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

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Fifth Aircraft Fire and Cabin Safety Research Conference
October 29- November 1, 2007

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

- Study of the suppression Mechanism of Small Flames by Water Mist, Ndubizu et al. (1995, 1998, 2000)
- Minimum Performance Standard for Aircraft cargo compartment Halon Replacement Fire suppression Systems, Reinhardt et al. (2003)
- 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)
- Aircraft Cabin Fire Suppression by Means of an Interior Water Spray System, Whitfield et al. (1988)
- 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 causes a drop in oxygen concentration.

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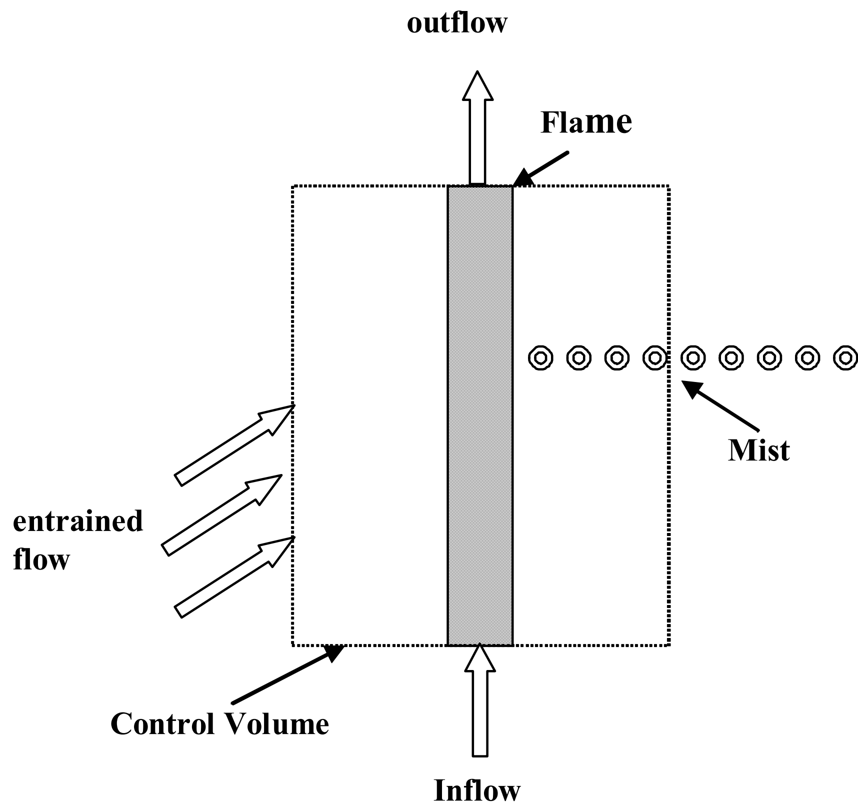
Water Mist Interaction in Flame Zone

$$\dot{n}_d V_{d,w}\rho_w (Y_{vap}L_v + c_{p,w}\Delta T_w) + \dot{m}_f\ h_c(\eta_c - \eta_{c,w}) =$$

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

Issues:

- Mist droplet penetration into the flame zone, fn (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

$$\iint_{\inf low} \rho u c_p \, dT dA + \dot{Q}_c = \iint_{outflow} \rho u c_p \, dT dA + \iint_{entrained} \rho v c_p \, dT dA_x$$

$$\iint_{\inf low} \rho u c_p \, dT dA + (\dot{Q}_{c,m} - \dot{Q}_{latent}) = \iint_{outflow} \rho u c_p \, dT dA + \iint_{entrained} \rho v c_p \, dT dA_x + (m c_p \dot{\Delta} T)_w$$

$$(\dot{Q}_c - \dot{Q}_{c,m}) + \dot{Q}_{latent} = (\dot{m} c_p \Delta T)_{out} - (\dot{m} c_p \Delta T)_{out,m} + (\dot{m} c_p \Delta T)_{ent} - (\dot{m} c_p \Delta T)_{ent,m} - (\dot{m} c_p \Delta T)_w$$

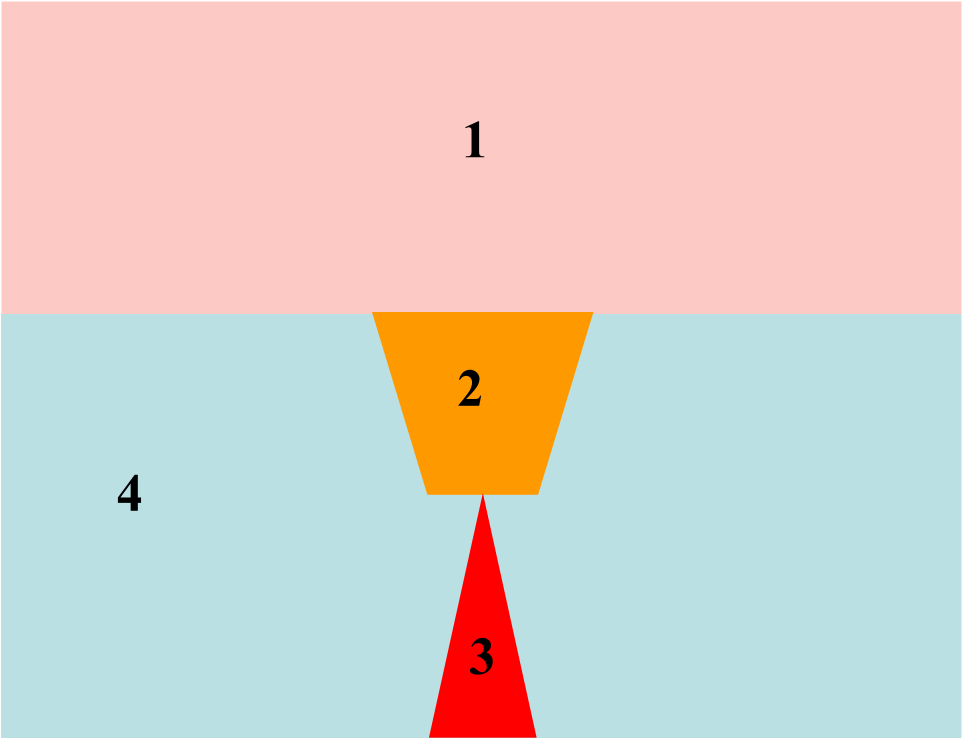
$$(\dot{Q}_c - \dot{Q}_{c,m}) = \dot{Q}_{O2,Displ.} = (\dot{m}_f \, \Delta h_c \eta_c - (\dot{m}_f \, \Delta h_c \eta_{c,m}) = \dot{m}_f \, \Delta h_c (\eta_c - \eta_{c,m})$$

A multi-zone model has been developed using conservation of mass and energy equations.

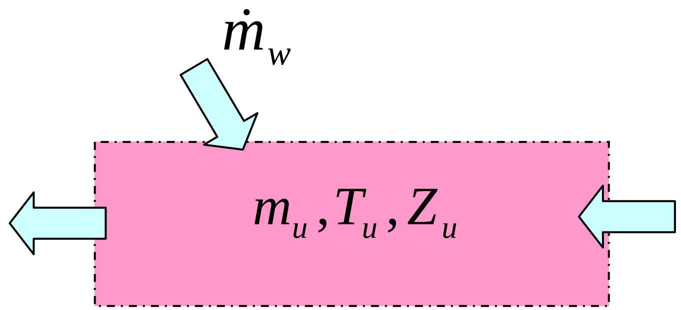
Four Distinct Zones

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:



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

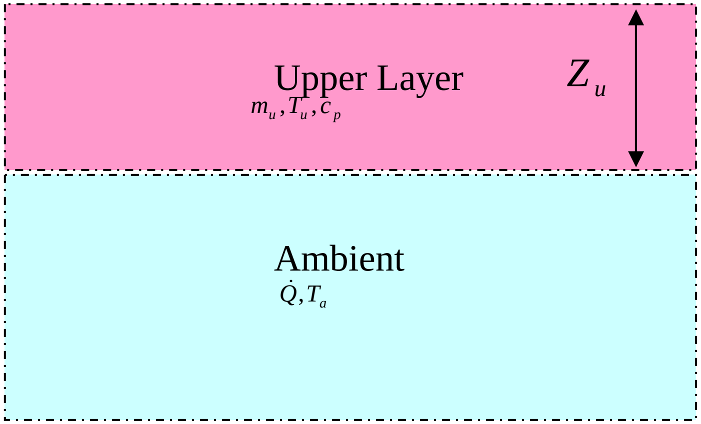
$$\dot{Q}_{water} = \dot{m}_w c_{p,w}(T_b - T_0) + \dot{m}_w Y_e\left(L + c_{vap}\left(T_u - T_b\right)\right)$$

Y_e, Evaporation Rate

L, Latent heat of evaporation

$$m_u = \rho A Z_u \qquad m_{evaporated} = \dot{m}_w dt Y_e$$

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

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

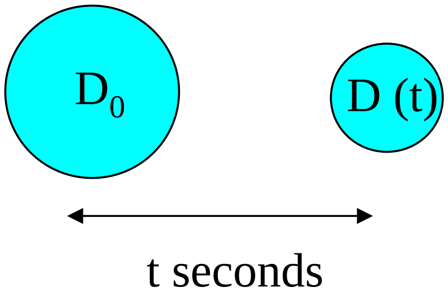
$$T_{u_{i+1}} = \left(\frac{\dot{Q}_i - \dot{m}_{e_i} c_p (T_u - T_a)}{m_{u_i} c_p} \right) \Delta t + T_{u_i}$$

$$m_{u_i} = \rho_a A Z_{u_i}$$

Water Droplet Evaporation Rate

According to D^2 Law for droplet evaporation:

$$D^2(t) = D_0^{\ 2} - Kt$$



D (t): diameter of droplet as a function of time

D_0 : initial diameter of the droplet

K: Evaporation constant

$$\dot{m}_w = \dot{m}_{in} \frac{Kt}{\rho D_0^2}$$

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

Evaporation Rate Formulation

$$K = \frac{8k_g}{\rho_l c_{pg}} \ln\left(B_q + 1\right)$$

$$B_q = \frac{c_{pg}\left(T_\infty - T_{boil}\right)}{h_{fg}}$$

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

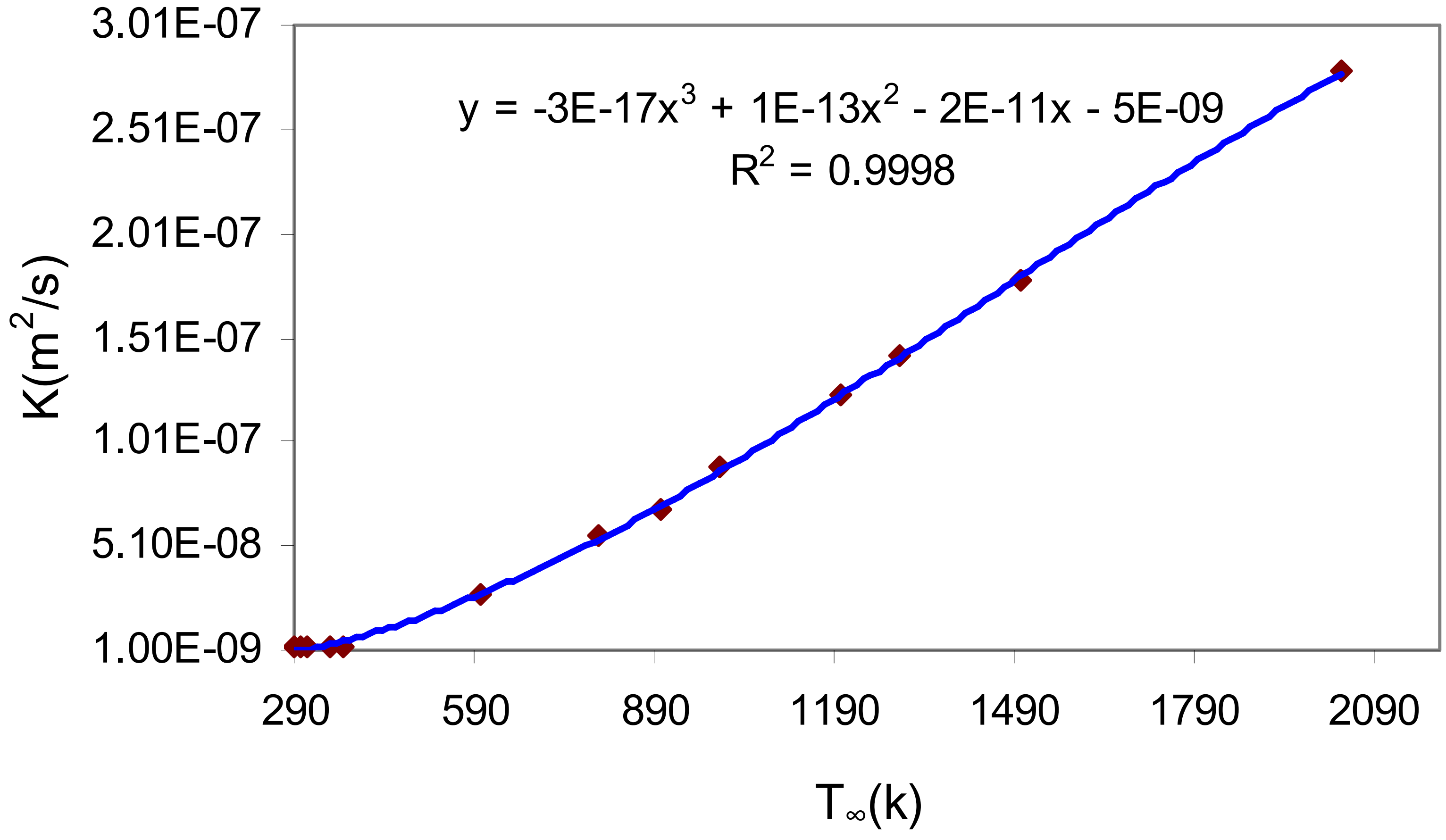
$$k_g = 0.4k_F\left(\bar{T}\right) + 0.6k_\infty\left(\bar{T}\right)$$

$$\bar{T} = \frac{T_{boil} + T_\infty}{2}$$

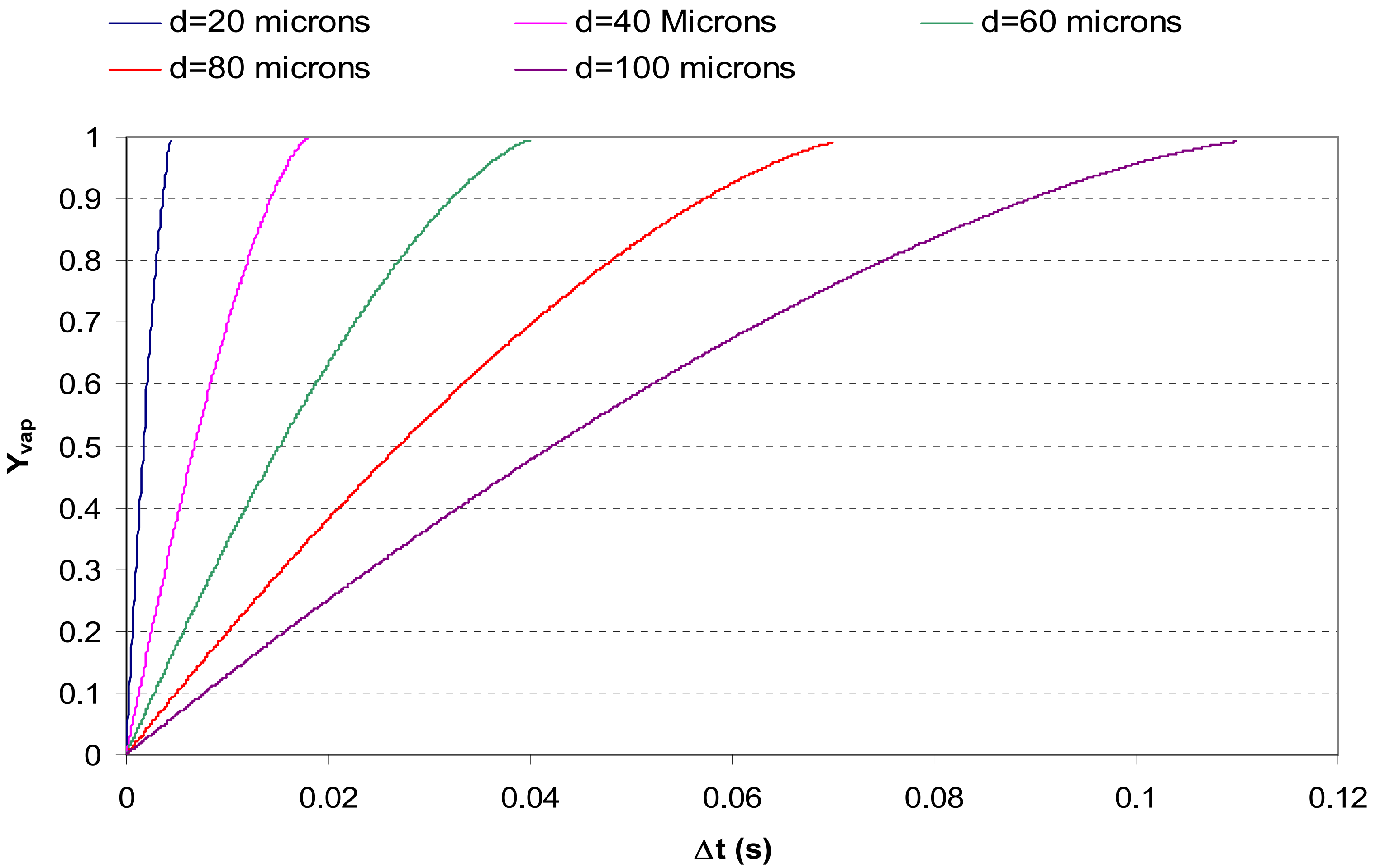
T_{boil}, the boiling temperature of the droplet (water droplet)

k_∞ , thermal conductivity of gas

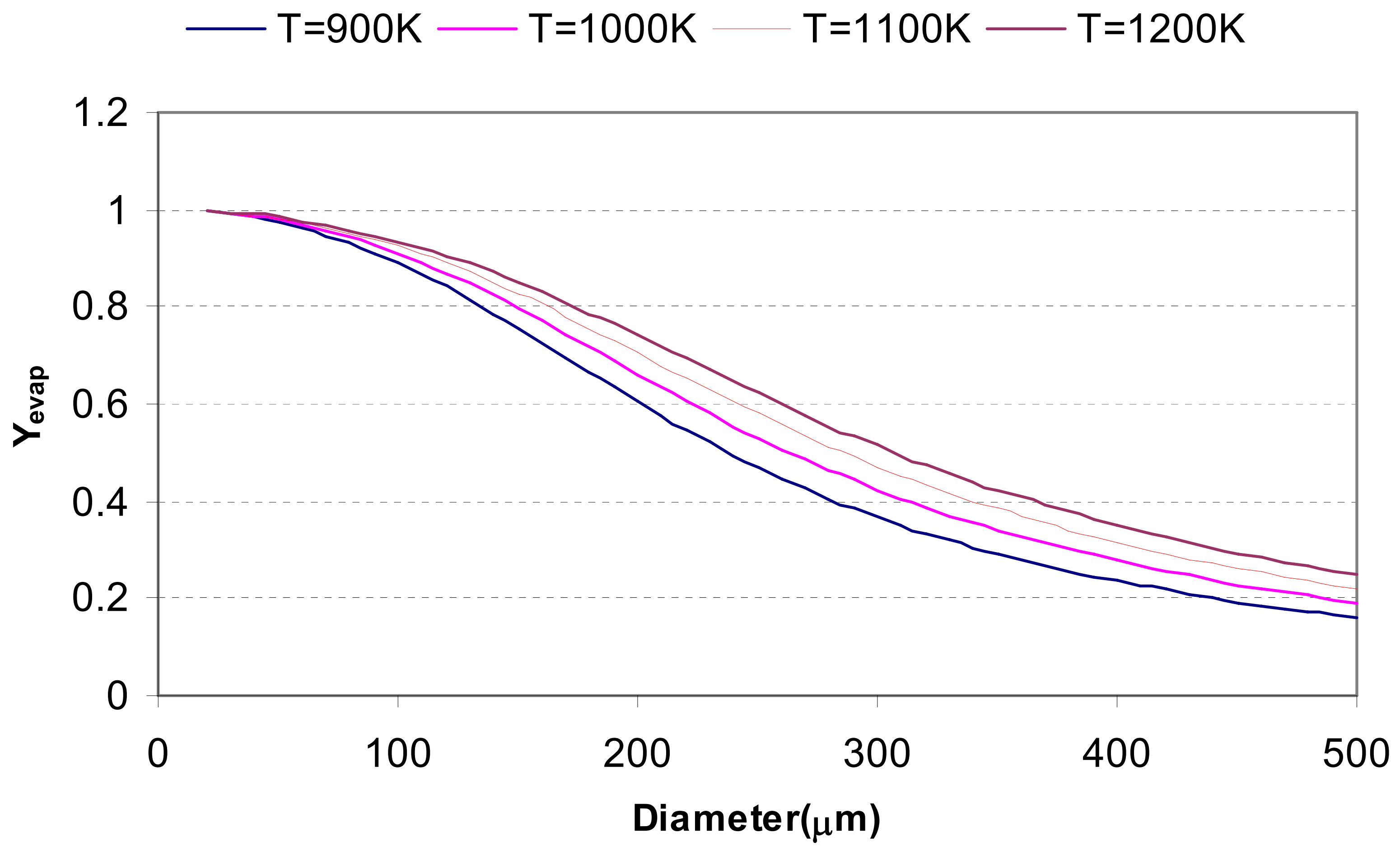
Evaporation constant for $290 \le T(k) \le 2037$



Evaporation Rate for Different Droplet Sizes



Evaporation Rate for Different Droplet Sizes, Different Ambient Temperature

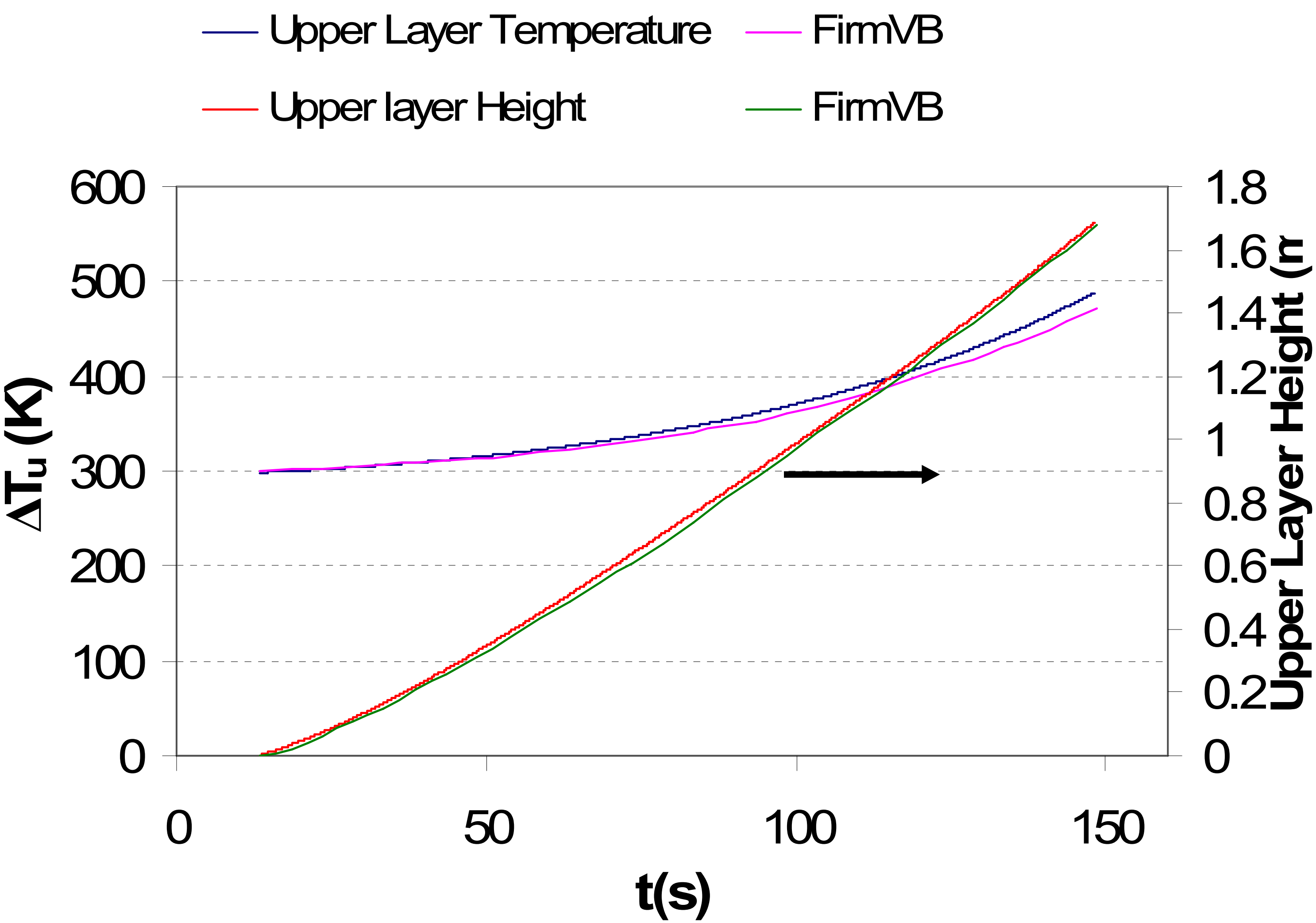


Results for Upper Layer Temperature

Dimensions of Enclosure: Area : 12 m^2 , Height: 3 m

Time Step (Δt=0.15 seconds)

Slow Fire Growth

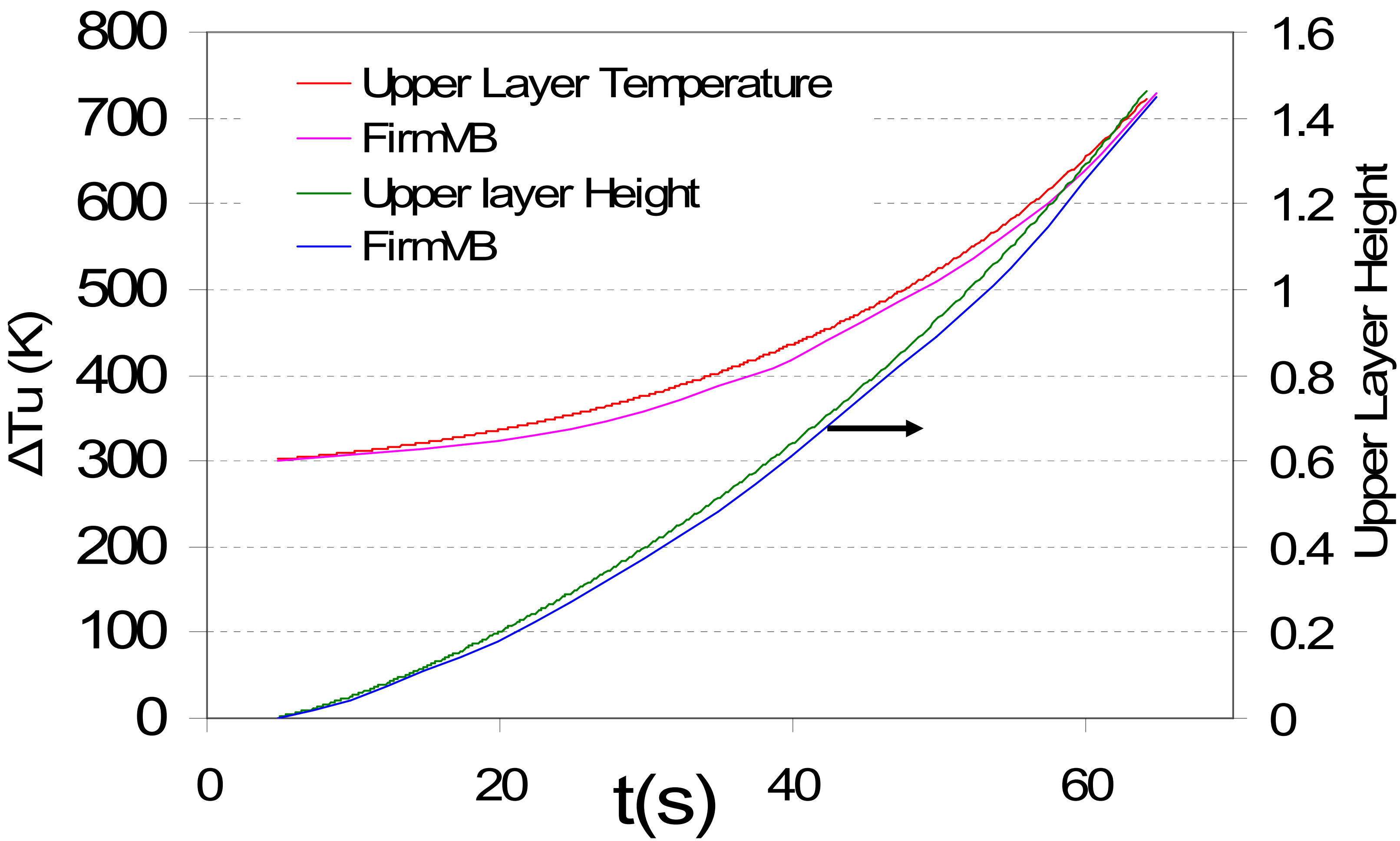


Results for Upper Layer Temperature

Dimensions of Enclosure: Area : 12 m^2 , Height: 3 m

Time Step (Δt=0.15 seconds)

Fast Fire Growth

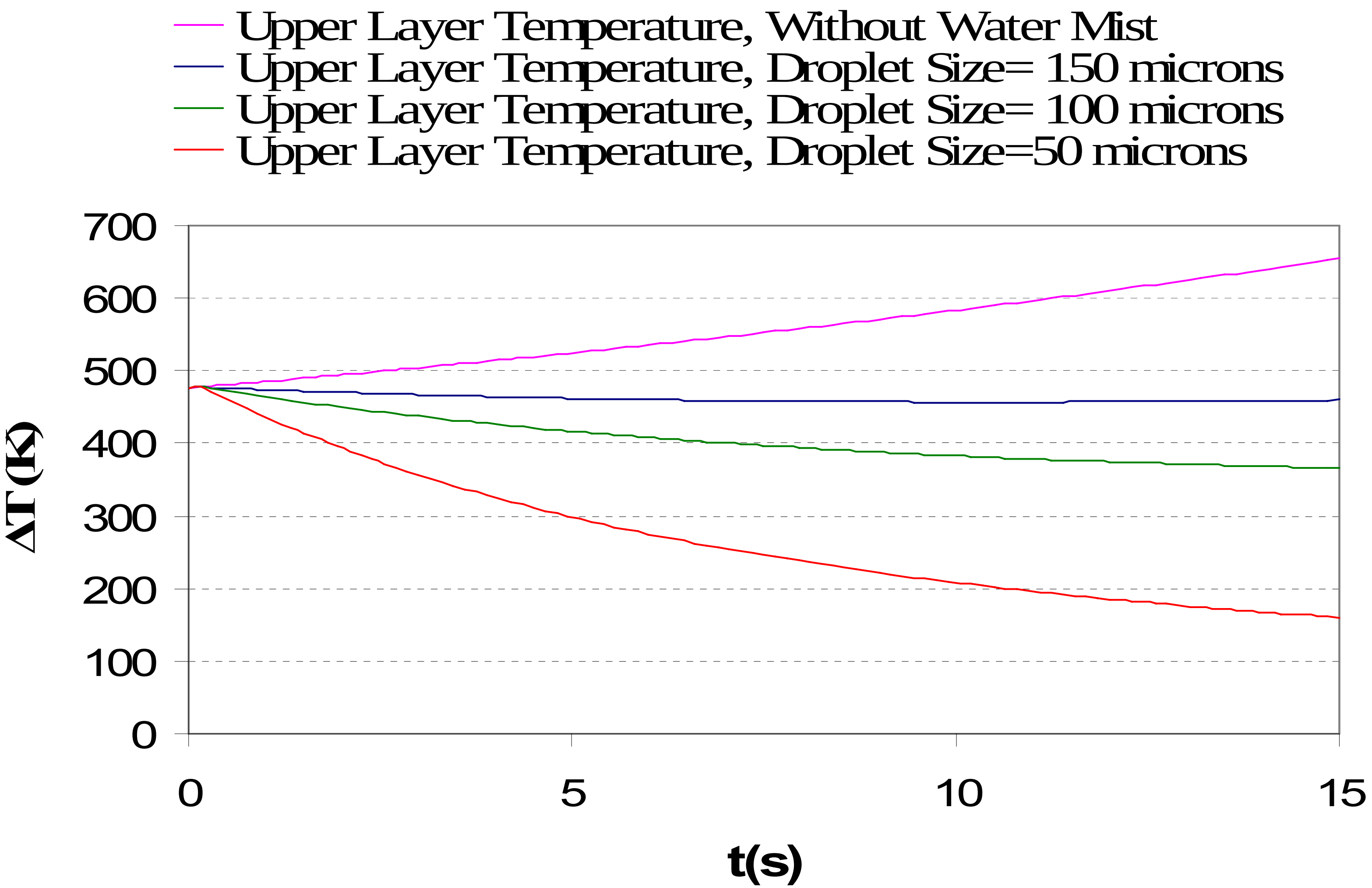


Fire Scenario: **Fast Fire Growth**

Water Flow rate: **0.5 kg/s**, Droplet size: **150 μm, 100 μm, 50 mm**

Total water used: **13.5 kg**

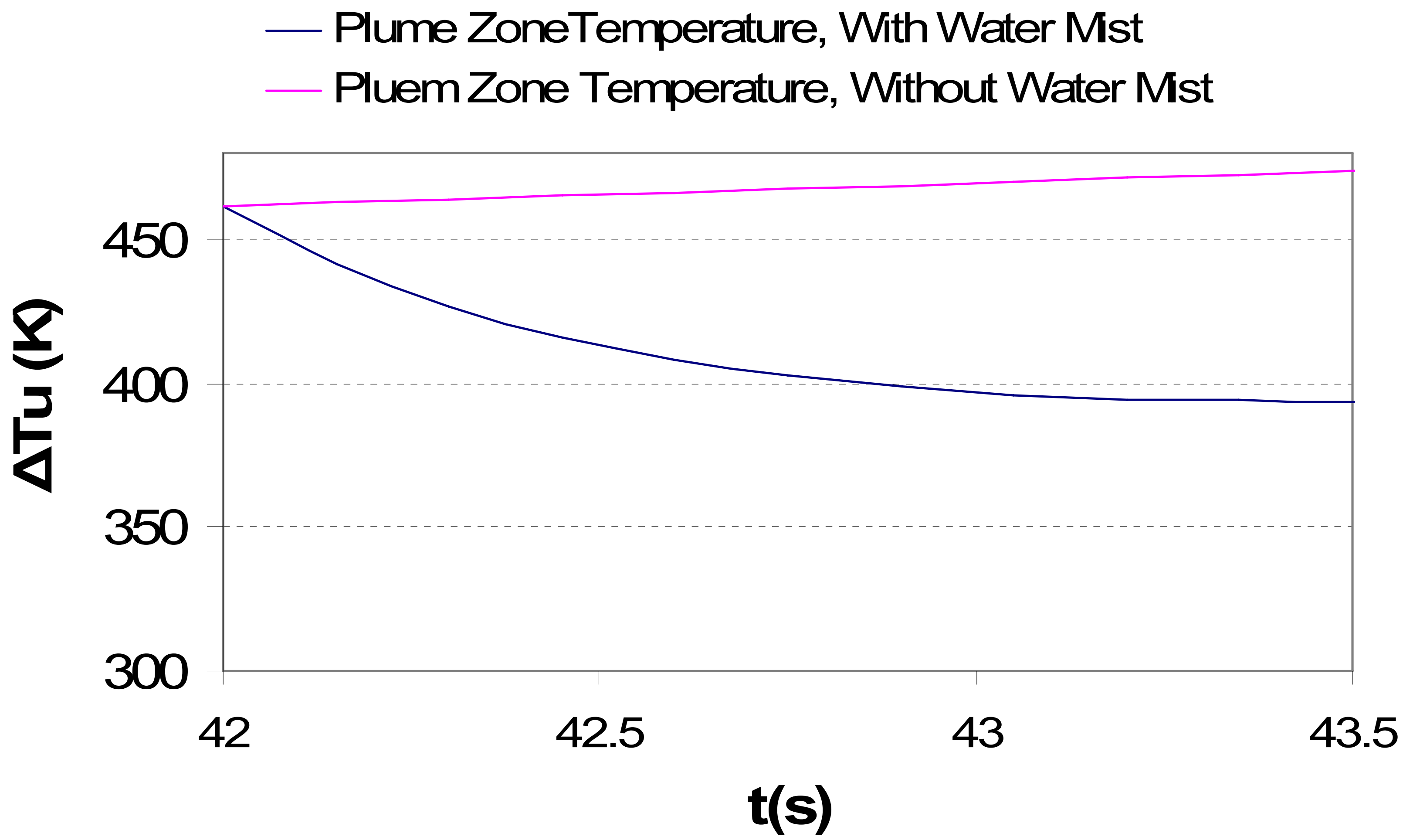
Average rate of change for upper layer temperature, **-1.102 °/s, -7.342 °/s, -21.08 °/s**



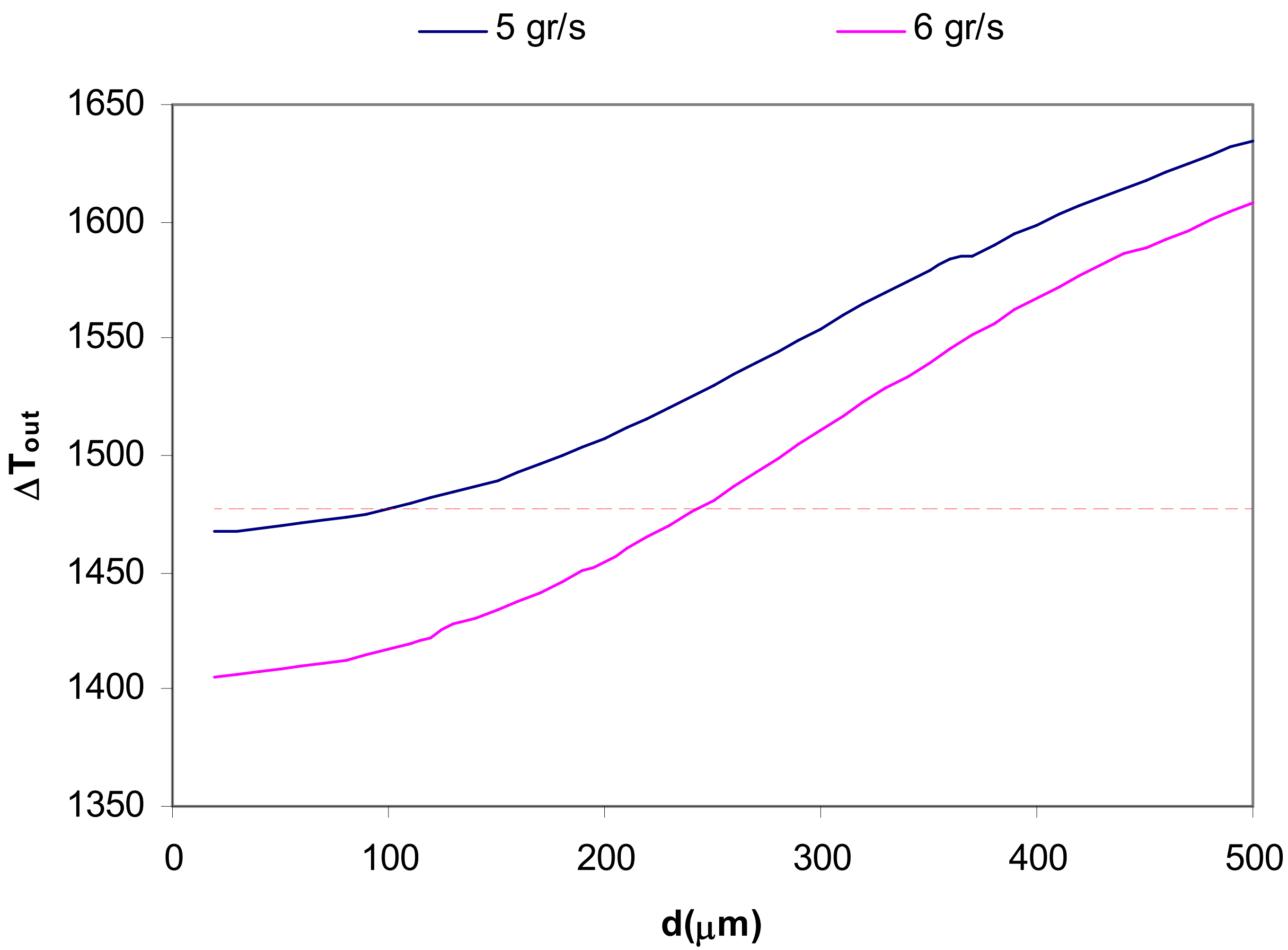
Fire Scenario: **Fast Fire Growth**

Water Flow rate: **0.35 kg/s**, Droplet size: **100 μm,** Total water used: **0.5775 kg**

Average rate of change for Plume zone temperature, **-8.115 °/s**



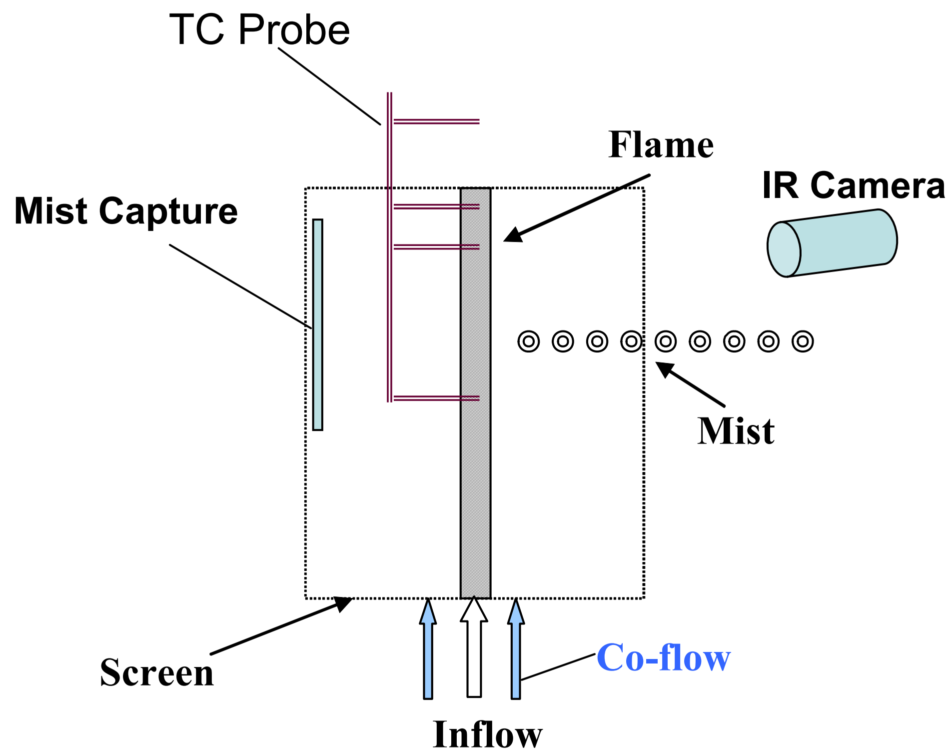
Water Droplet Size Effect in The Flame Zone
Thermodynamic Effect Only



Proposed Experimental Approach

MEASUREMENTS

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



Premixed or Diffusion Flame

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