A Numerical Study on the Effect of Ceiling Slope on Sprinkler Activations and Spray Transport

Prateep Chatterjee and Karl V. Meredith

Fire Hazards & Protection Area
Background

- Limited prior research related to protection of storage under ceilings with slopes > 2/12 (9.5°)
- Sprinkler activation pattern relative to fire source location
- Optimal sprinkler installation orientation
- Numerical modeling would provide understanding of protection challenges
  - ceiling slope
  - sprinkler type and orientation
Collaborative Research

FM Global

PIRG

CUSTOM SPRAY SOLUTIONS
Introduction

- **FPRF project on “Protection of Storage Under Sloped Ceilings – Phase 1”**
  - support NFPA 13 in development of new protection requirements for sprinkler installation
  - phase 1 aim to develop a plan for future research
  - FM Global conducted the numerical modeling
  - CSS reviewed current storage configurations

- **Numerical model (FireFOAM) based investigation of**
  - effect of ceiling slope on sprinkler activations
  - spray transport to evaluate the effect of sprinkler installation orientations
Past Work

- Majority of experimental studies involved use of residential sprinklers, compartment or tunnel fire scenarios and/or weak plumes
  - Vettori (2003), Kung et al. (1991), Floyd et al. (2010), Bill and Hill (1995)
- Numerical modeling studies
  - attractive tool since large-scale testing can be prohibitively expensive
  - meaningful results provided models used within their limitations
  - HRR range of 100 kW – 1.1 MW
  - use of “saw-tooth” meshes
  - Vettori (2003), Floyd et al. (2010), Davis et al. (1994), Floyd et al. (2008), Carlsson (2013)
Objectives

- Evaluate sprinkler activation times and patterns from ceiling jet simulations
  - under unconfined ceilings having a range of slopes
  - with large-scale growing fires as plume sources (max 15 MW convective HRR)
- Evaluate effect of ceiling inclination on water mass flux distributions over a rack-storage commodity
- Understand the effect of sprinkler orientation
  - two sprinkler orientations: deflector parallel-to-ceiling or parallel-to-floor
Technical Approach

- Sprinkler activation simulations

<table>
<thead>
<tr>
<th>Fire plume source</th>
<th>3-tier high rack storage of CUP commodity (growing fire HRR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling clearances (H)</td>
<td>3.05 m (10 ft)</td>
</tr>
<tr>
<td>Ceiling inclinations (θ)</td>
<td></td>
</tr>
<tr>
<td>Ceiling slopes</td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>9.5°</td>
</tr>
<tr>
<td>0</td>
<td>0.167</td>
</tr>
<tr>
<td>2 / 12 in.</td>
<td>4 / 12 in.</td>
</tr>
</tbody>
</table>
Technical Approach

- Sprinkler sprays simulations

<table>
<thead>
<tr>
<th>Fire plume source</th>
<th>3-tier high rack storage of CUP commodity (fixed HRR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling clearances (H)</td>
<td>3.05 m (10 ft)</td>
</tr>
<tr>
<td>Ceiling inclinations (θ)</td>
<td>0°</td>
</tr>
<tr>
<td>Ceiling slopes</td>
<td>0</td>
</tr>
<tr>
<td>Sprinkler type</td>
<td>K200 lpm/bar^{0.5} (K14.0 gpm/psi^{0.5}) at 3.4 bar (50 psi)</td>
</tr>
<tr>
<td>Deflector orientations</td>
<td>Parallel to ceiling</td>
</tr>
</tbody>
</table>
Numerical Model

- FireFOAM 2.2.x solver (available from http://www.fmglobal.com/modeling)
- Combustion, turbulent flow and radiation models used for fire plume and ceiling jet
  - model validated against inclined ceiling jet temperature and velocity experimental data
- Lagrangian model for sprinkler spray transport
- No suppression simulations
- Pyrolysis model* used to
  - generate spatiotemporally varying fuel mass loss rates from the CUP commodity
  - time varying mapped BC applied

*developed by Dr. Ankur Gupta
Numerical Model

- STL objects – ceiling, rack-storage array
- No saw-tooth mesh
- Boundary layer mesh below ceiling
  - (4 in.)^3 resolution
- Rack-storage mesh
  - (1 in.)^3 resolution
Instantaneous Temperature Snapshots (100 s after ignition)
Sprinkler Activation Setup

- Activations 0.33 m (13 in.) perpendicular distance from ceiling
  - using a scalar variable for activation time ($t_{act}$)
  - discrete sprinkler location activations (10 ft x 10 ft) extracted from $t_{act}$ distributions
- Two types of sprinklers: QR/OT and SR/HT
- Assumption
  - no sprays: first-order effect of ceiling inclination on activation times and patterns

<table>
<thead>
<tr>
<th>Name</th>
<th>Response</th>
<th>Activation Temperature K (°F)</th>
<th>RTI (m/s)^{0.5} ((ft/s)^{0.5})</th>
<th>C-Factor (m/s)^{0.5} ((ft/s)^{0.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>QR/OT</td>
<td>Quick</td>
<td>347 (165)</td>
<td>30 (54)</td>
<td>0.22 (0.40)</td>
</tr>
<tr>
<td>SR/HT</td>
<td>Standard</td>
<td>414 (286)</td>
<td>119 (216)</td>
<td>0.95 (1.72)</td>
</tr>
</tbody>
</table>
Sprinkler Activation Results (0°, 10 ft cl, QR/OT spk)
Sprinkler Activation Results (9.5°, 10 ft cl, QR/OT spk)
Sprinkler Activation Results (18.4°, 10 ft cl, QR/OT spk)
Sprinkler Activation Results (26.6°, 10 ft cl, QR/OT spk)
Sprinkler Activation Results (33.7°, 10 ft cl, QR/OT spk)
Sprinkler Activation Results (18.4°, 10 ft cl, SR/HT spk)
Sprinkler Activation Results (18.4°, 10 ft and 20 ft cl)
Sprinkler Activation Observations

- For QR/OT sprinklers, ceiling inclination ≤ 18.4°
  - similar activation times and patterns as horizontal ceiling
  - for four sprinklers immediately adjacent to fire source
- For inclinations ≥ 26.6°
  - significant activation delays on lower side of ceiling
  - number of activations on elevated side greatly exceed activations on lower side
Sprinkler Activation Observations

- **For SR/HT sprinklers**
  - average activation delay for the four sprinklers increases for 18.4° case
  - four more activations on elevated side occur before sprinklers below lower side activate
  - activation pattern skewness accentuated

- **For 18.4° inclination, increasing clearance from 10 ft to 20 ft, for four sprinklers surrounding the ignition location**
  - average activation time delays of ~3 s (QR/OT) and ~5 s (SR/HT) occur
  - such delays may have adverse impact on protection design
Spray Setup (Single Sprinkler)

- Irrespective of ceiling inclination, activation time for a QR/OT sprinkler located above the ignition location was 25 s
  - spray only simulations
  - with fire: convective HRR of 600 kW
Spray Results (Single Sprinkler, 18.4°, deflector parallel-to-floor)

- Comparing water flux distributions above rack-storage array
  - no fire and fire cases
  - 2 ft x 2 ft “buckets”
Spray Results (Single Sprinkler, 18.4°)

- Deflector orientation strongly affects water flux reaching the fire source and pre-wetting region
- In presence of a 600 kW plume, reduction was 25% for 18.4° inclination
Spray Results (Single Sprinkler, 33.7°)

- With increasing ceiling inclination, water flux above commodity reduces when deflector is parallel-to-ceiling
- In presence of a 600 kW plume, reduction was 49% for 33.7° inclination

- With increasing inclination, parallel-to-floor orientation maintained fairly constant water flux to the fire region
Spray Results (Single Sprinkler)

- **No Fire**
  - Mass Flow Rate vs. Ceiling Inclination

- **Fire**
  - Mass Flow Rate vs. Ceiling Inclination

Legend:
- ● - deflector parallel to floor
- ■ - deflector parallel to ceiling
Spray Setup (Four Sprinklers)

- With increasing ceiling inclination, average activation times for four QR/OT sprinklers surrounding the ignition location reduced
  - with fire: average convective HRR of 2.6 MW

<table>
<thead>
<tr>
<th>Ceiling Inclination</th>
<th>0°</th>
<th>18.4°</th>
<th>33.7°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elevated side</td>
<td>63</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>Sprinkler Activation Times [s]</td>
<td>48</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Average Activation Time, $t_{avg}$ [s]</td>
<td>49</td>
<td>46</td>
<td>38</td>
</tr>
<tr>
<td>Convective HRR at $t_{avg}$ (MW)</td>
<td>3.0</td>
<td>2.7</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Spray Results (Four Sprinklers, 2.6 MW fire plume)

- 0°, Deflector parallel-to-floor
- 18.4°, Deflector parallel-to-floor
- 18.4°, Deflector parallel-to-ceiling
Spray Results (Four Sprinklers, 2.6 MW fire plume)

- 0°, Deflector parallel-to-floor
- 33.7°, Deflector parallel-to-floor
- 33.7°, Deflector parallel-to-ceiling
Spray Results (Four Sprinklers)

- For 33.7° inclination
  - low spray density on the fire region due to highly skewed activation pattern
  - water flux to fire region reduced by 54-76% as compared to horizontal ceiling

- For inclinations ≤ 18.4°, deflector parallel-to-ceiling
  - water from the sprinklers on the lower side is projected towards the fire region
Deflector Orientation

- Significant effect on water flux to the fire region for the single sprinkler cases
- Reduced effect for the four sprinklers cases
- Parallel-to-floor orientation preferable for the scenarios investigated
Future Work

- Phase 2 research involving FireFOAM simulations
  - effect of ceiling obstructions on sprinkler activations and patterns
  - spray simulations with ESFR and non-ESFR sprinklers
  - collaboration with FPRF/PIRG contractor
  - develop large-scale testing recommendations
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