ALTASIM TECHNOLOGIES
REALIZING TOMORROW'S TECHNOLOGY

Analysis of Burning Candle

COMSOL Conference

October 7-9, 2010

Candle Multiphysics

- Heat
  - Conduction
  - Radiation
  - Convection
- Fluid flow
- Phase change
- Combustion

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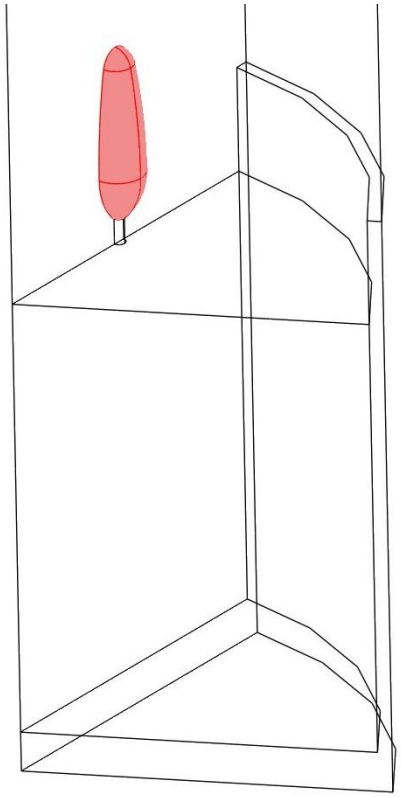
Simplifying assumptions

- Heat of combustion approximated by a simple heat source
- Stationary analysis
- Symmetric boundary conditions



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Model set up

- **Air flow is described by conservation of mass, momentum, and energy**

$$\nabla \cdot \left(\rho \, \mathbf{u} \right) = 0$$

$$\rho \, \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left(\eta \left(\nabla \mathbf{u} + \left(\nabla \mathbf{u} \right)^T \right) - \frac{2}{3} \eta \left(\nabla \cdot \mathbf{u} \right) \mathbf{I} \right) + \rho \, \mathbf{g}$$

$$\nabla \cdot \left(-k \nabla T \right) = Q - \rho \, c_p \mathbf{u}$$

- **Artificial diffusion added in plume**

Model set up

- **Conduction in the solid domains:**

$$\nabla \cdot \left(-k \nabla T \right) = Q$$

- **Anisotropic thermal conductivity**

- **Convective term added in fluid domains**

Model set up

- **Surface heat flux due to radiation**

$$q_r = \varepsilon\left(G_m + F_{amb}\sigma\ T_{amb}^4 - \sigma\ T^4\right)$$

- **Mutual irradiation (G_m) is a function of the radiosity**

$$J = (1-\varepsilon)\left(G_m + F_{amb}\sigma\ T_{amb}^4\right) + \varepsilon\sigma\ T^4$$

- **Flame surface radiation is non-locally coupled to the radiating gas volume**

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Model set up

- Surface radiosity is a function of the average value of T^4 in the radiating gas volume
- Heat flux q_r is set to zero at the boundary
- Source term is included in the flame region to account for cooling due to radiation

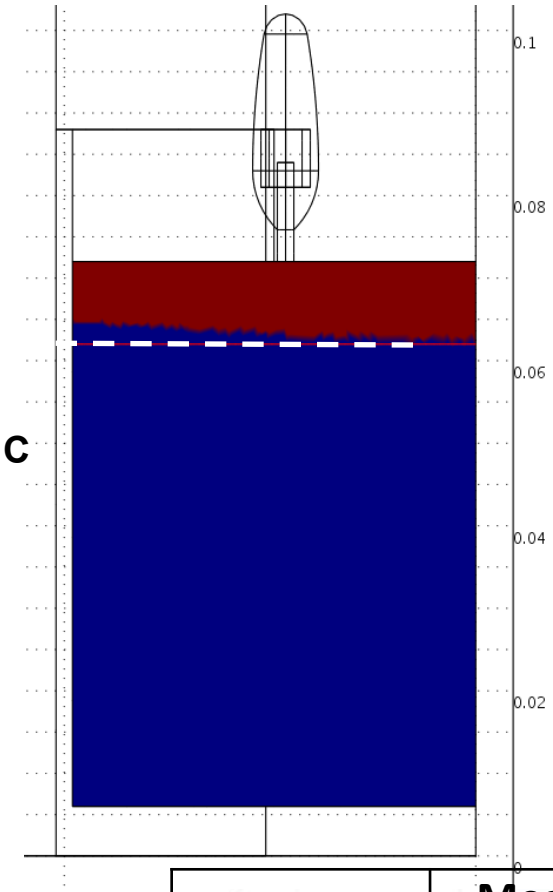
$$Q = -\frac{\varepsilon\sigma\ T^4 A}{V}$$

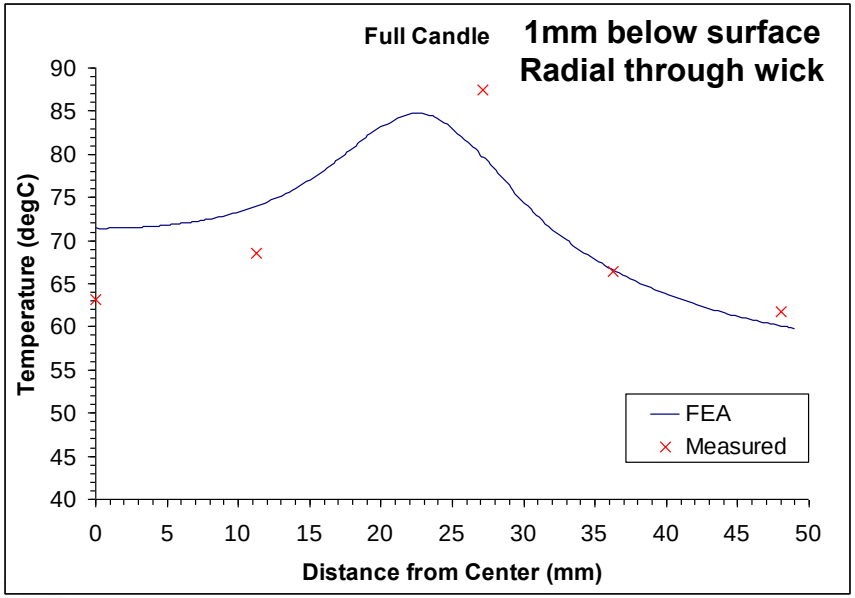
Model validation

- Temperature as function of position along wax surface
- Temperature as a function of candle height
- Location of interface between solid and liquid

Validation

S-L interface: 54 C
Line: Measured
Area: Predicted





	Measured (C)	FEA (C)
Full Candle	40	46
Half Candle	44	49

Average temperature of glass along top outer edge

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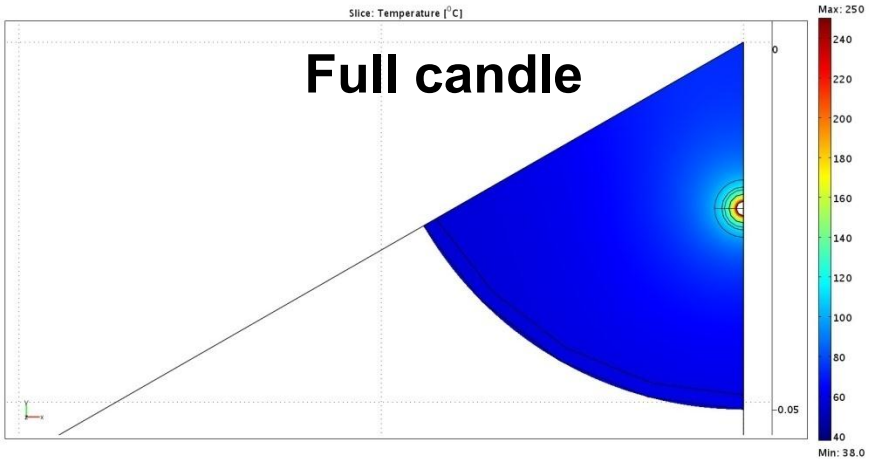
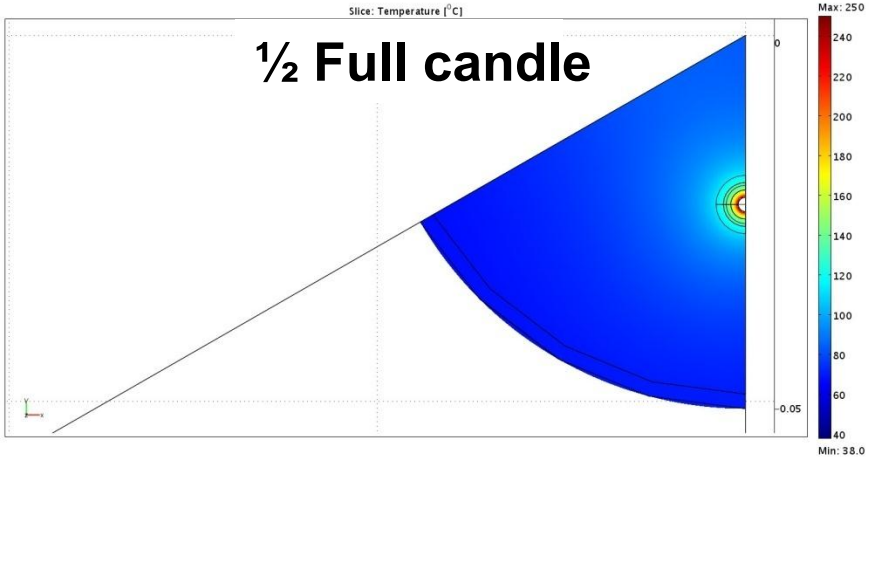
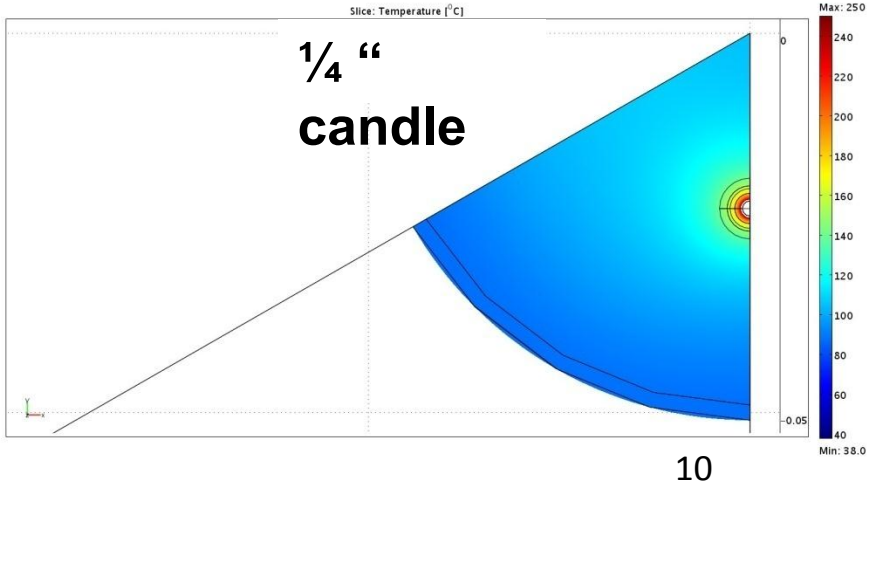
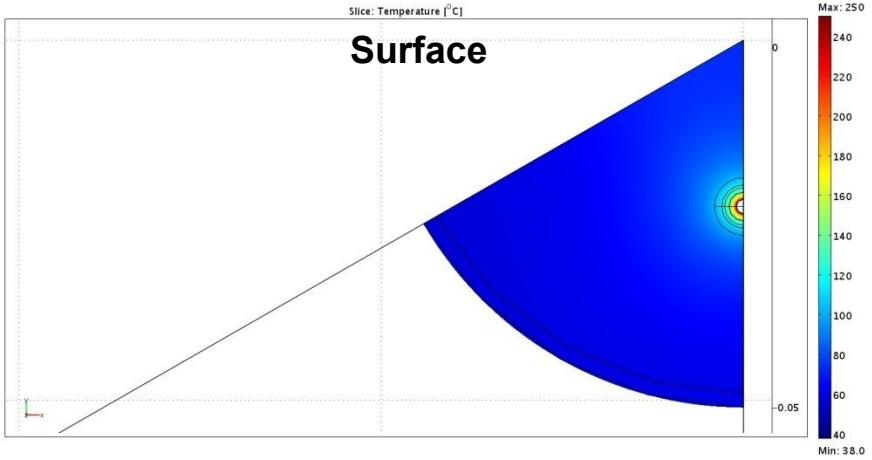
Results: Temperature @ Wax surface

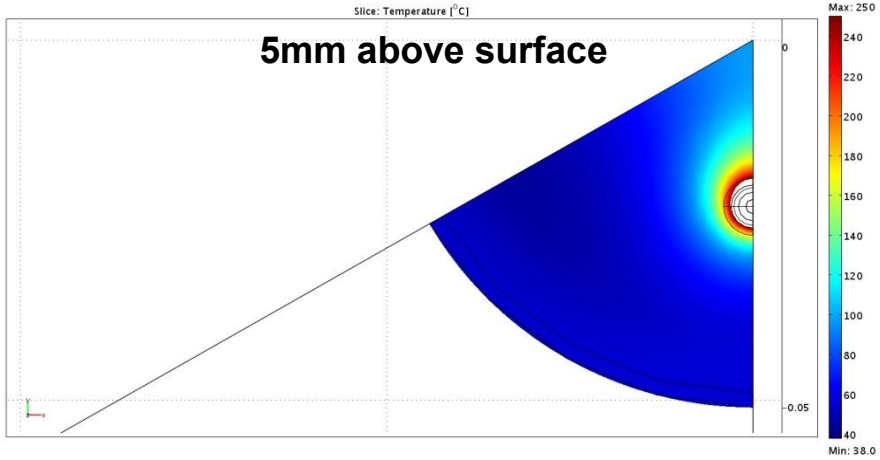


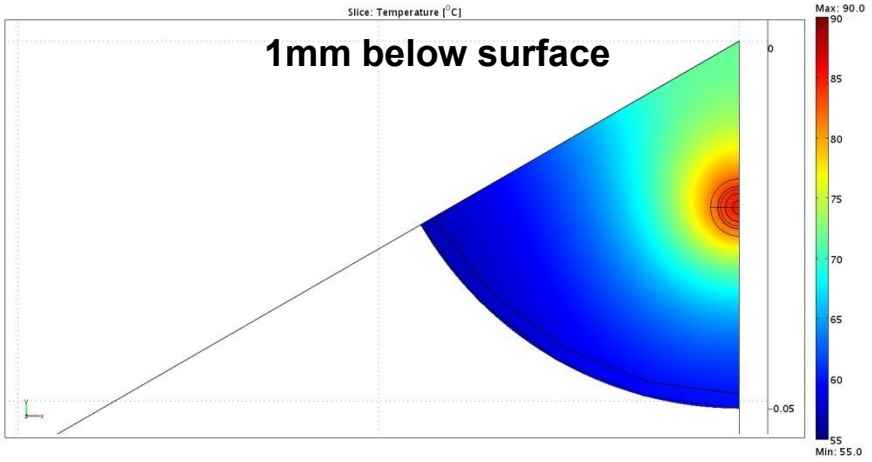


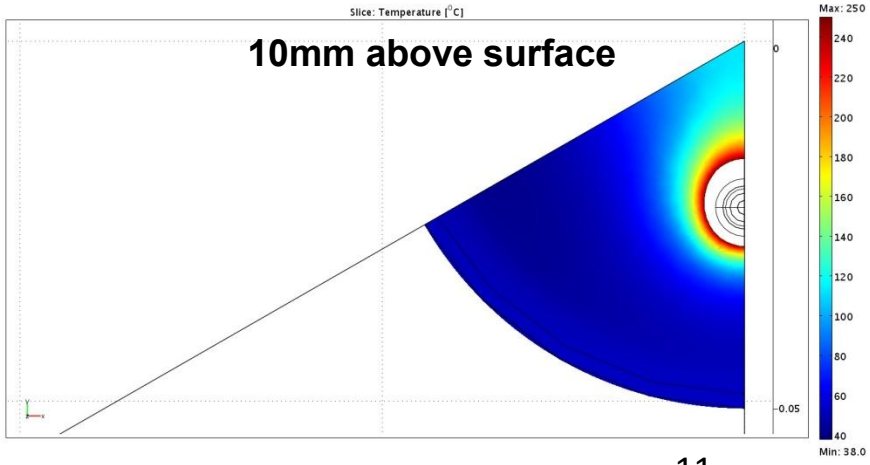


Results: Temperature

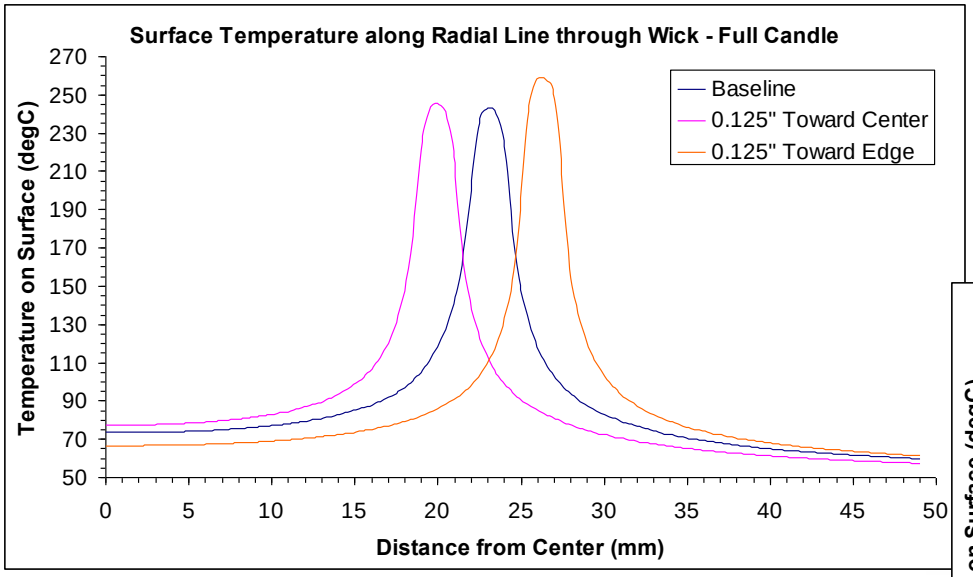


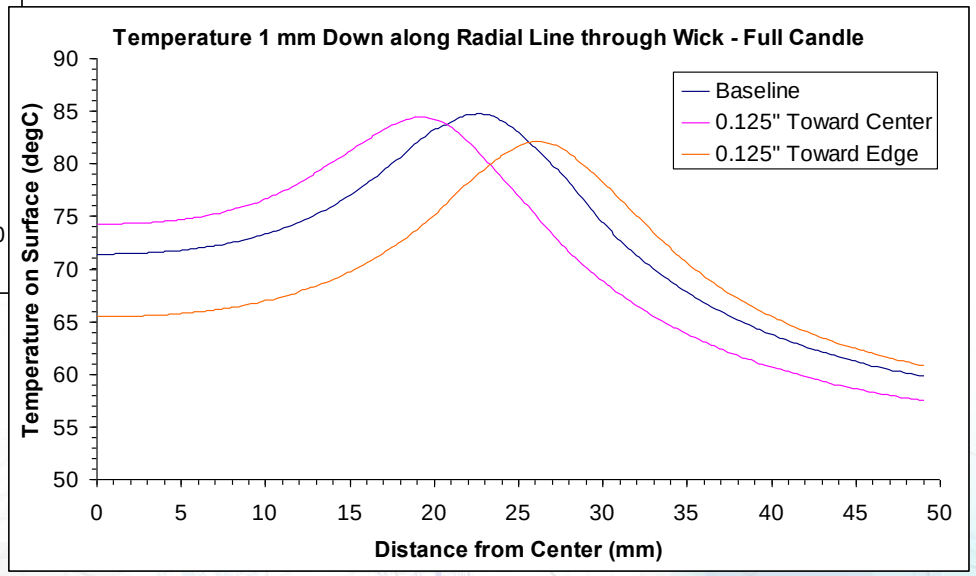






Results: Wick location





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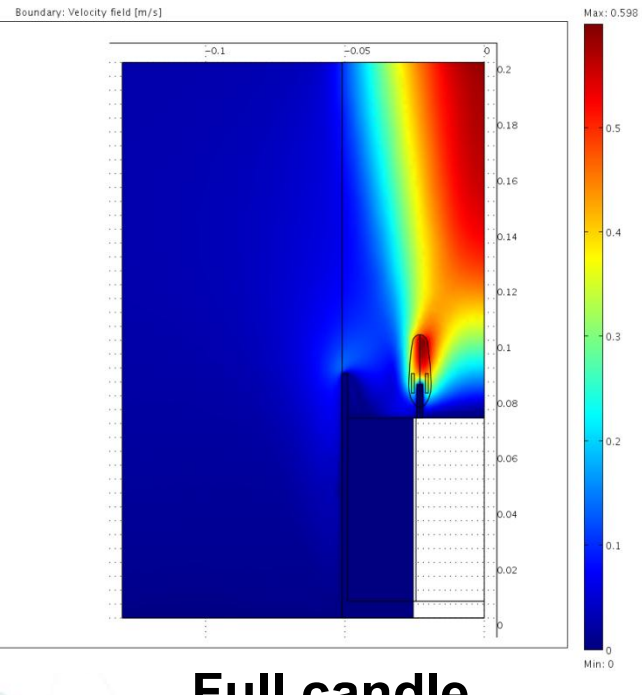
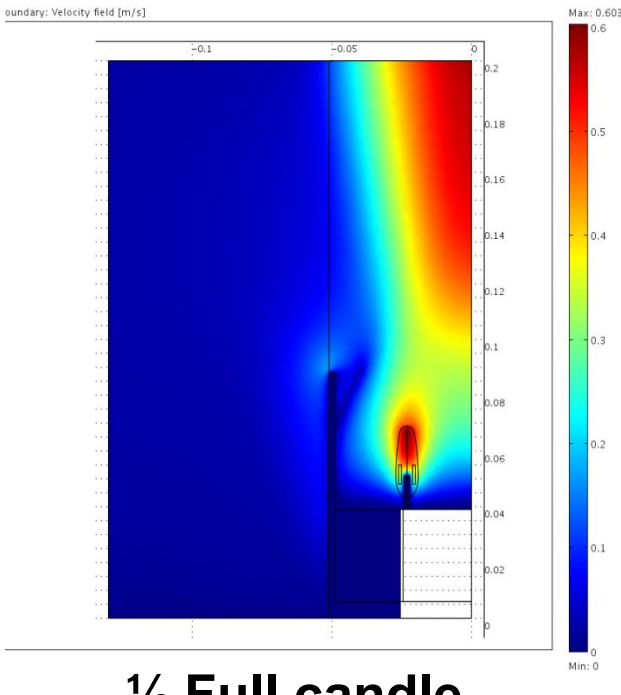
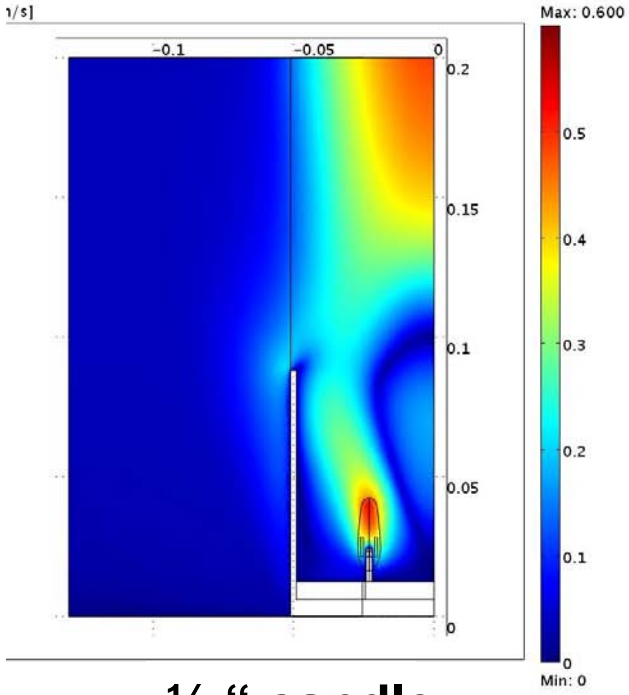
Results: Flow



Full candle



½ Full candle



¼ “ candle

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Summary

- **Analysis incorporating**
  - **Conduction**
  - **Convection**
  - **Radiation**
  - **Phase change**
- **Validated model**
- **Effects of candle location/height**
  - **Temperature distribution**
  - **Flow**