Laboratory of Applied Mathematics & Mechanics

Modeling and simulations of flame mitigation by fine water spray

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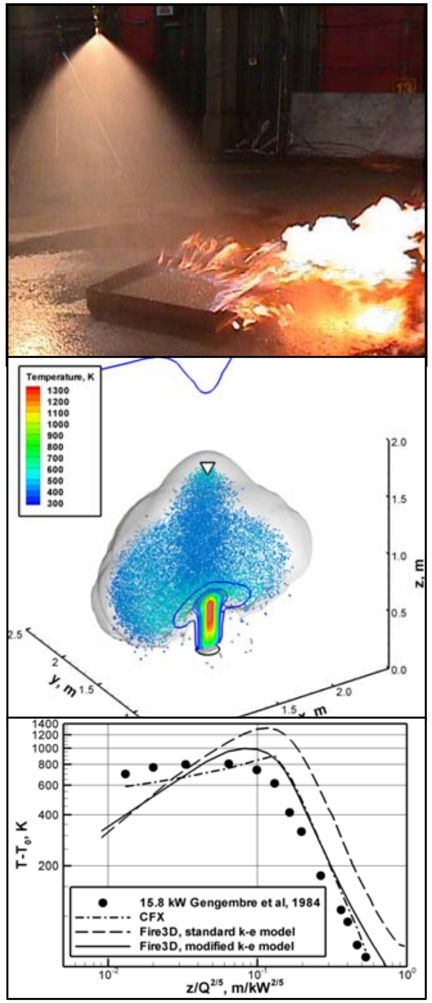
JASS 2009

Agenda

- Introduction and objectives
- Model description
  - Gas phase modeling
  - Liquid phase modeling
  - Modeling of injection
- Results of flame suppression by fine water spray
- Effect of initial spray dispersion

Introduction

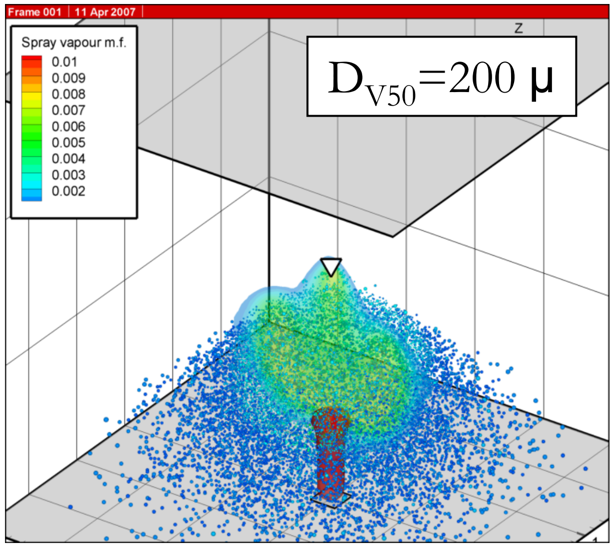
- Advantages:
  - Water is environmentally friendly and toxically safe extinguishing agent
  - Cheap, clean, available
  - Effective if optimized (may prevent unacceptable damage to protected property)
  - A possible halon (CF_3Br, CF_2BrCl, …) substitute (such FEA are prohibited)



FEA – Fire Extinguishing Agent

Objectives

- Understanding fundamental mechanisms of the interaction of fine water spray and turbulent diffusion flame
- Development of the appropriate mathematical model of a evaporating spray
- Incorporation of the model into the existing in-house software - Fire3D
- Computational study of interaction of water spray and buoyant turbulent diffusion flame



Fine water spray fire suppression

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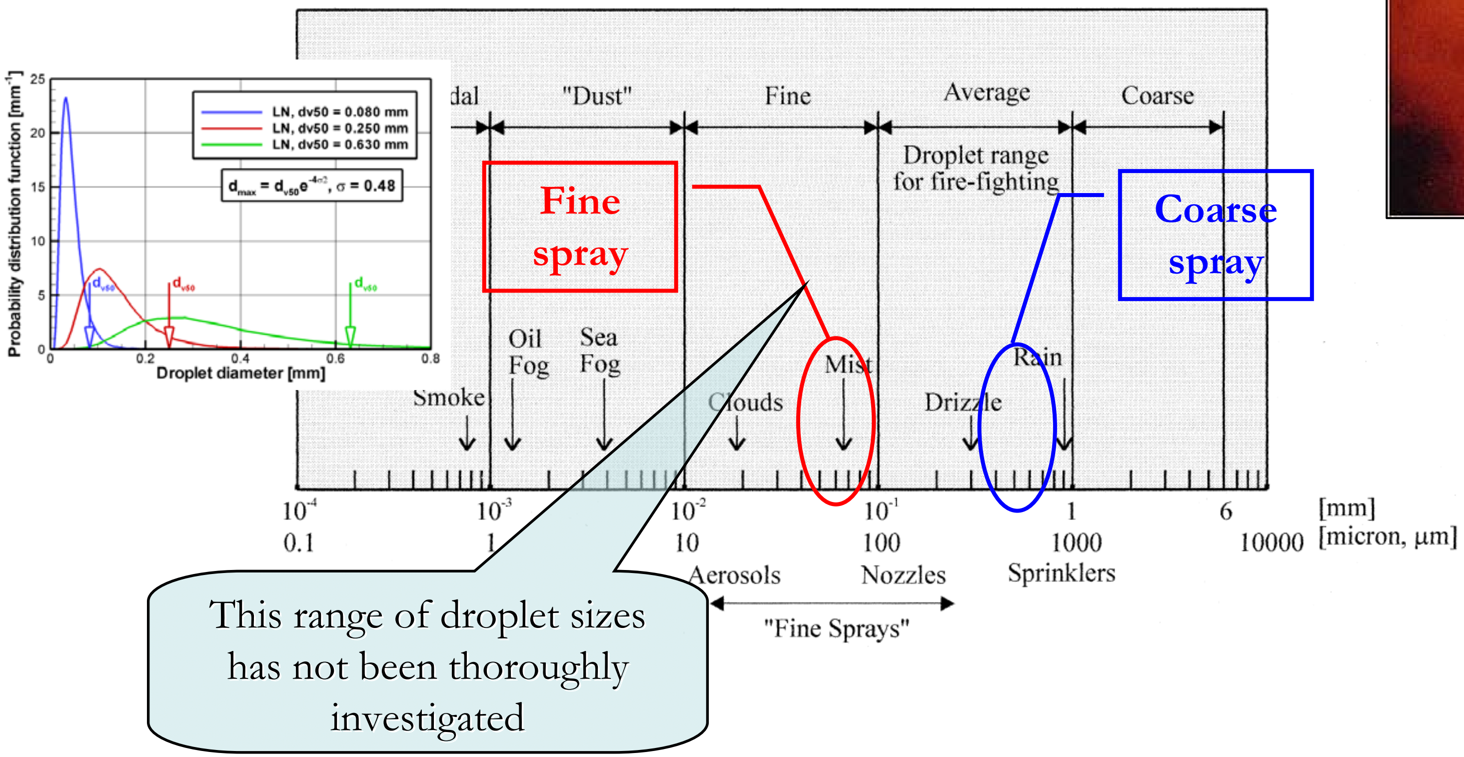
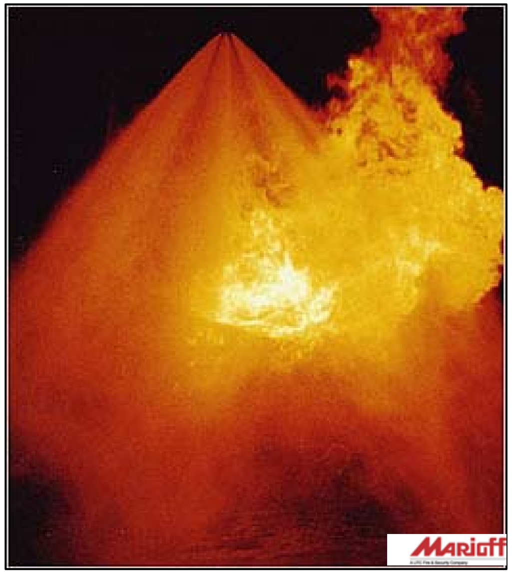
- Initial droplet size is a key parameter that switches extinguishment regimes
- Fine water spray is special: behaves similar to the gas (total flooding) extinguishing agents

G. Grant et al. / Progress in Energy and Combustion Science 26 (2000) 79–130





High pressure fine water spray **can** be more efficient

Why and when?

Optimum use of fine water spray

- Two opposite requirements:
  - efficient delivery is needed for wetting of flame surface
  - rapid droplet evaporation is required for cooling of the flame
- Water spray physics: two droplet delivery regimes
  - Large droplets, coarse spray – gravity mode (weak plume-spray interaction, droplet penetration is determined by droplet diameter)
  - Small droplets, fine spray – momentum mode (strong plume-spray interaction, penetration may not occur, it is determined by the ratio of spray and plume momentums)
- Optimal solution can't be universal – it depends on a possible fire scenario, geometry etc.
- Need in careful CFD modeling and costly simulations

Model description

Euler-Lagrange approach :

- gas phase – multicomponent reacting mixture
- dispersed phase – large number of droplets

Full interaction assumed (two-way coupling):

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

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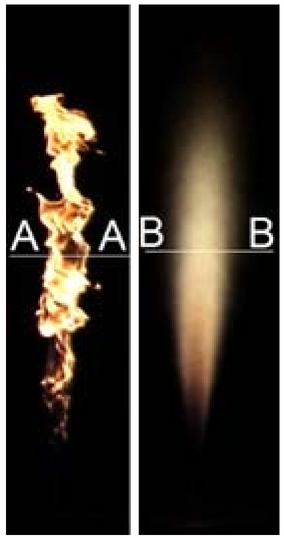
Gas phase modeling

- 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)



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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

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

$$C_D = \begin{cases} 24/\mathrm{Re}_p(1+0.15\mathrm{Re}_p^{2/3}) & ,\mathrm{Re}_p < 1000 \\ 0.44 & ,\mathrm{Re}_p > 1000 \end{cases} \qquad \mathrm{Re}_p = \frac{d_p|\vec{\tilde{u}} - \vec{u}_p|}{\nu}$$

Droplet dispersion $u = \tilde{u} + u'$ $u' = \sqrt{2k/3}$ $l_t = C_\mu^{3/4} k^{3/2} / \varepsilon$

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

Turbulence may have a considerable effect!

Heat transfer from and to the carrying gas

Droplet heating

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

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

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

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

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Droplet mass loose due to evaporation

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

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

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

Inter-phase exchange

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

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

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

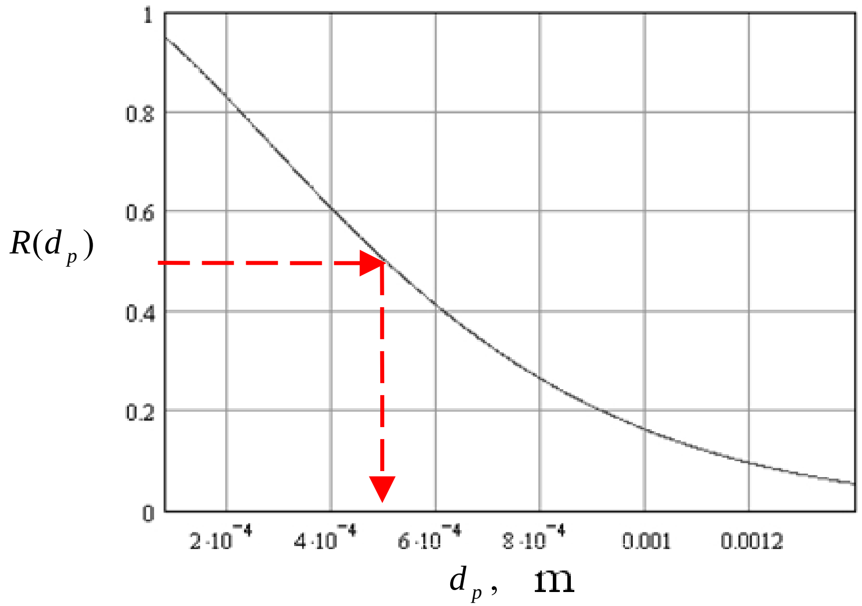
$h_{vap}(T_p)$ - is the vapor enthalpy at droplet temperature

Modeling of injection

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

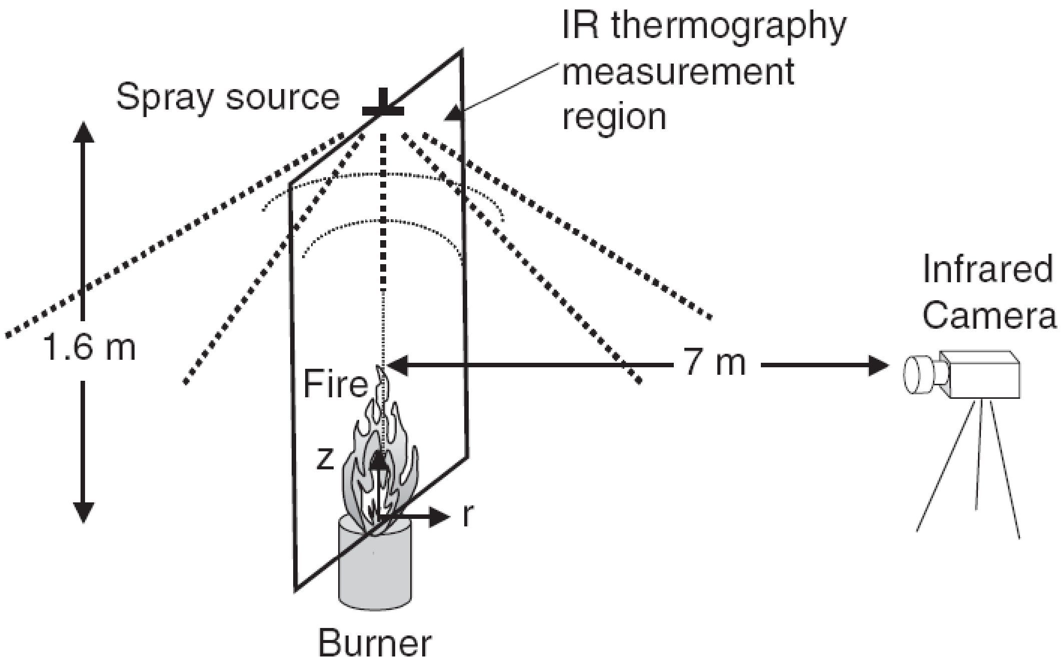
$$R(d_p) = \exp\left(-\ln 2\left(\frac{d_p}{d_{V50}}\right)^{\gamma}\right)$$

- Velocity vectors uniformly distributed inside the cone



Fine water spray flame suppression

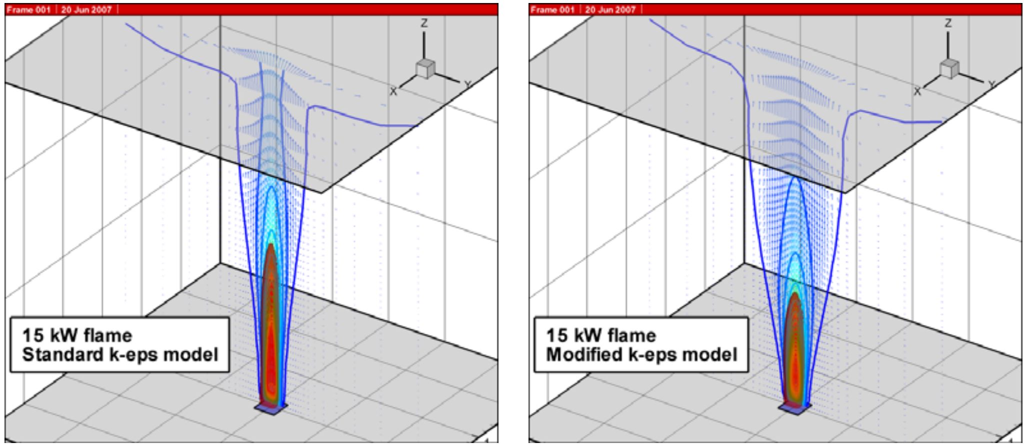
- Schwille & Lueptow experiment
- 15 kW, 18 cm diameter burner, methane
- d_{v50} = 0.630 mm
- 3–11.7 l/min
- 120º cone angle, 1.6 m height
- Spray cone is much wider than the flame base



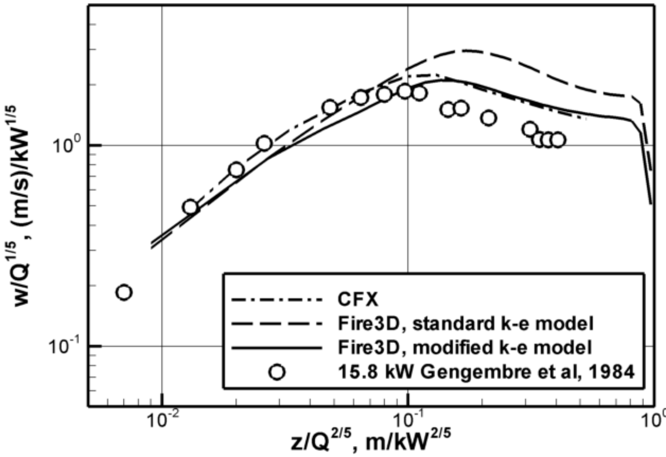
J.A. Schwille, R.M. Lueptow / Fire Safety Journal 41 (2006) 390–398

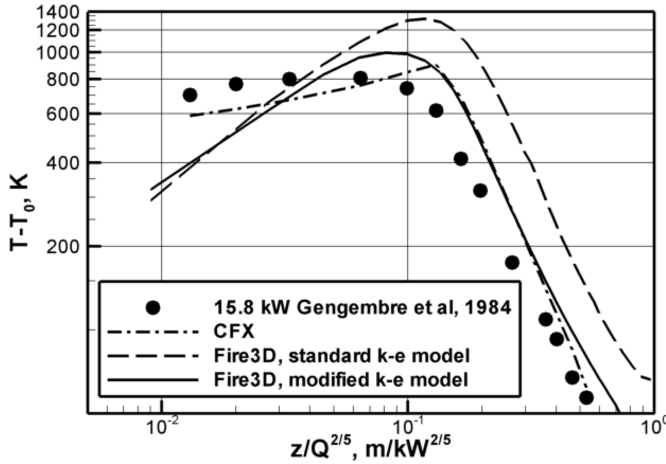
Flame without water spray

- 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

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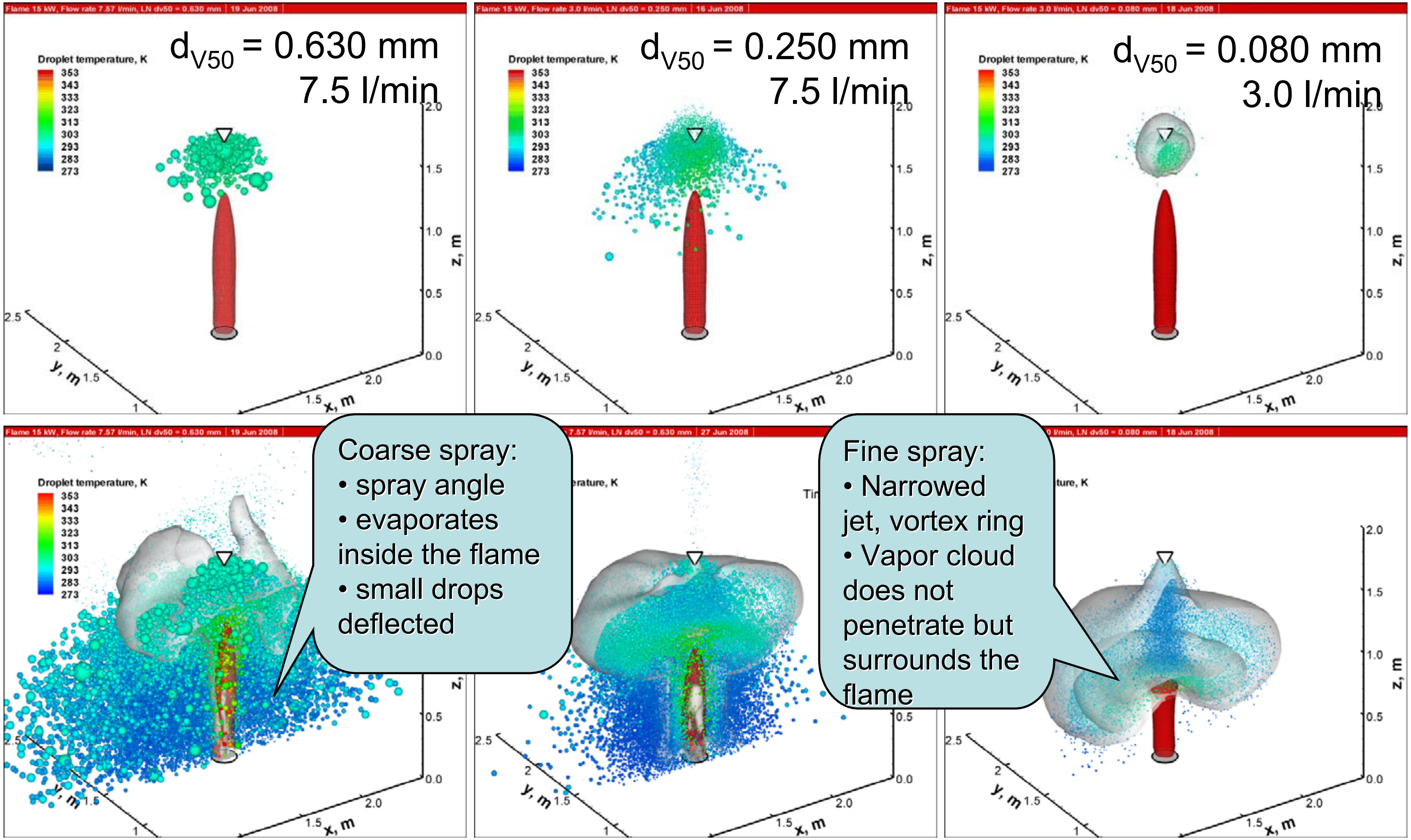
Fine water spray flame suppression



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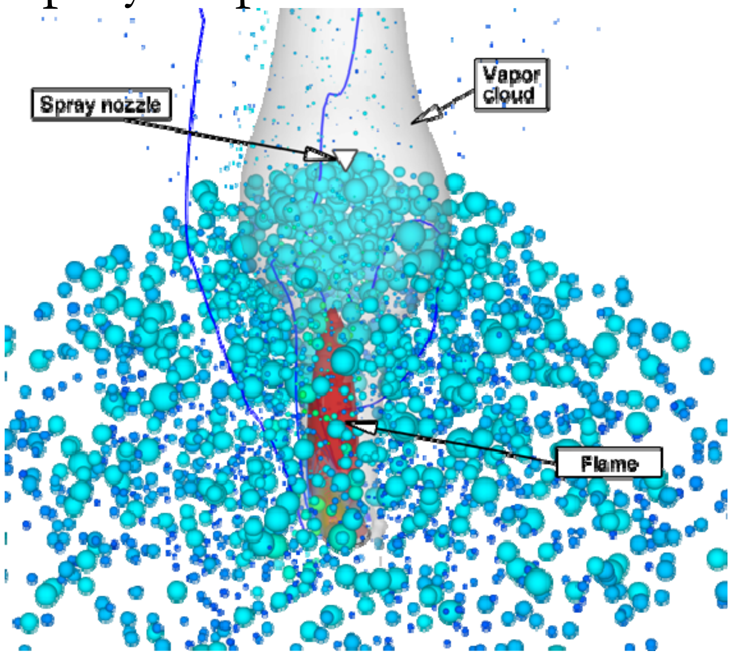
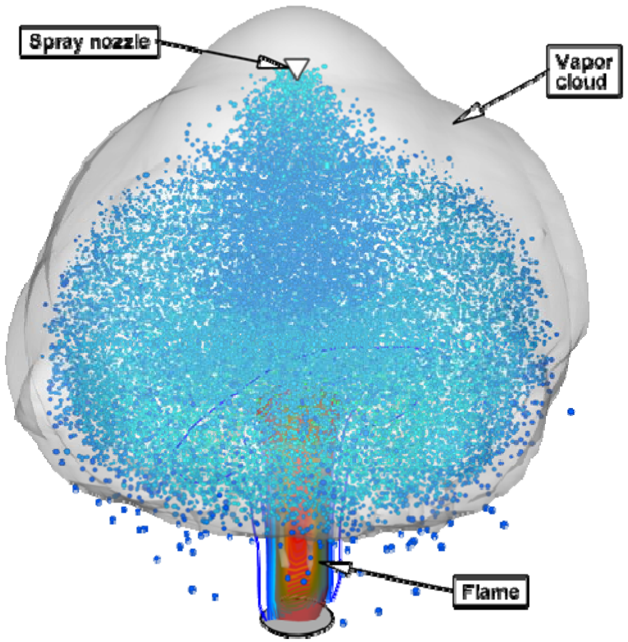
Effect of initial spray dispersion

- Spray dynamics and flame-spray interaction is very sensitive to initial spray dispersion



Coarse spray, d_{V50} = 0.630 mm
15 kW, 7.57 l/min

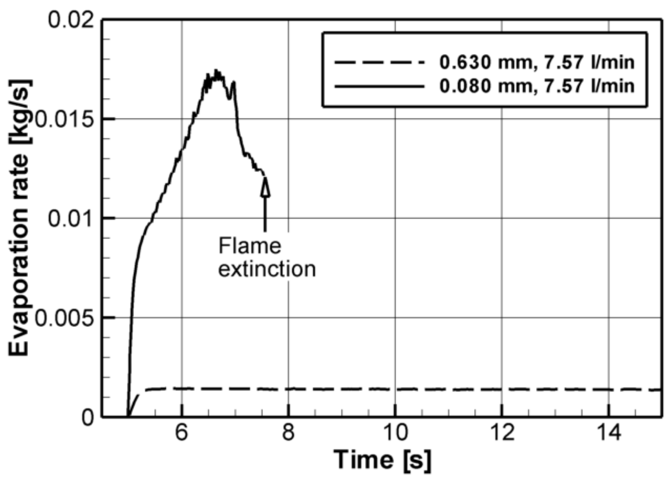


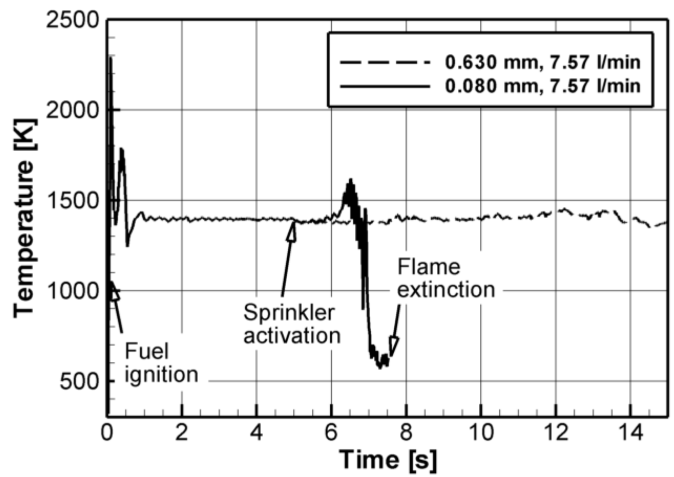
Fine spray, d_{V50} = 0.080 mm
15 kW, 7.57 l/min

- Fine spray suppresses flame faster with smaller water supply rate because of: (i) faster evaporation; (ii) higher and more focused momentum

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





Conclusion

- Model of evaporating spray is developed and incorporated into CFD software
- Mechanisms of spray-flame interaction are identified and demonstrated
- Fine water spray causes faster flame extinguishment with smaller water flow rate

Thank you!

Discussion