Analysis of Burning Candle

COMSOL Conference
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Candle Multiphysics

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

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

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

\[ \nabla \cdot (\rho \ u) = 0 \]

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

\[ \nabla \cdot (-k \nabla T) = Q - \rho \ c_p u \]

• Artificial diffusion added in plume
Model set up

• Conduction in the solid domains:

\[ \nabla \cdot (-k\nabla T) = Q \]

• 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
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

<table>
<thead>
<tr>
<th></th>
<th>Measured (C)</th>
<th>FEA (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Candle</td>
<td>40</td>
<td>46</td>
</tr>
<tr>
<td>Half Candle</td>
<td>44</td>
<td>49</td>
</tr>
</tbody>
</table>

Average temperature of glass along top outer edge

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

1mm below surface
Radial through wick

Distance from Center (mm)
Results: Temperature @ Wax surface

Full candle

½ Full candle

¼ " candle
Results: Temperature

Surface

5mm above surface

1mm below surface

10mm above surface
Results: Wick location

Surface Temperature along Radial Line through Wick - Full Candle

Temperature 1 mm Down along Radial Line through Wick - Full Candle
Results: Flow

Full candle

½ Full candle

¼ " candle
Summary

• Analysis incorporating
  – Conduction
  – Convection
  – Radiation
  – Phase change

• Validated model

• Effects of candle location/height
  – Temperature distribution
  – Flow