</td>
<td>115</td>
<td>3 x 3</td>
<td>8.1</td>
</tr>
</tbody>
</table>
Fire Suppression Factors

- Cooling of Fire Environment
- Air inerting and displacement
- Radiation attenuation

Traditional attributes for suppressing enclosure fires

- Water flux landed on fuel surfaces
  - Application density
  - Fire plume penetration capability
  - Propensity of droplet deposition on fuel surfaces in gas stream
Relative Fire Plume Penetration of Droplets

Compare relative evolution of single droplets discharged downward into an upward hot gas stream corresponding to an expected fire plume condition:

- **Hot gas stream:** 500°C, 10 m/s upward, 3% vapor concentration.
- **Water mist discharge:** 50 m/s downward, 20°C starting droplet temperature.
- **Sprinkler droplet discharge:** 1000 μm, 10 m/s downward, 20°C starting droplet temperature.
Relative Fire Plume Penetration of Droplets
Propensity of Droplet Deposition on Fuel Surface

Stoke number $= \frac{\text{Time for droplet response}}{\text{Time for flow change}}$

$$St = \left( \frac{\rho_w d^2}{18 \mu} \right) \left( \frac{dU}{dz} \right)$$

$\rho_w$ : water density; $d$ : droplet diameter; $\mu$ : gas viscosity

$dU / dz$ : Inverse of time for flow change

When $St < 1$ $\Longrightarrow$ low propensity of droplet deposition on fuel surface.

$St > 1$ $\Longrightarrow$ high propensity of droplet deposition on fuel surface.

Estimated Stoke numbers at $dU/dz = 23 \text{ s}^{-1}$ and $500^\circ C$ gas temperature:

<table>
<thead>
<tr>
<th>Droplet Diameter (µm)</th>
<th>Stoke Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>0.2</td>
</tr>
<tr>
<td>200</td>
<td>1.4</td>
</tr>
<tr>
<td>300</td>
<td>3.2</td>
</tr>
<tr>
<td>1000</td>
<td>35.8</td>
</tr>
</tbody>
</table>
Fire Test Under 20-MW Calorimeter

Class 2 Commodity

- Fuel array ignited at the base of the central vertical flue
- Water supply started when fire convective heat flow rate reached 1000 kW
Fire Test under 20-MW Calorimeter

Cartoned Expanded Plastic (CEP)

- Fuel array ignited at the base of the central vertical flue
- Water supply started when fire convective heat flow rate reached 1000 kW
## Test Conditions Under 20-MW Calorimeter

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Commodity</th>
<th>Sprinkler/Nozzle</th>
<th>Clearance above Fuel Array (m)</th>
<th>Application Density (mm/min)</th>
<th>Spinkler/Nozzle Spacing (m x m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cal-1</td>
<td>Class 2</td>
<td>Sprinkler</td>
<td>1.7</td>
<td>6.1</td>
<td>3 x 3</td>
</tr>
<tr>
<td>Cal-2</td>
<td>CEP</td>
<td>Sprinkler</td>
<td>1.7</td>
<td>8.1</td>
<td>3 x 3</td>
</tr>
<tr>
<td>Cal-3</td>
<td>Class 2</td>
<td>Nozzle A</td>
<td>1.7</td>
<td>6.1</td>
<td>2.6 x 2.6</td>
</tr>
<tr>
<td>Cal-4</td>
<td>Class 2</td>
<td>Nozzle C</td>
<td>1.7</td>
<td>6.1</td>
<td>3 x 3</td>
</tr>
<tr>
<td>Cal-5</td>
<td>Class 2</td>
<td>Nozzle C</td>
<td>1.7</td>
<td>4.1</td>
<td>3 x 3</td>
</tr>
<tr>
<td>Cal-6</td>
<td>CEP</td>
<td>Nozzle C</td>
<td>1.7</td>
<td>8.1</td>
<td>3 x 3</td>
</tr>
<tr>
<td>Cal-7</td>
<td>CEP</td>
<td>Nozzle B</td>
<td>1.7</td>
<td>8.1</td>
<td>3 x 3</td>
</tr>
</tbody>
</table>
Test Cal-1

Sprinkler; Class 2; 6.1 mm/min

Images showing a fire test with time stamps: 1:05, 1:27, 1:28, 1:30, 3:00, 7:15, 11:00, 20:00.
Test Cal-2

Sprinkler; CEP; 8.1 mm/min

1:07  1:11  1:16  1:29

1:46  2:46  5:16  6:50
## Class 2 Fire Test Summary

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Sprinkler/Nozzle</th>
<th>Application Density</th>
<th>Median Droplet Diameter</th>
<th>Combined Spray Thrust Force in the Fire Plume</th>
<th>Plume Uplift Force at Sprinkler/Nozzle Elevation at Water Application Time</th>
<th>Fire Spread to the Ends of Fuel Array?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cal-1</td>
<td>Sprinkler</td>
<td>6.1</td>
<td>1400</td>
<td>3.2</td>
<td>15.1</td>
<td>One End → Marginally Suppressed</td>
</tr>
<tr>
<td>Cal-3</td>
<td>Nozzle A</td>
<td>6.1</td>
<td>75</td>
<td>52.9</td>
<td>14.6</td>
<td>Both Ends → Not Suppressed</td>
</tr>
<tr>
<td>Cal-4</td>
<td>Nozzle C</td>
<td>6.1</td>
<td>265</td>
<td>21.5</td>
<td>16.9</td>
<td>No → Suppressed</td>
</tr>
<tr>
<td>Cal-5</td>
<td>Nozzle C</td>
<td>4.1</td>
<td>345</td>
<td>9.6</td>
<td>13.6</td>
<td>Both Ends → Not Suppressed</td>
</tr>
</tbody>
</table>
Class 2 Fire Test Summary

![Graph showing fire heat release rate versus time from ignition for different nozzles.

- K-80 Sprinkler, 6.1 mm/min
- Nozzle A, 6.1 mm/min
- Nozzle C, 6.1 mm/min
- Nozzle C, 4.1 mm/min

The graph illustrates the fire heat release rate in kW over time in seconds. The data points show a peak heat release rate around 1200 seconds, with different nozzles performing at varying rates. The graph helps in understanding the effectiveness of the sprinkler and nozzles in controlling the fire heat release.]
## CEP Fire Test Summary

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Sprinkler/Nozzle</th>
<th>Application Density</th>
<th>Median Droplet Diameter</th>
<th>Combined Spray Thrust Force in the Fire Plume</th>
<th>Plume Uplift Force at Sprinkler/Nozzle Elevation at Water Application Time (N)</th>
<th>Fire Spread to the Ends of Fuel Array?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cal-2</td>
<td>Sprinkler</td>
<td>8.1</td>
<td>1200</td>
<td>6.7</td>
<td>16.7</td>
<td>No → Suppressed</td>
</tr>
<tr>
<td>Cal-6</td>
<td>Nozzle C</td>
<td>8.1</td>
<td>220</td>
<td>38.0</td>
<td>13.2</td>
<td>One End → Marginally Suppressed</td>
</tr>
<tr>
<td>Cal-7</td>
<td>Nozzle B</td>
<td>8.1</td>
<td>218</td>
<td>21.0</td>
<td>15.1</td>
<td>No → Suppressed</td>
</tr>
</tbody>
</table>

### Graph

- Sprinkler, 8.1 mm/min
- Nozzle C, 8.1 mm/min
- Nozzle B, 8.1 mm/min
Conclusions

• Fire suppression was affected by application density and spray characteristics such as droplet size, discharge velocity and spray thrust force, not by nozzle configuration and operating pressure.

• Fire suppression in open environment could not be achieved if the sprays’ median droplet diameter was not sufficiently large for the fire challenge.

• Fire suppression in open environment with water mist required water densities comparable to those of sprinkler protection.

• The downward spray thrust force was not a critical factor for fire suppression. However, when the spray exceedingly overpowered the fire plume, the highly disturbed flames tended to increase fire spread and thus worsened the suppression result.
Thank You