DALHOUSIE UNIVERSITY
mechanical engineering

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Lab of Applied MultiPhase Thermal Engineering

Modeling Convection during Melting of a Phase Change Material

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Thermal Energy Storage

- **Sensible Heat Storage:**

  A heat storage system that uses a heat storage medium, and where the addition or removal of heat results in a change in temperature

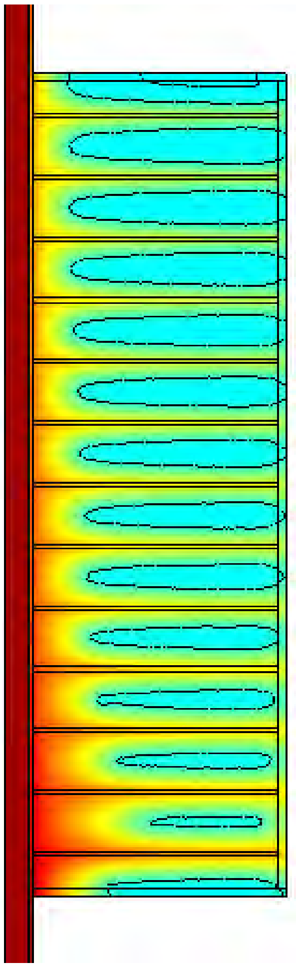
- **Thermochemical Storage:**

  Storage of energy is the result of a chemical reaction

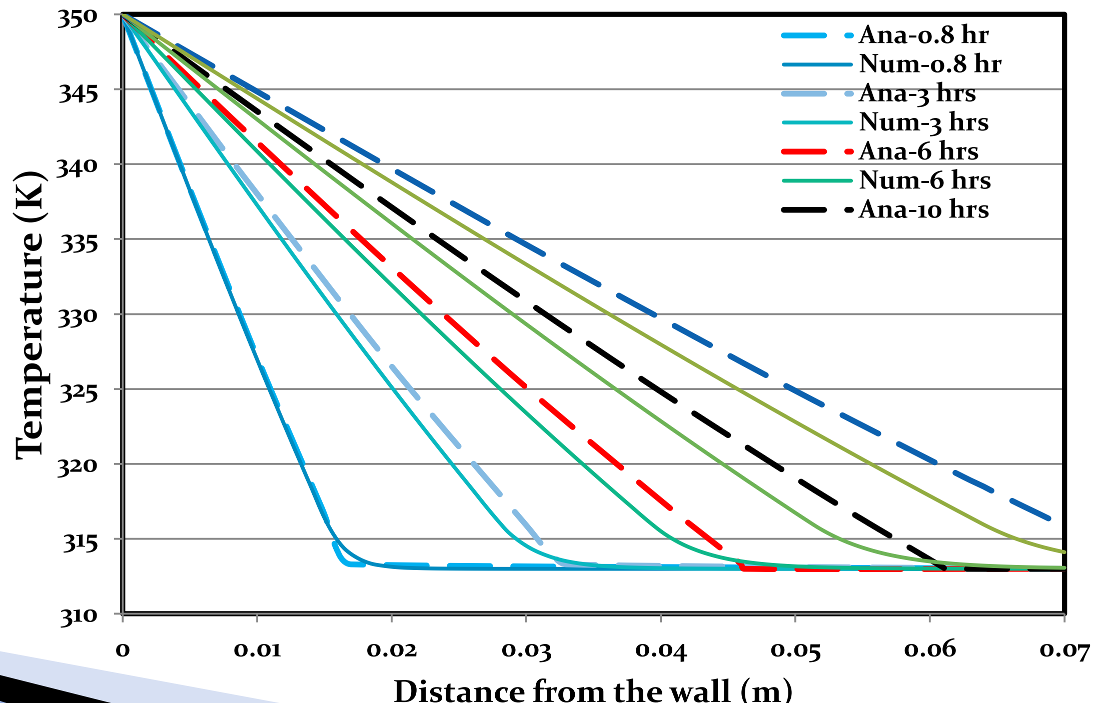
- **Latent Heat Storage:**

  The storage of energy is the result of the phase change (solid-liquid or solid-solid) of a phase change material (PCM). The process happening over a small temperature range.

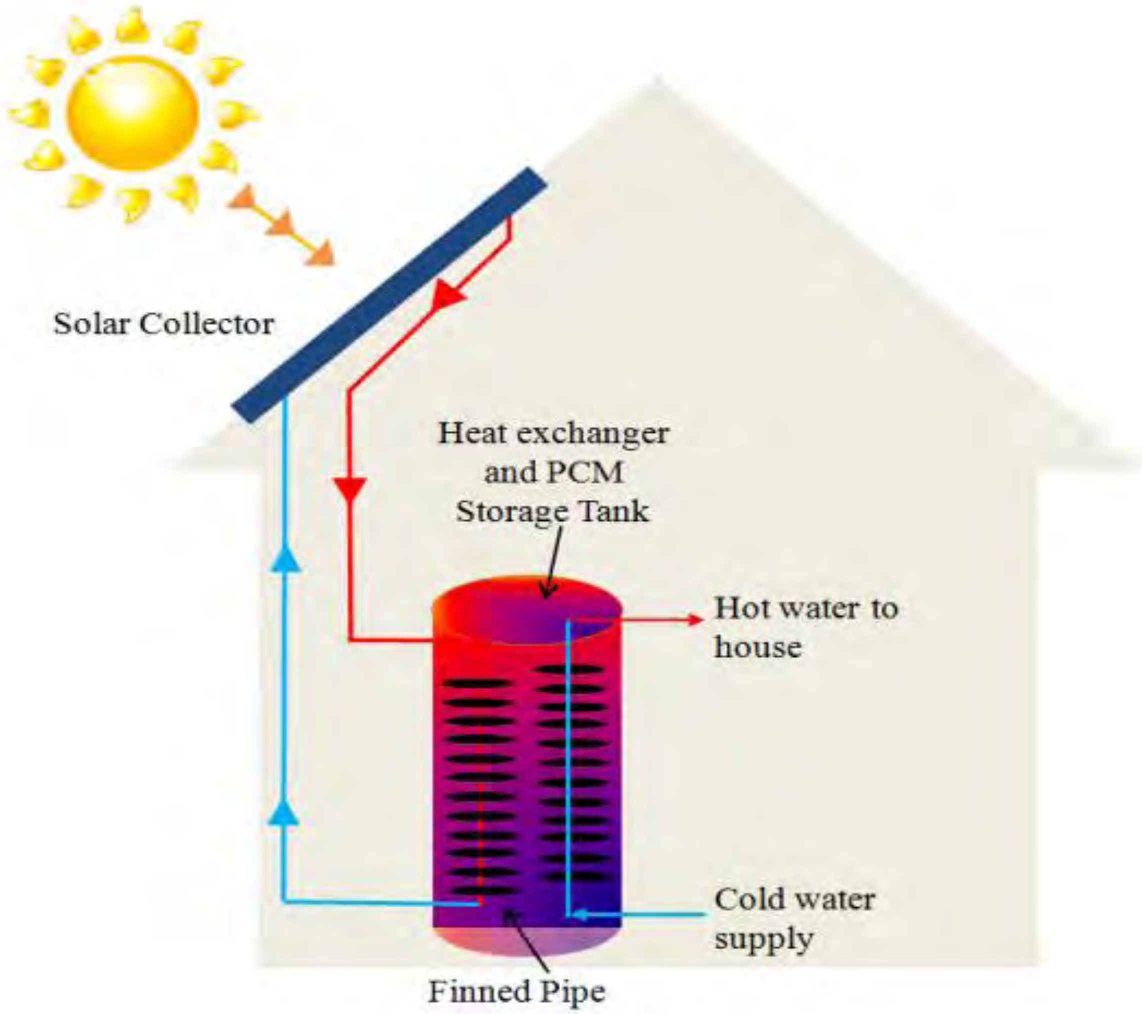
Previous Work



- Finite Elements can be used to help in the design of Latent Heat Energy Storage Systems (LHESS):
  - Determination of the application-dependent size of the LHESS;
  - Choice of geometry;
  - Heat Transfer enhancement (fins for example);
  - Etc ...
- All neglected convection in the liquid melt.



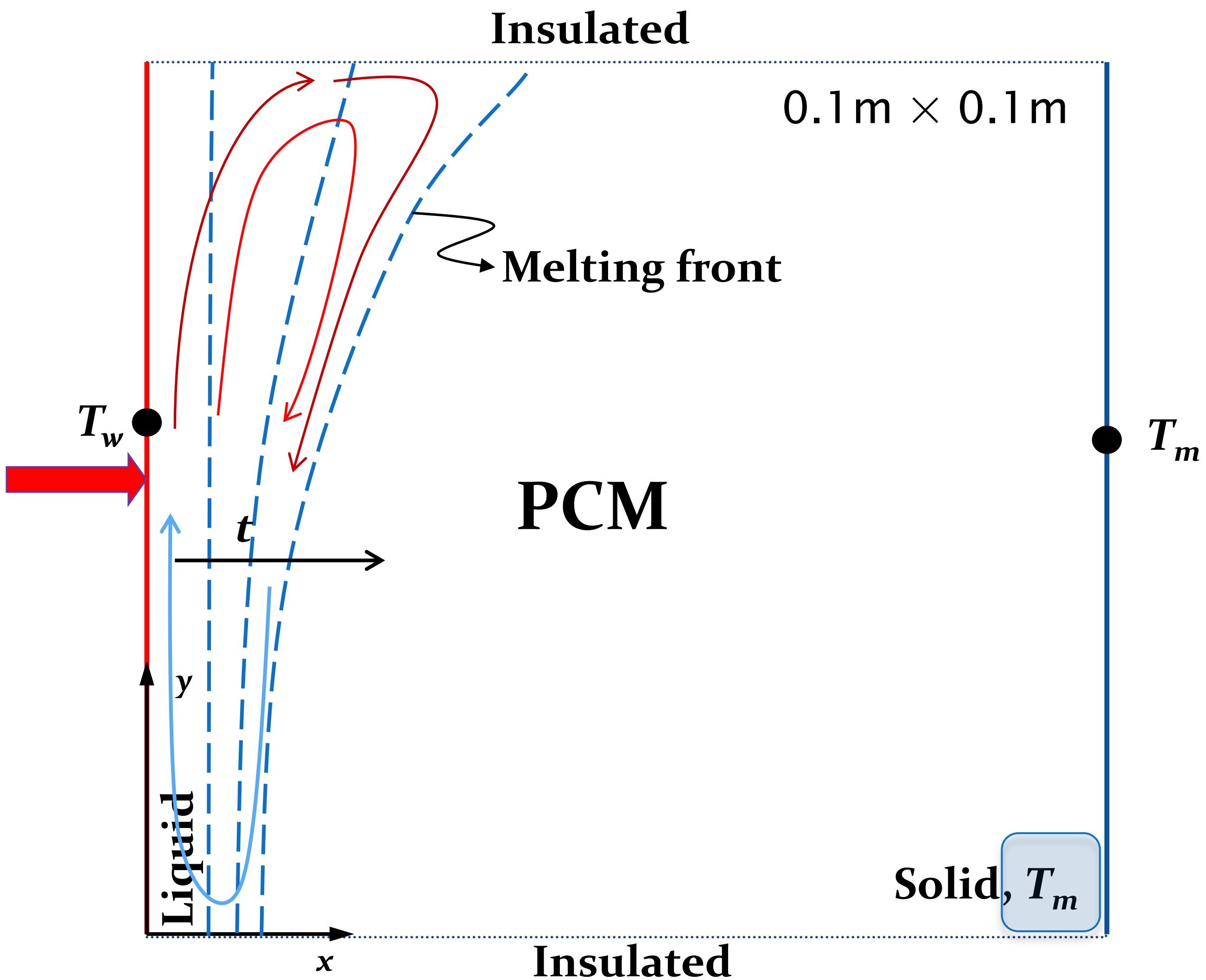
Application



Geometry Studied

- 2D Convection Dominated

Geometry



- O. Bertrand et al., Melting driven by natural convection- A comparison exercise: first results, *International Journal of Thermal Sciences*, **38**, pp. 5-26 (1999)

PCM

The phase change material used in the validation study is ideal Octadecane

Thermal Conductivity	0.2 W/m·K
Density	800 kg/m^3
Dynamic Viscosity	0.008 Pa·s
Heat Capacity	1.25 kJ/kg·K
Enthalpy of Fusion	125 kJ/kg
Melting Temperature	303 K

Numerical Modeling

- 2D Convection Dominated

Governing Equations

- Navier-Stokes and energy equation:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

Body Force

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho g\alpha\left(T-T_0\right)$$

Natural Convection

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)$$

- Boundary Conditions:

$$T\left(x=0,t>0\right)=T_w$$

$$T\left(x=0.1m,t>0\right)=T_m$$

- Energy balance at the melting interface $\delta(x,y,t)$:

$$-\rho_l L\frac{d\delta\left(x,y,t\right)}{dt}=k_l\frac{\partial T_l\left(\delta,t\right)}{\partial x}=-\rho_l L u_m$$

Modeling in COMSOL

- Problem type: Transient thermal fluid*

- Model used: Laminar Flow
  Heat Transfer in a Liquid
  ↳ Transient Analysis

  These models encompass:
  - Laminar flow driven by the body force
  - Heat transfer by conduction and convection

    } Over the entire domain
  - Modified using the Effective Heat Capacity Method and a properly defined viscosity over the entire temperature range.

- 2D Geometry

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* The treatment of phase change renders the problem non-linear as well.

Modified C_p Method

$$C_p = \begin{cases} C_{p,s} & T < 303\ K \\ C_{p,m} & 313\ K < T < 313 + \Delta T_m\ K \\ C_{p,l} & T > 313 + \Delta T_m\ K \end{cases}$$

Where

$$C_{p,m} = \frac{L_f}{(\Delta T_m)}$$

$C_{p,s}$ = Solid phase C_P
= 1.25 kJ/kg

$C_{p,l}$ = Liquid phase C_P
= 1.25 kJ/kg

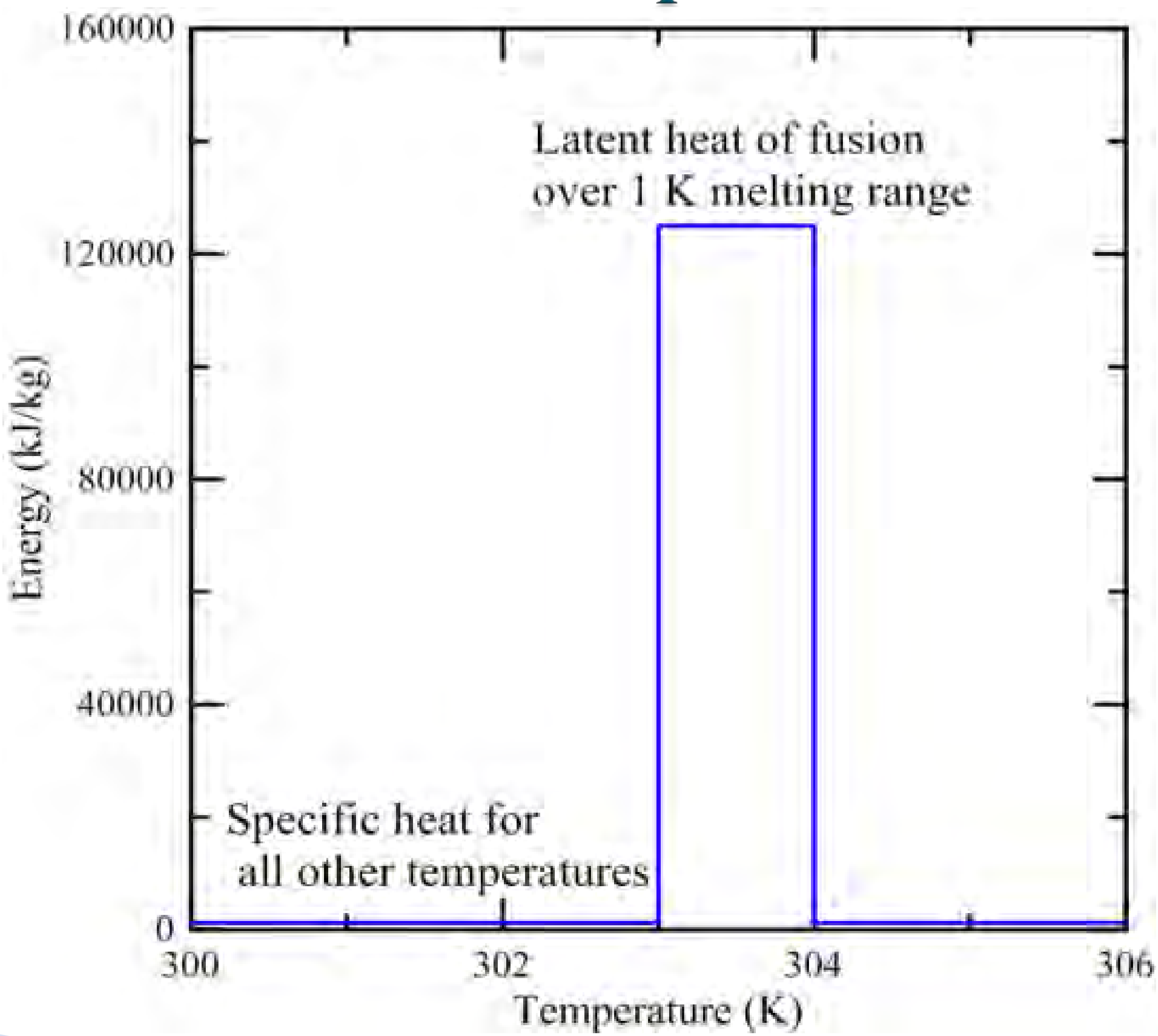
L = Latent heat of fusion
= 125 kJ/kg

ΔT_m = Melting Temperature range

Modified C_p

Numerically, the modified C_p is incorporated in COMSOL using the piecewise function in the material properties.

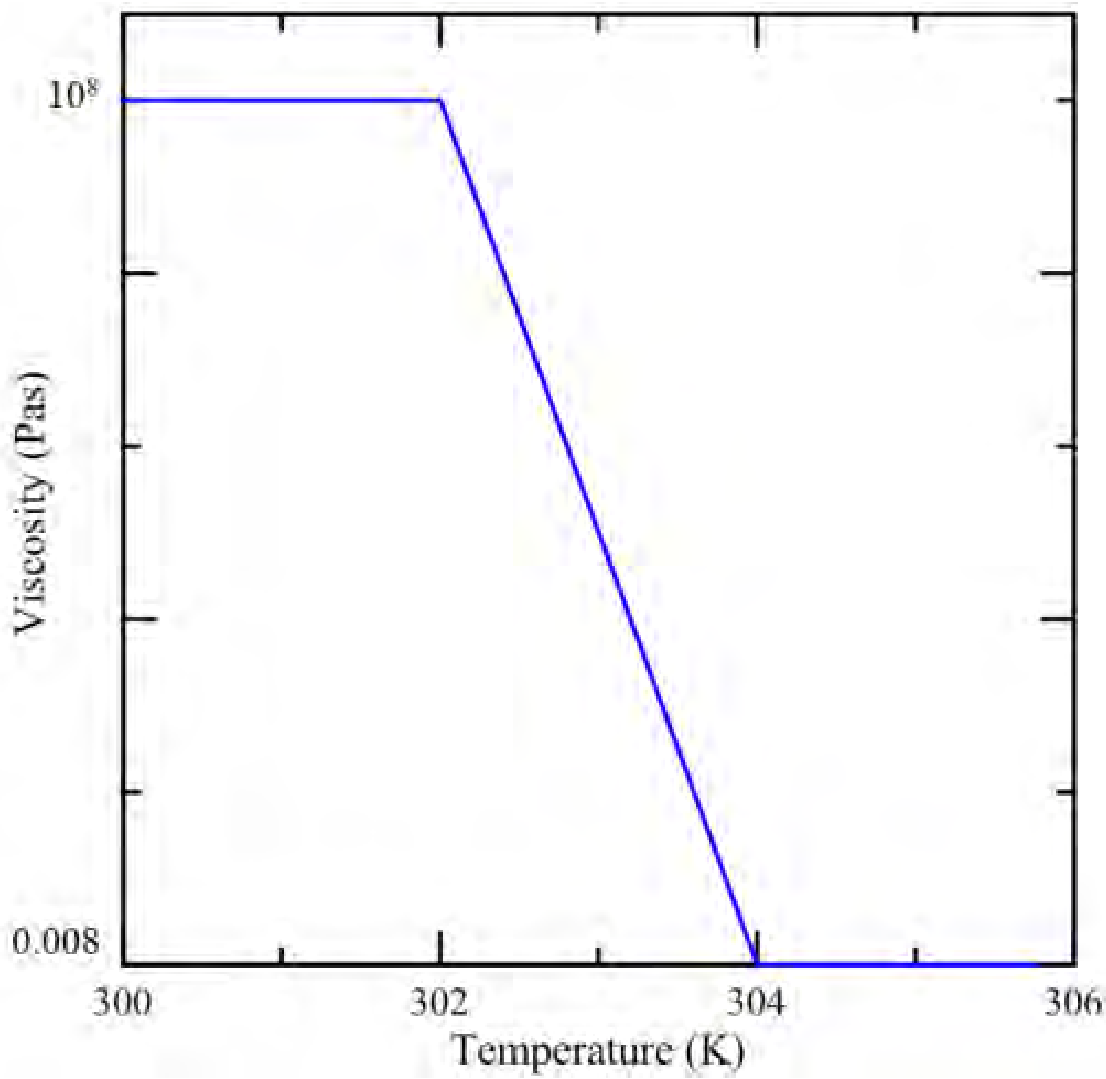
A continuous second derivative is used.



Modified μ

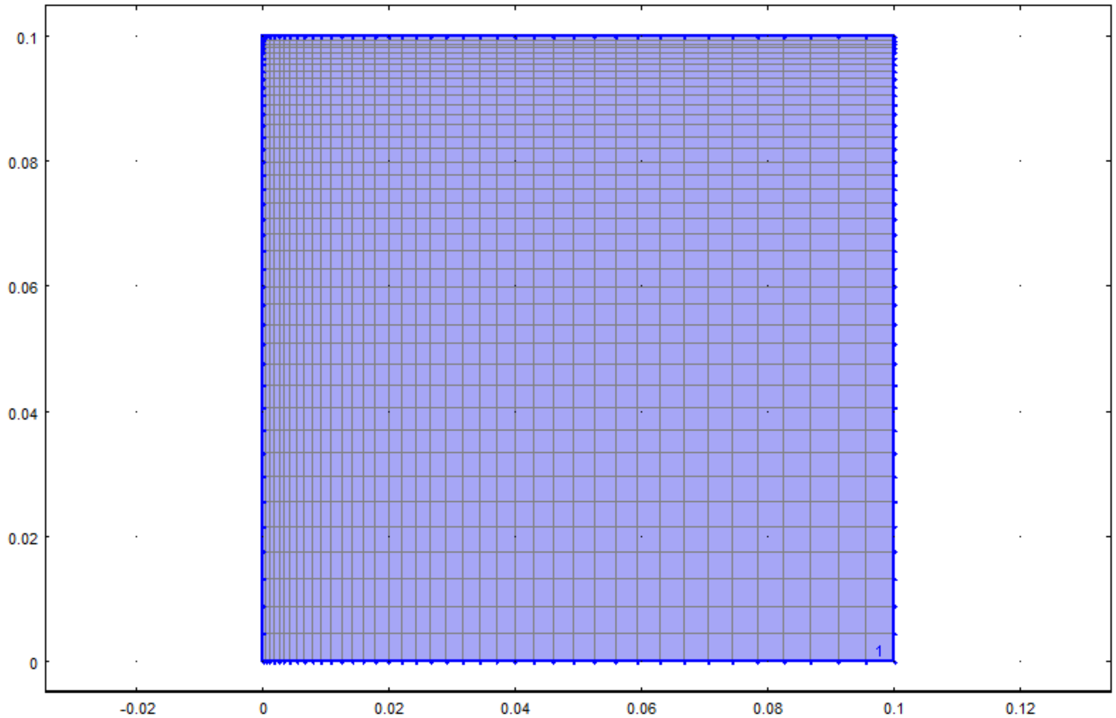
The dynamic viscosity, was input as a piecewise, continuous, second derivative function centered about T_m.

It accounted for the viscosity of the liquid PCM in the melted region and forced the solid PCM to remain fixed by having a solid viscosity of 10^8



Mesh

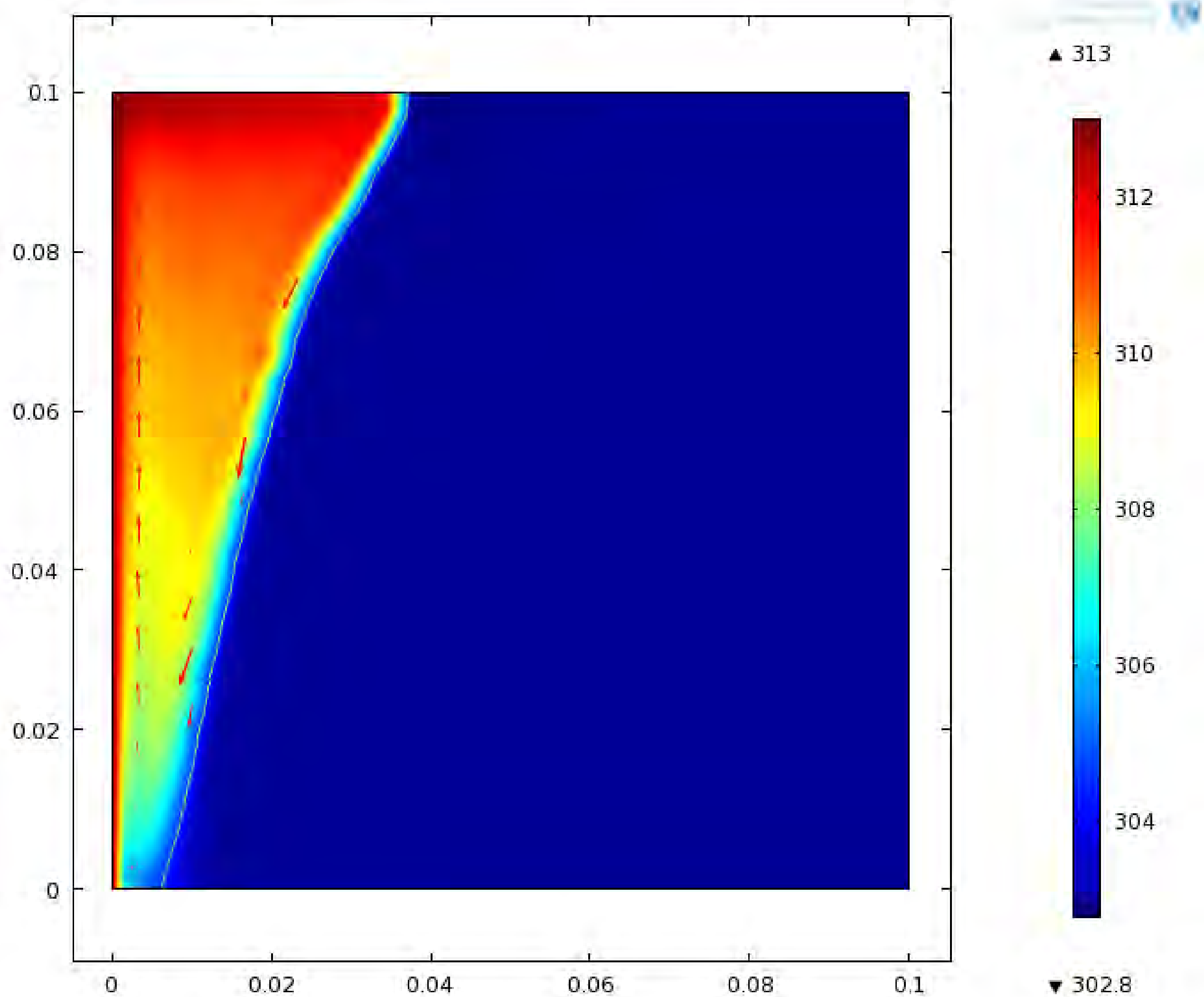
- 2D quadrilateral elements;
- 4096 elements were selected, average element size of 2.44×10^{-6} m^2, selected after a mesh convergence study;
- Element size provided convergence at a relatively low run time, simulations took on average 7 hours on an Intel dual core processor.



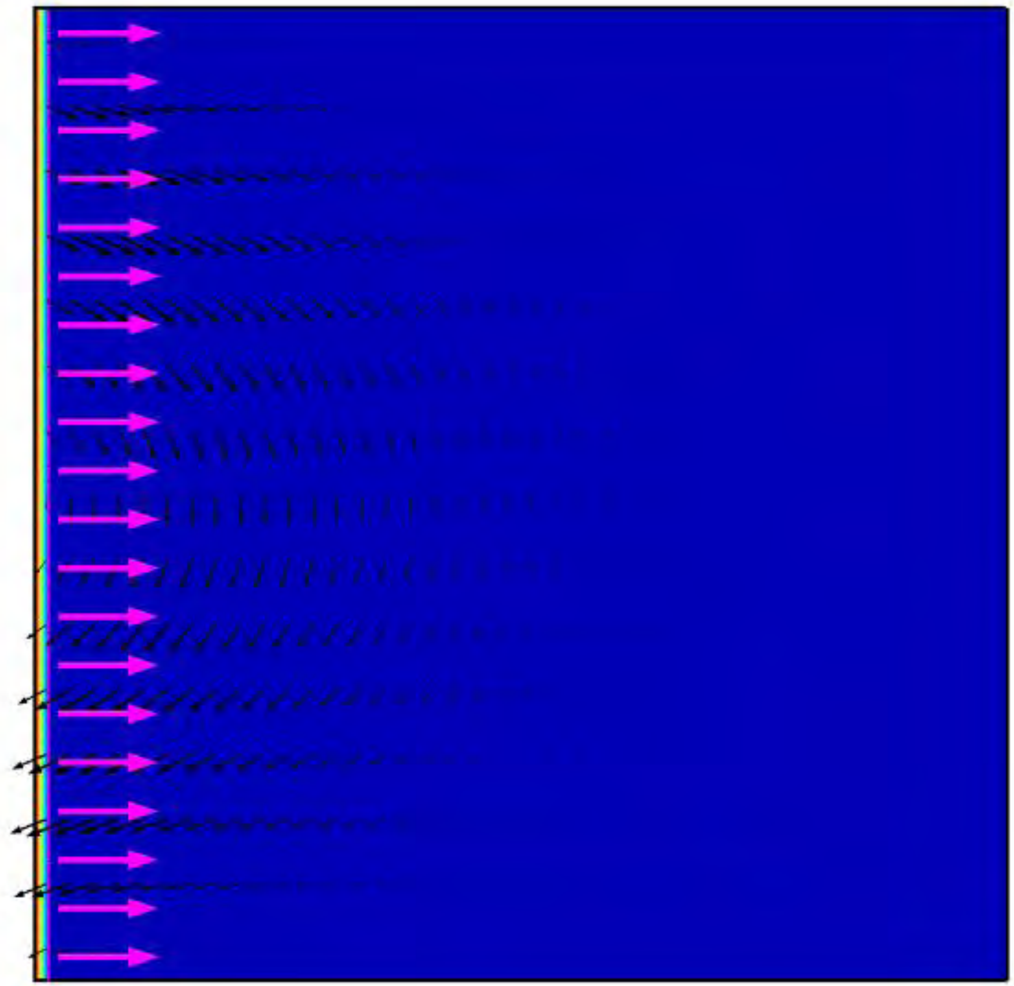
Results

- 2D Convection Dominated

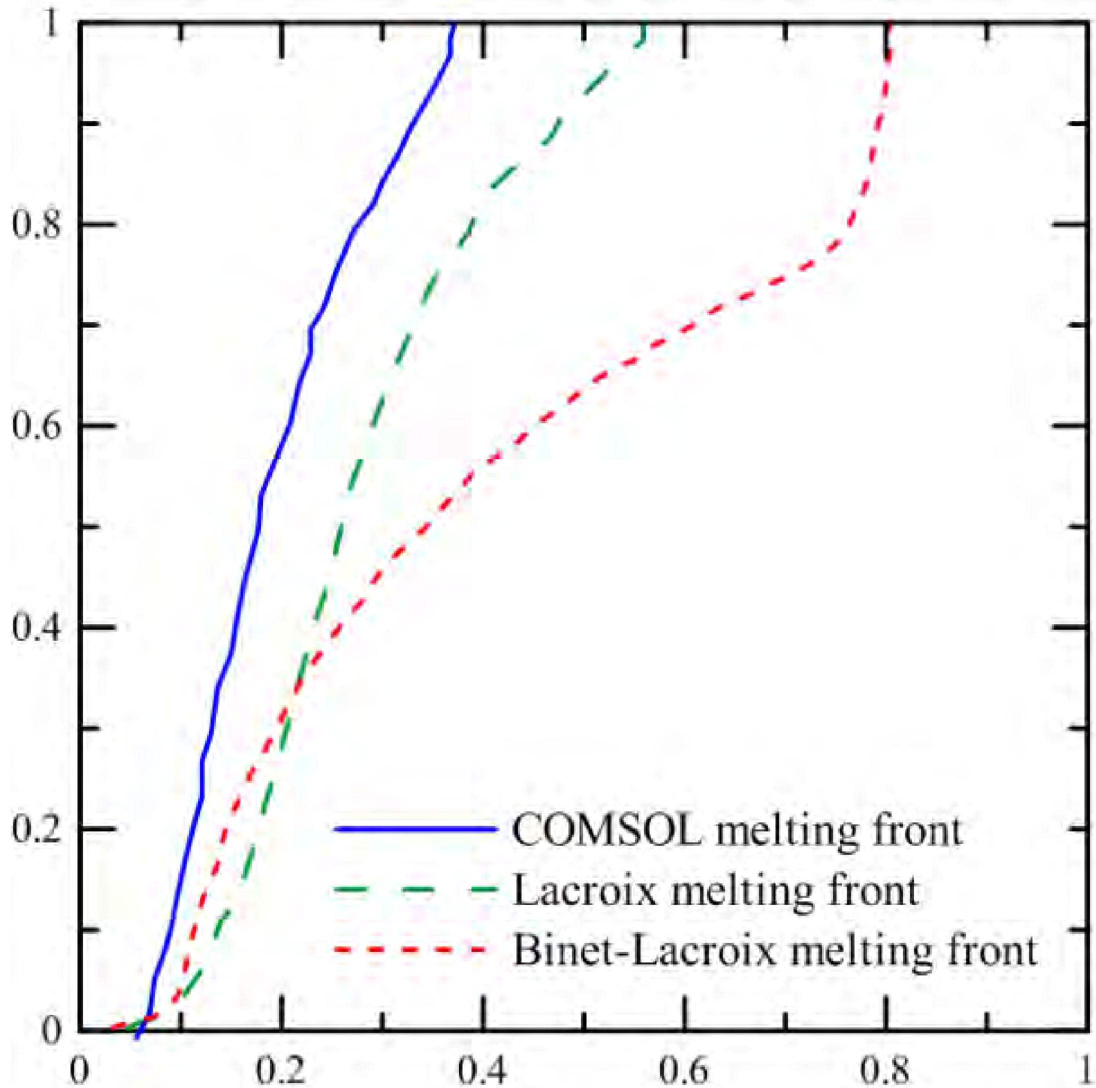
Convection Dominated Melting



Melting interface and velocity profile at 5,000s for $\Delta T_m = 1$ K

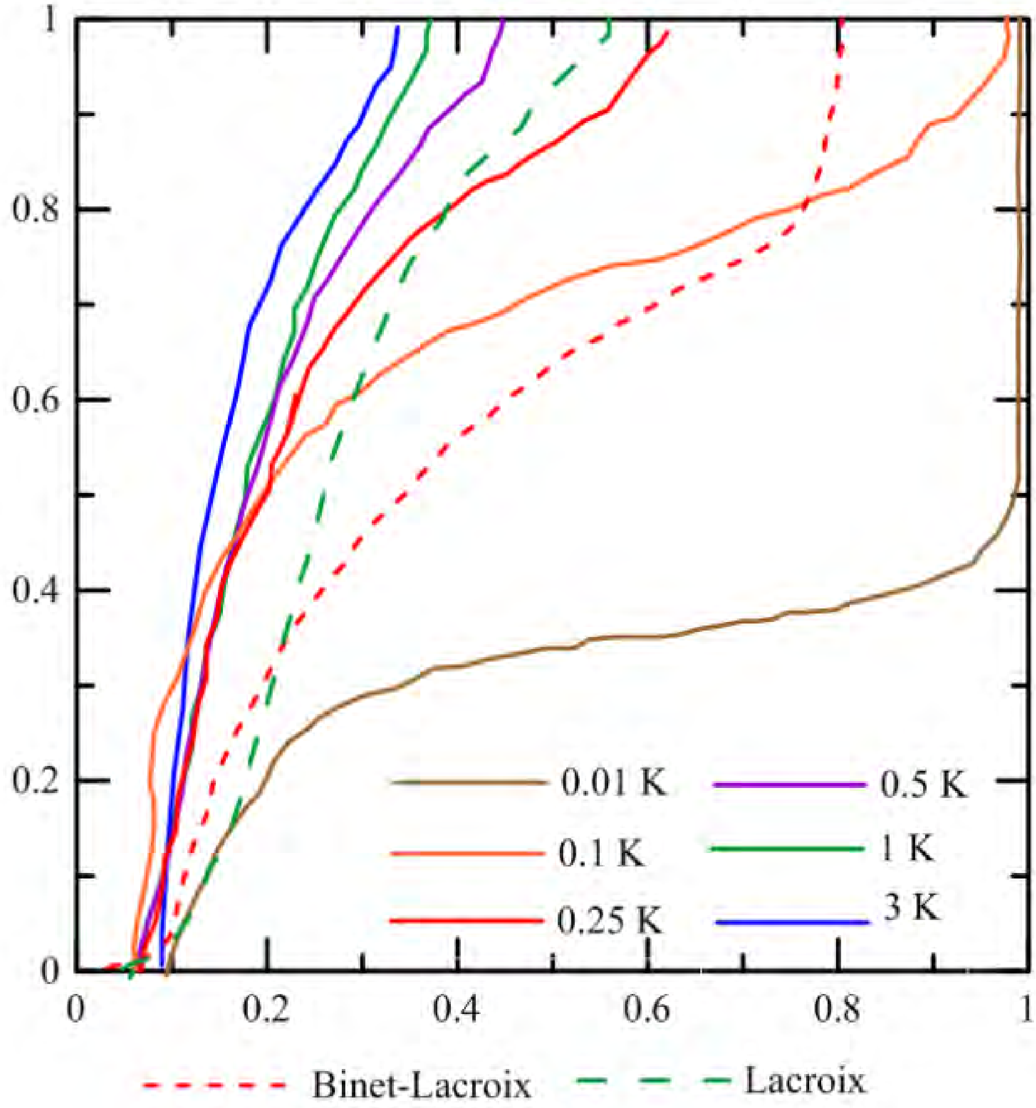


Result vs Bertrand et al.

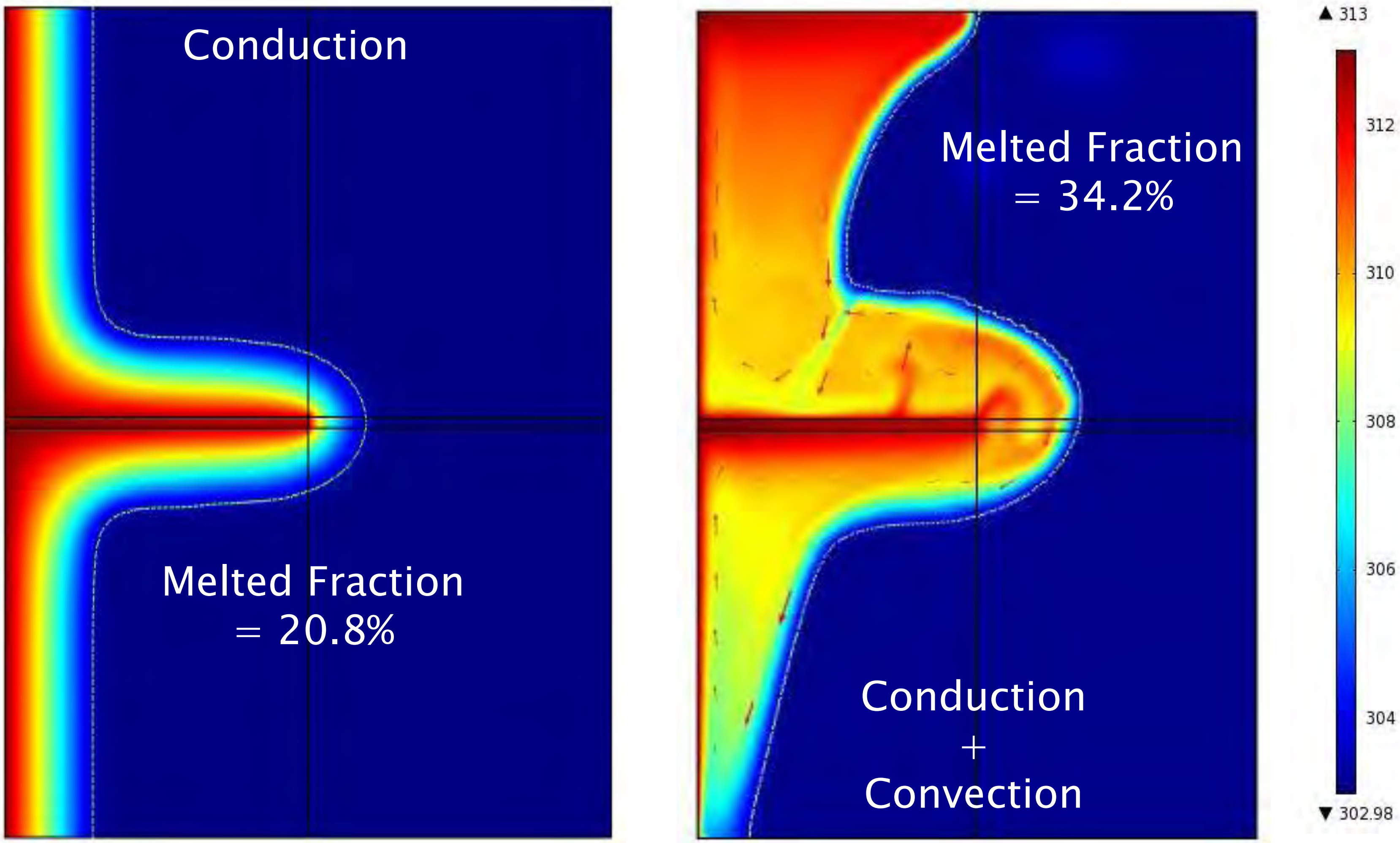


Melting interface at 5,000s for $\Delta T_m = 1$ K

Effect of Melting Temperature Range



Real Impact of Convection



At 5,000s for $\Delta T_m = 1$ K

Source: CHANG, L., GROULX, D. (2011) *Numerical Study of the Effect of Fins on the Natural Convection Driven Melting of Phase Change Material*, COMSOL Conference 2011, Boston.

Conclusion

- The physical processes encountered during **transient phase change heat transfer**, coupled with conduction and convection, in a PCM can be modeled numerically using COMSOL Multiphysics;

- The appearance and the behavior of the melting front can be simulated by:
  - **modifying the specific heat of the PCM** to account for the increased amount of energy, in the form of latent heat of fusion, needed to melt the PCM over its melting temperature range.
  - modeling the entire PCM as a liquid with a **modified viscosity** taking an extremely high value that forces the "solid" PCM to behave as a solid.

- The simulation showed the impact the **melting temperature range** selected has on the overall convection driven phase change process.