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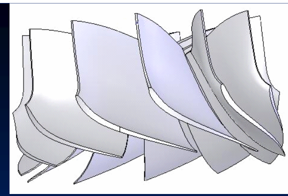

SIMULATION OF THE FIRE EXTINGUISHMENT PROCESS BY FINE WATER SPRAY

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JASS 2008

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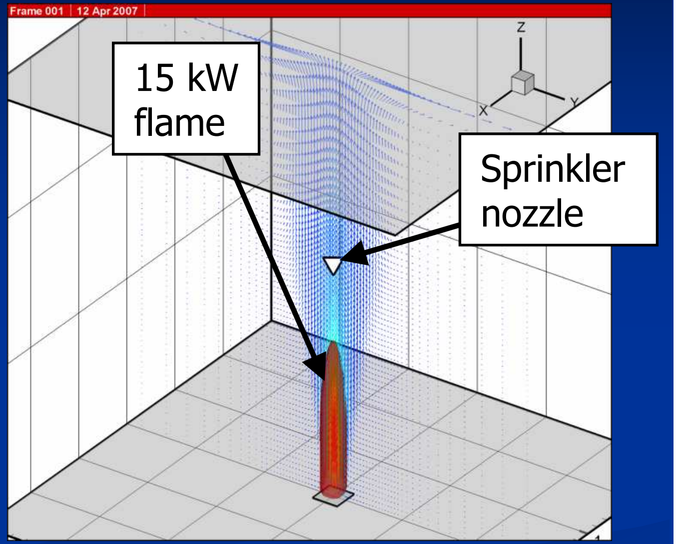
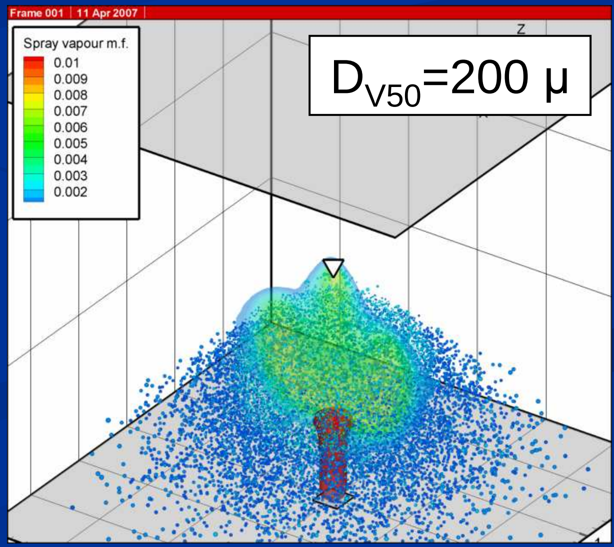
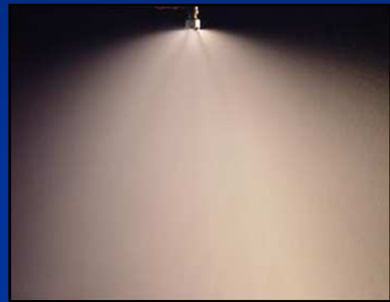




Fire suppression by high-pressure fine water spray

Advantages of technology:

- A possible halon substitute (prohibited)
- Water is environmentally friendly and toxically safe extinguishing agent
- Cheap, available
- Less damage to surroundings
- Effective if optimized – leads to faster mitigation with smaller flow rate



Optimum use

- Two opposite requirements:
  - efficient delivery is needed for wetting of flame surface
  - rapid droplet evaporation is required for cooling of the flame
- Initial droplet size is a key parameter that switches extinguishment regimes
- Optimal solution can't be universal – it depends on a possible fire scenario, geometry etc.
- Need in careful modeling and costly simulations

Aims of work and results

- To develop the appropriate mathematical model of a evaporating spray
- To incorporate the model into the existing in-house software - Fire3D
- To investigate numerically the interaction of water spray and buoyant turbulent diffusion flame – it may be different for fine and coarse sprays
- Mechanisms of spray-flame interaction are identified
- Effect of spray characteristics on fire suppression efficiency is determined and demonstrated

Model description

Two interacting phases:

- gas phase (multicomponent reacting mixture)
- liquid phase (dispersed water)

Full interaction assumed:

- droplet-gas heat transfer
- droplet evaporation (mass transfer)
- momentum exchange
- droplet dispersion due to turbulence

Gas phase modeling

- Navier-Stokes system based on Favre-averaged component, momentum and enthalpy transport equations
- Modified *k*-ε, eddy break-up and thermal radiation models are used as closing relationships
- Low Mach number flow is considered
- Finite volume technique for discretization

Langman et al, 2007
A – momentary image
B – photo with exposure
(analogue to averaging)

Liquid phase modeling

- Lagrangian approach to model evaporating spray - multiple discrete droplets are tracked along their trajectories in gas-flow with given characteristics
- Momentum, mass, energy conservation equations are considered for groups of similar droplets (particles)

Droplet movement due to gravity and drag forces

$$\frac{du_{p,i}}{dt} = -\left(\frac{3\bar{\rho} C_D}{4 d_p \rho_p}\right) | u_{p,i} - \tilde{u}_i | (u_{p,i} - \tilde{u}_i) + g_i \left(1 - \frac{\bar{\rho}}{\rho_p}\right)$$

$$\frac{dx_{p,i}}{dt} = u_{p,i}$$

$$C_D = \begin{cases} 24/\mathrm{Re}_p (1 + 0.15 \mathrm{Re}_p^{2/3}) & , \mathrm{Re}_p < 1000 \\ 0.44 & , \mathrm{Re}_p > 1000 \end{cases}$$

$$\mathrm{Re}_p = \frac{d_p | \vec{\tilde{u}} - \vec{u}_p |}{\nu}$$

Droplet dispersion

$u = \tilde{u} + u'$

$u' = \sqrt{2k/3}$

$l_t = C_\mu^{3/4} k^{3/2} / \varepsilon$

Turbulence may have a considerable effect!

Particle transit time through single examined eddy

$$\tau_p = \begin{cases} -\tau_D \ln\left(1 - \dfrac{l_t}{\tau_D \left|\vec{u}_p - \vec{u}_p^*\right|}\right) & , \text{if } l_t < \tau_D \left|\vec{u}_p - \vec{u}_p^*\right| \\ \infty & , \text{if } l_t > \tau_D \left|\vec{u}_p - \vec{u}_p^*\right| \end{cases}$$

Interaction time

$$\tau_{p,t} = \min\left(\tau_p, l_t / \sqrt{2k/3}\right)$$

Droplet heating

Heat transfer from and to the carrying gas

$$m_p C_p \frac{dT_p}{dt} = \begin{cases} q_p + \Delta h_{vap}(T_p) \dfrac{dm_p}{dt} & , T_p < T_{boil} \\ 0 & , T_p = T_{boil} \end{cases}$$

$$q_p = q_{p,conv} + q_{p,rad}$$

$$q_{p,conv} = -\pi d_p \mathrm{Nu} \frac{\mu_g}{\mathrm{Pr}} C_{P,g} \left(T_p - \tilde{T}\right)$$

$$\mathrm{Nu} = 2 + 0.6\, \mathrm{Re}_p^{1/2}\, \mathrm{Pr}^{1/3}$$

Latent heat of evaporation

$$\Delta h_{vap}(T_p) = \Delta h_{vap,boil} + \int_{T_p}^{T_{boil}} C_p(T)\, dT$$

Droplet mass loose due to evaporation

$$\frac{dm_p}{dt} = \begin{cases} -\pi d_p \mu_g \dfrac{\mathrm{Sh}}{\mathrm{Pr}} \ln\left(1+B_m\right) & ,T_p < T_{boil} \\ -\dfrac{q_p}{\Delta h_{vap}(T_{boil})} & ,T_p = T_{boil} \end{cases}$$

$$\mathrm{Sh} = 2 + 0.6\,\mathrm{Re}_p^{1/2}\,\mathrm{Sc}^{1/3}$$

$$B_m = \frac{Y_{vap,sat}\left(T_p\right) - Y_{vap,\infty}}{1 - Y_{vap,sat}\left(T_p\right)}$$

Inter-phase exchange

$$\dot{r}_M = -\sum \frac{n_p}{\Delta V} \frac{dm_p}{dt}$$

$$\vec{r}_V = -\sum \frac{n_p}{\Delta V} \left(m_p \frac{\vec{u}_p - \tilde{\vec{u}}}{\tau_D} - \vec{u}_p \frac{dm_p}{dt} \right)$$

$$\dot{r}_H = -\sum \frac{n_p}{\Delta V} \left(m_p C_p \frac{T_p - \tilde{T}}{\tau_T} - h_{vap}\left(T_p\right) \frac{dm_p}{dt} \right)$$

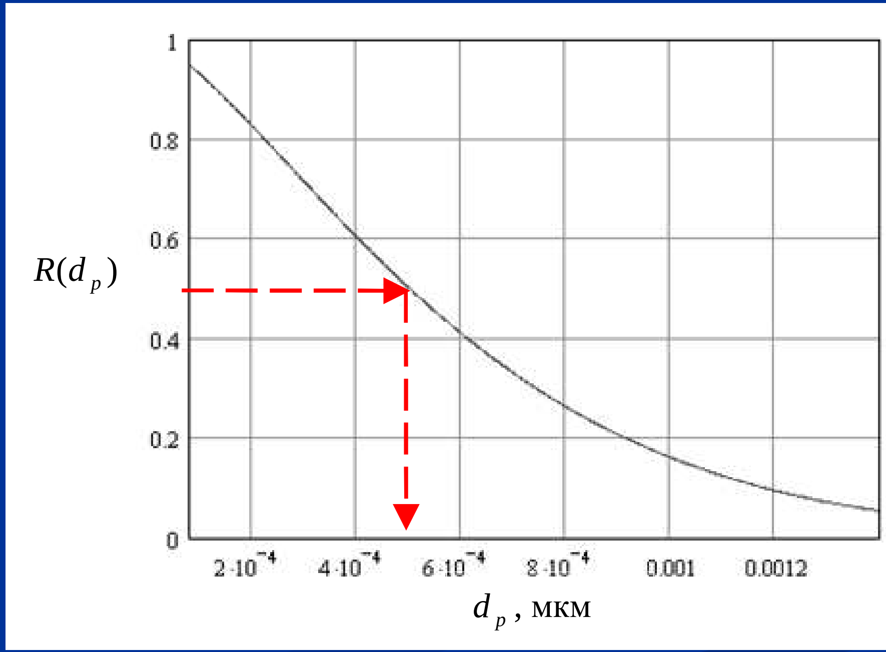
$h_{vap}\left(T_p\right)$ - is the vapor enthalpy at droplet temperature

Modeling of injection

- Sprinkler is modeled here as a point source
- Rosin-Rammler distribution - polidispersity

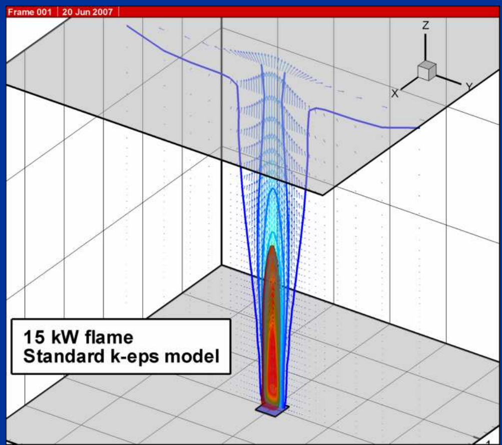
$$R(d_p) = \exp\left(-\ln 2\left(\frac{d_p}{d_{V50}}\right)^{\gamma}\right)$$

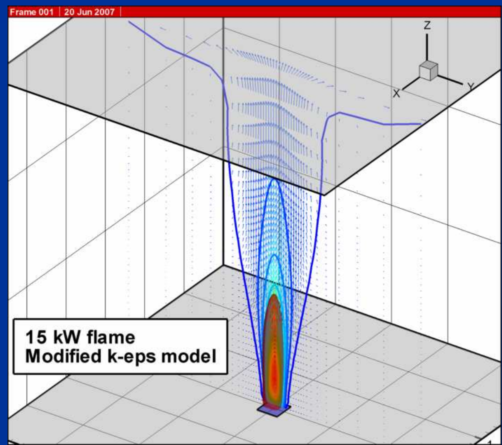
- Velocity vectors uniformly distributed inside the cone



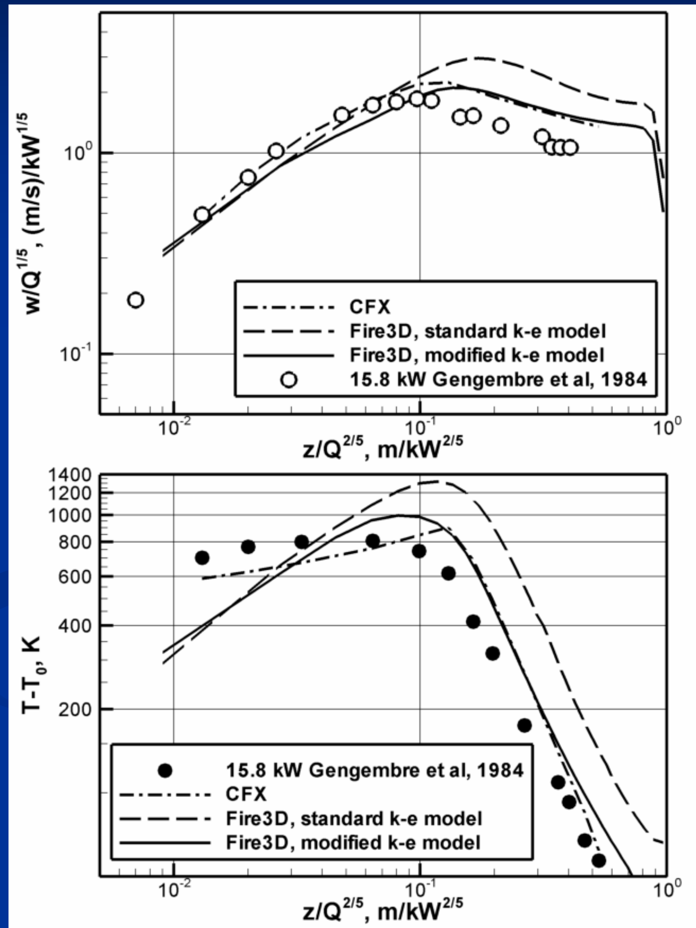
Validation. Flame without water spray

- Comparison with experiments
- Calorific power 15kW





Isosurfaces of temperature T=200°C

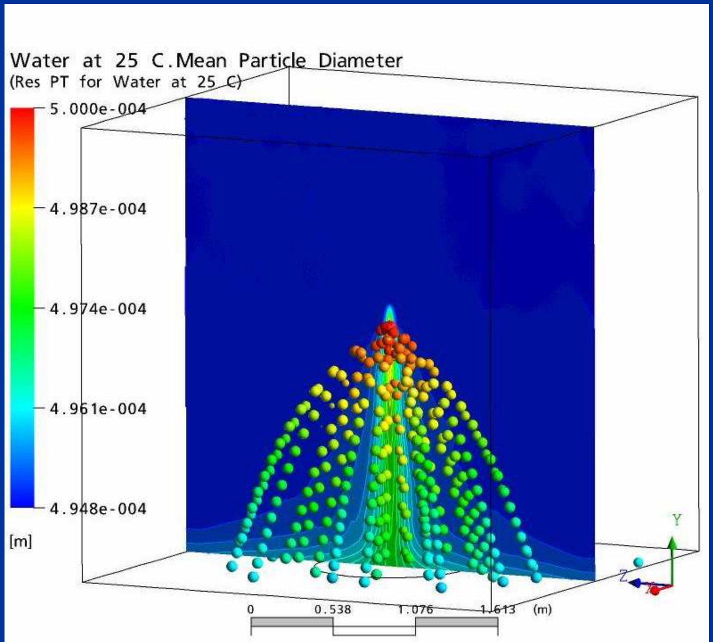


- Transient simulation of the gas flame are then used as initial conditions for case with spray

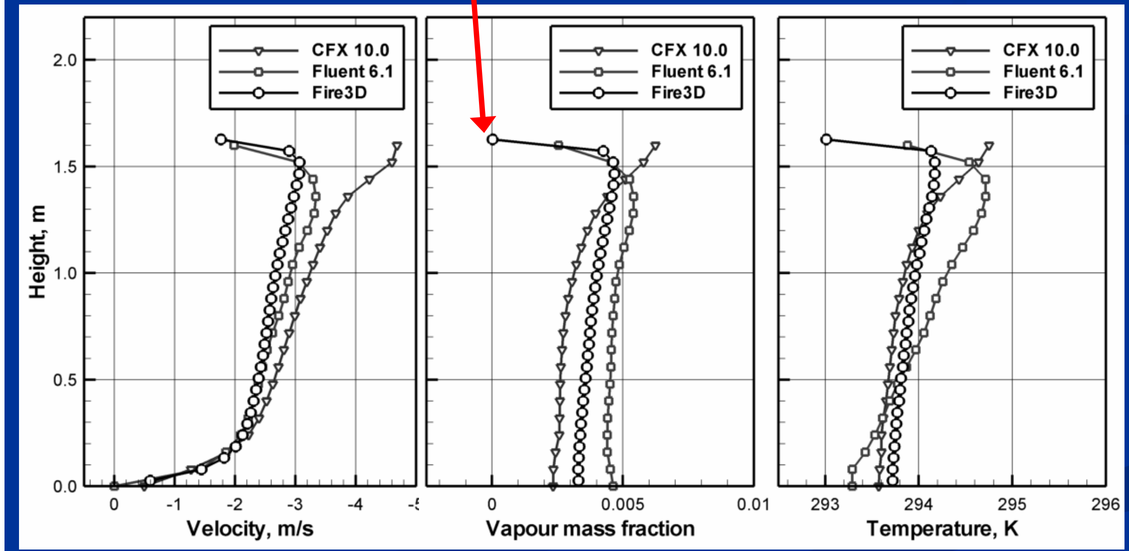
Validation. Water spray without flame

- Detailed measurements are lacking
- Comparison between 3 CFD codes – 0.500 mm, 7.5 l/min
- Qualitatively similar data

Injection point



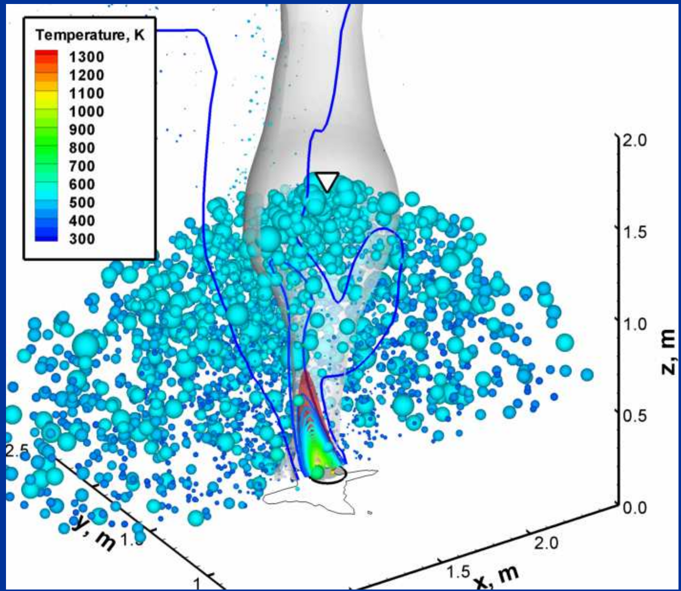
Trajectories of droplets
and vapor mass fraction

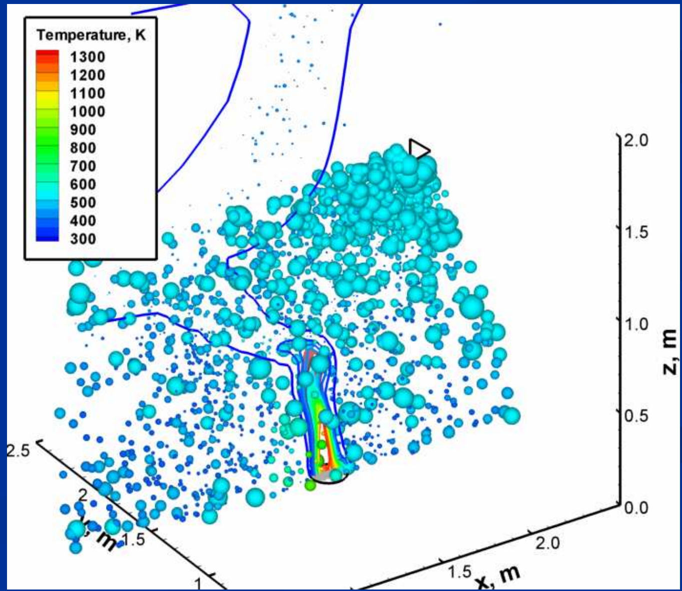


Spray simulations with three CFD codes

Water spray fire suppression

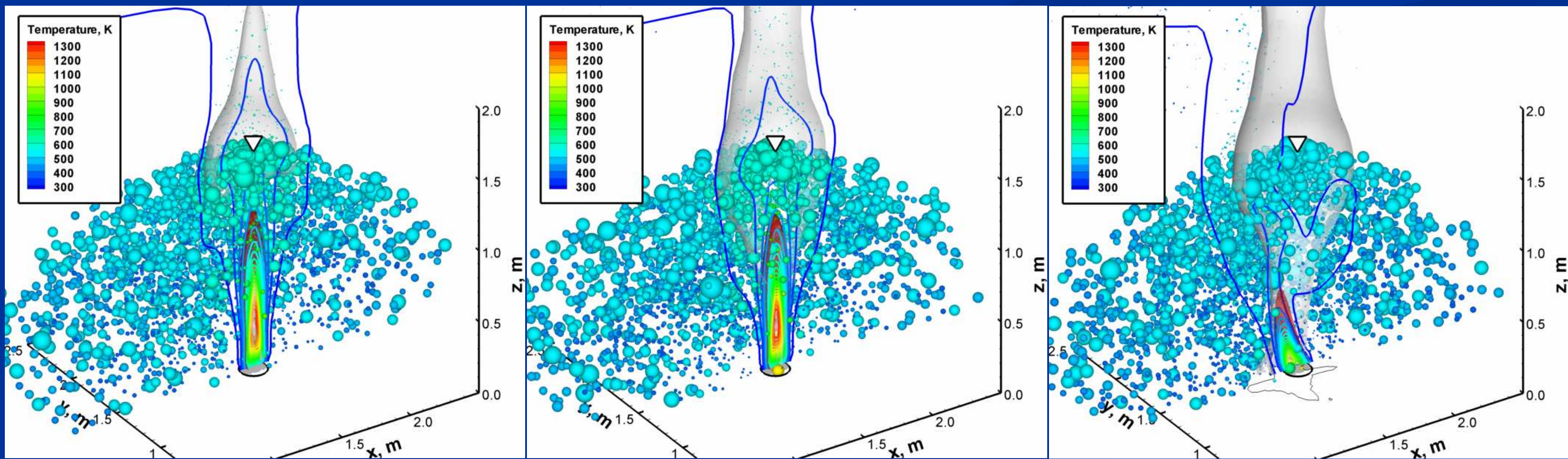
- Effect of spray dispersion – decrease of the initial droplet diameter changes the spray dynamics and extinguishment regime
- Effect of nozzle location and spray orientation





Coarse spray

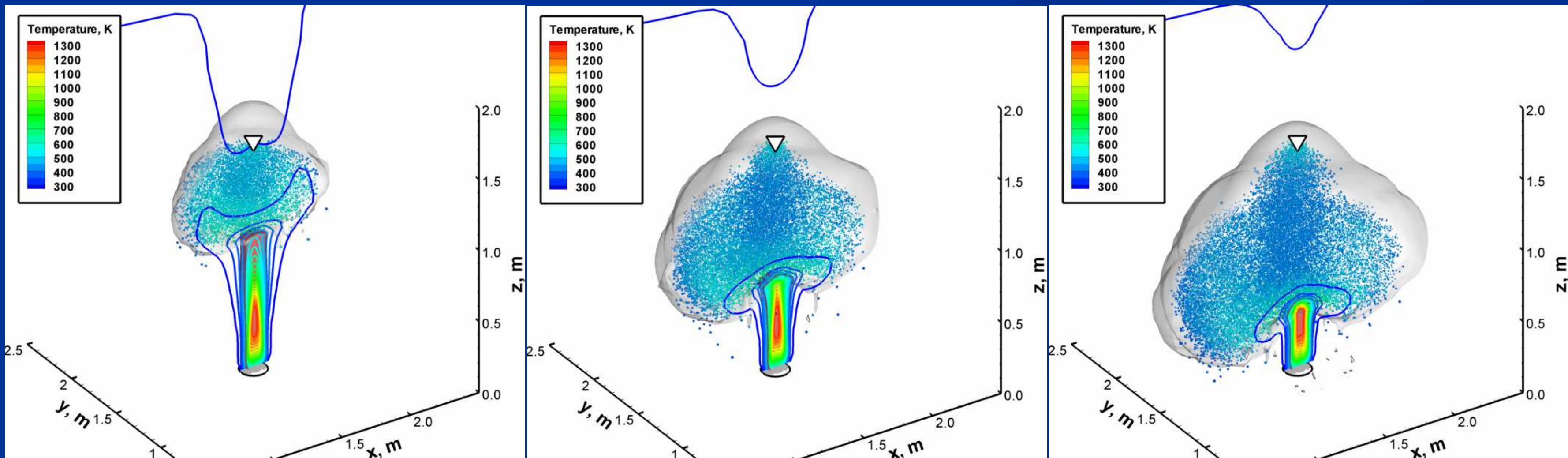
- 0.630 mm initial diameter
- Gas directly affected by spray momentum
- Majority of water is transported to flame surface
- Destabilizes flame but does not extinguish



2 s 4.7 s 17 s

Fine spray

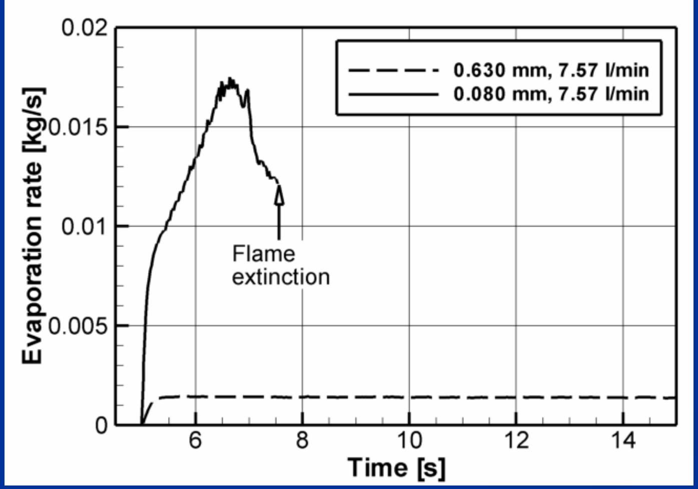
- 0.080 mm initial diameter
- Droplet evaporation rate and vapor concentration increase
- Form the vapor cloud – cooling of flame
- Finer spray suppresses flame more rapidly

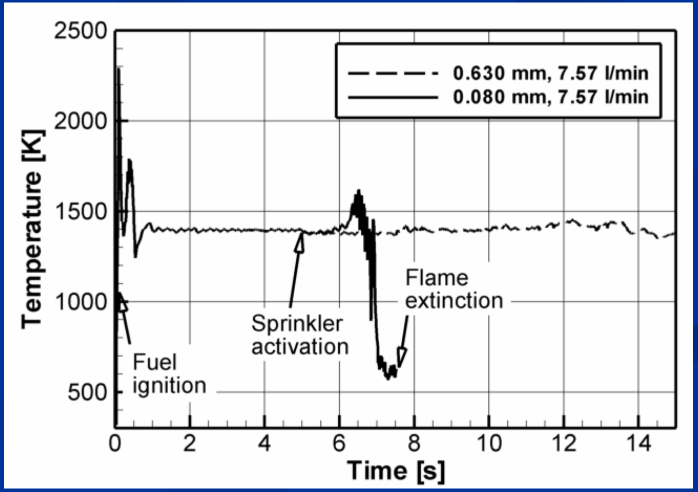


0.5 s | 1 s | 1.3 s

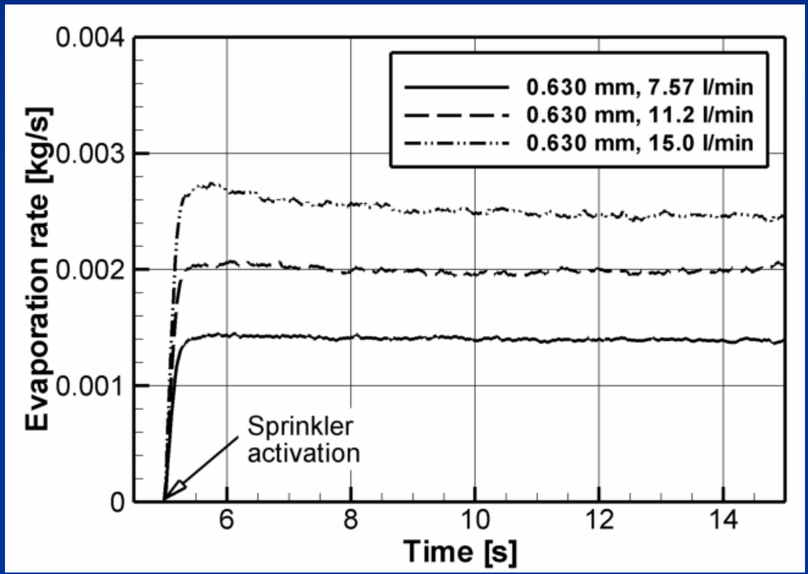
Effect of initial spray dispersion

- The fine spray produces the amount of vapor which is by more than an order of magnitude greater than that produced by the coarse spray
- Fine spray extinguishes the flame within few seconds after the nozzle activation

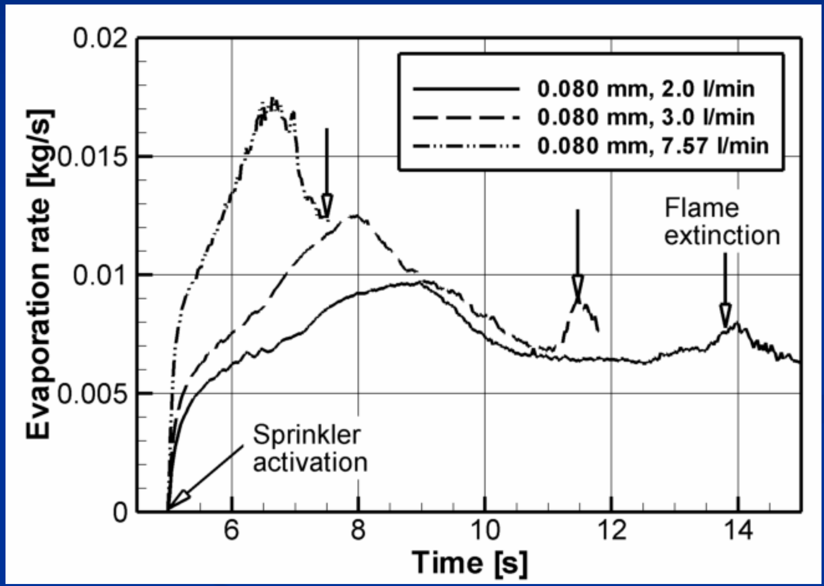




Proportionality of the evaporation rate to the nozzle flow rate



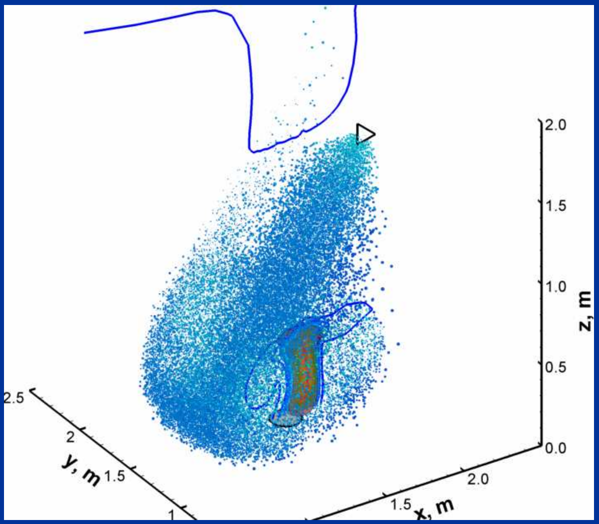
Coarse spray - initial median droplet diameter 0.630 mm

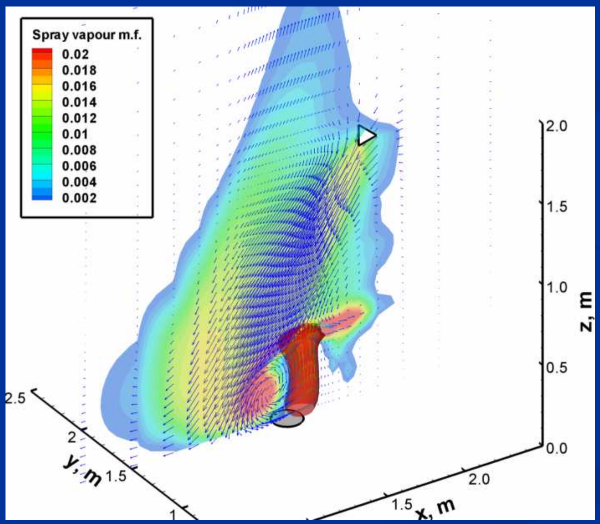


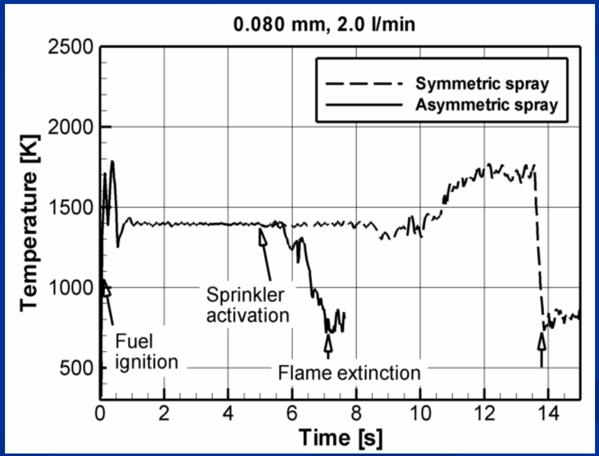
Fine spray - initial median droplet diameter 0. 080 mm

Effect of nozzle location and spray orientation

- Greater flame-spray cross section – more stronger influence
- Flame is deflected by secondary vertical flow







Conclusion

- Model of evaporating spray is developed and incorporated into CFD software
- Two distinct mechanisms of flame mitigation are demonstrated
- Fine water spray causes faster flame extinguishment with smaller water flow rate