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DALHOUSIE
UNIVERSITY
mechanical engineering

Lab of
Applied
MultiPhase
Thermal
Engineering

Natural Convection Driven Melting of Phase Change Material: Comparison of Two Methods

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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

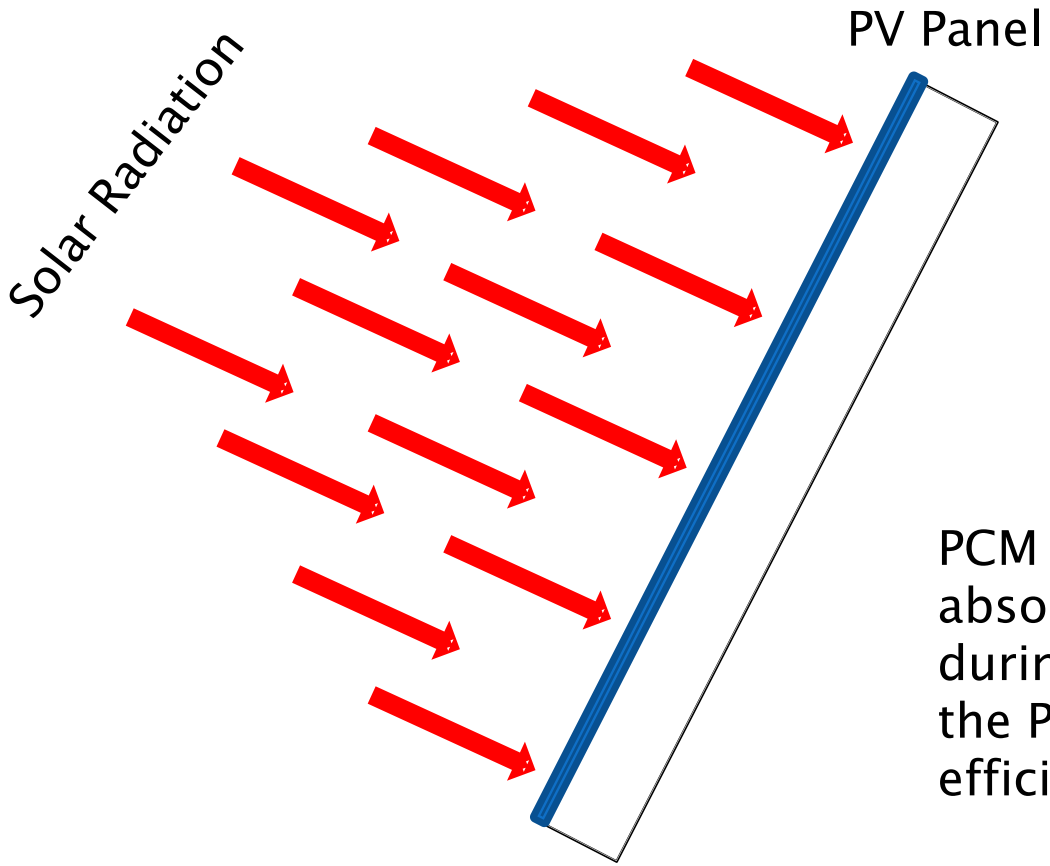
- Thermochemical Storage:

  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.

Application



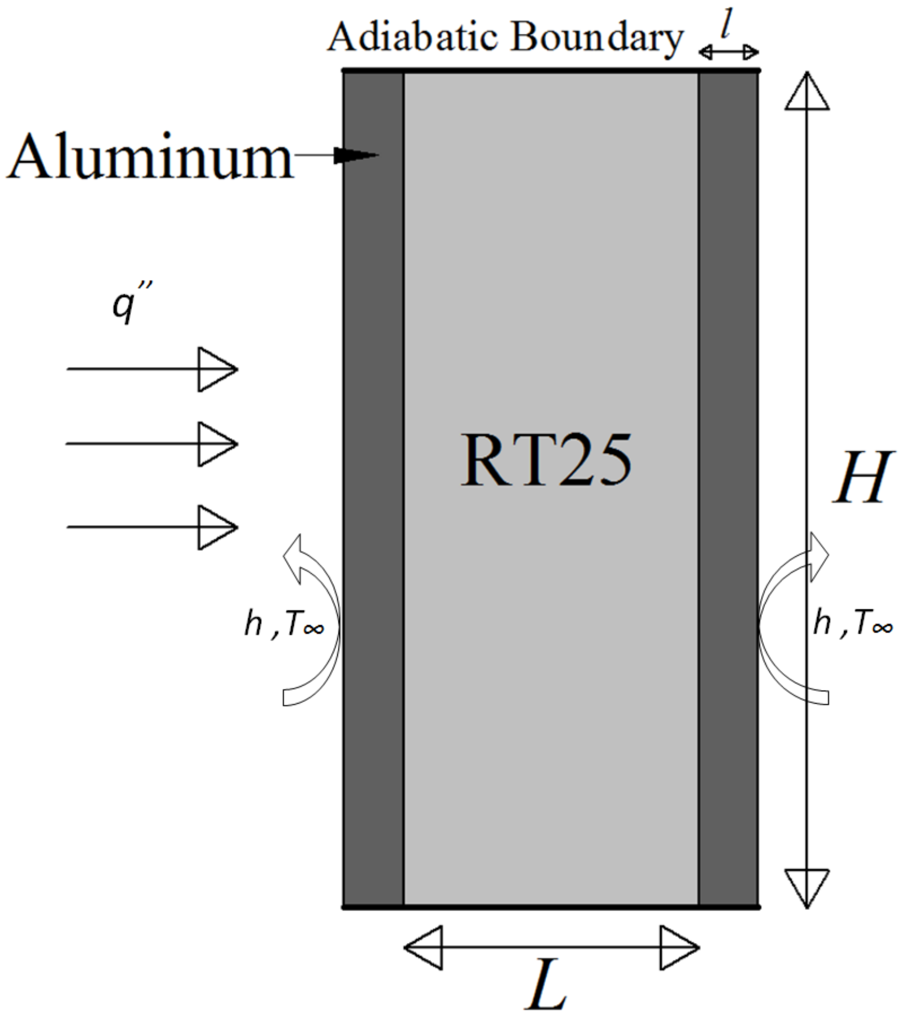
Unfortunately, the efficient of solar PV decreases with an increase in temperature!

PCM can be use to absorb the extra energy during the day, keeping the PV at a lower, more efficient, temperature.

Geometry Studied

- 2D Convection Dominated

Geometry



H = 0.132 m
L = 0.02m

Aluminum thickness l = 0.004 m

The entire PCM is initially solid at room temperature, T_o = 293 K.

At $t = 0$, $q'' = 1000$ W/m^2

Forced convection: ($T_\infty = T_o$)
Left wall: h = 10 W/m^{2}K
right wall: h = 5 W/m^{2}K

- Biwole, P., P. Eclache, and F. Kuznik, Improving the Performance of Solar Panels by the use of Phase-Change Materials, *World Renewable Energy Congress 2011*, Linköping, Sweden, 8 p. (2011)

PCM

The phase change material used in this comparison study is RT25

	Cp (J/kg·K)	k (W/m·K)	ρ (kg/m^3)
Solid RT25	1800	0.19	785
Liquid RT25	2400	0.18	749
Aluminum	903	211	2675
Other Properties of TR25			
L_F = 232000 J/Kg		T_m = 299.75 K	
$\beta = 10^{-3}$ 1/K		$\mu = 1.798 \times 10^{-3}$ kg/m·s	

Numerical Modeling

- 1st Method: Modified Viscosity
  2nd Method: Modified Volume Force

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.

1st: 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

$$C_{p,m} = \frac{C_{p,s} + C_{p,l}}{2} \frac{L_f}{(\Delta T_m)}$$

$C_{p,s}$ = Solid phase C_P
= 1.8 kJ/kg

$C_{p,l}$ = Liquid phase C_P
= 1.8 kJ/kg

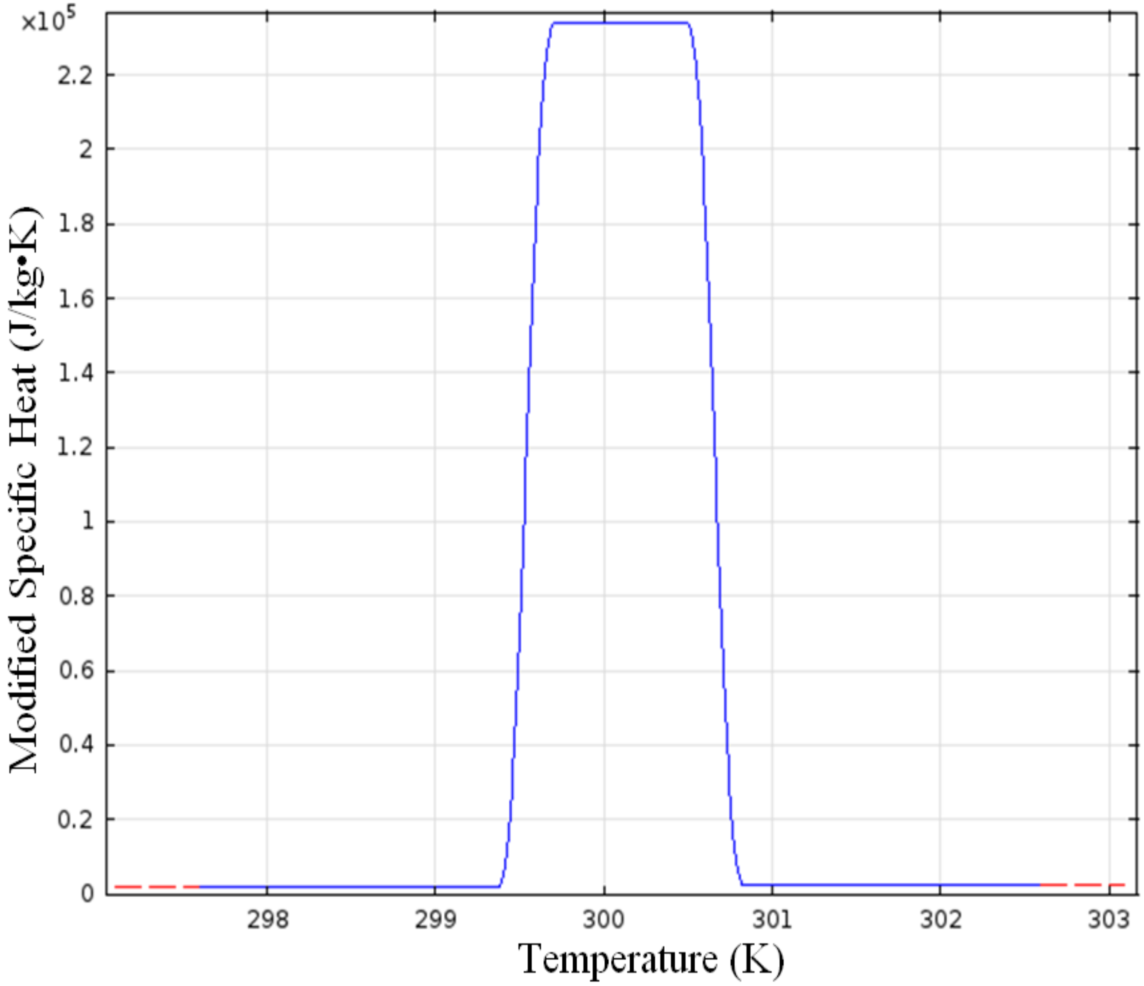
L = Latent heat of fusion
= 232 kJ/kg

ΔT_m = Melting Temperature range
= 1 K

1st: 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.

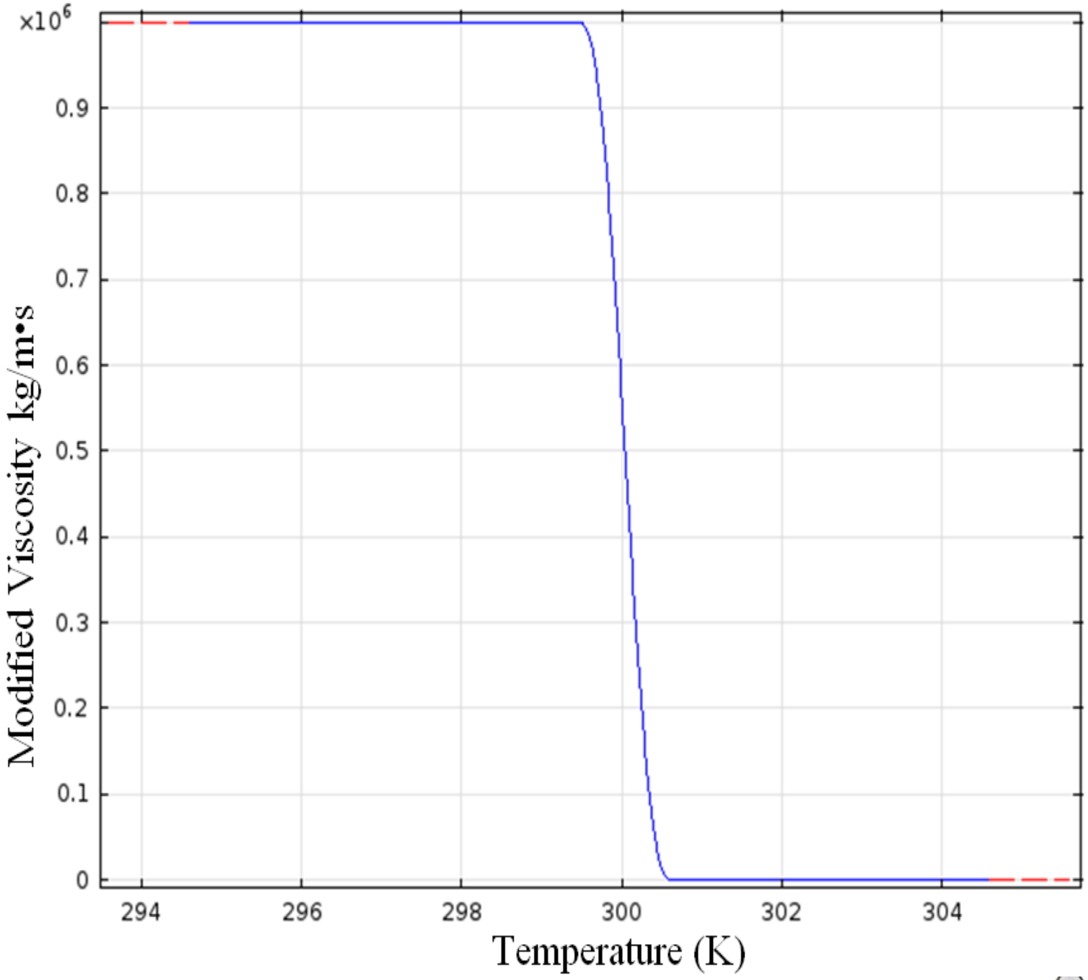


1^{st}: Modified μ

The dynamic viscosity, was input as a piecewise, continuous, second derivative function centered about $T_m + \Delta T/2$.

$$\mu(\mathrm{T}) = \begin{cases} 10^6, & x < T_m + \Delta T/2 \\ \mu_l, & x \geq T_m + \Delta T/2 \end{cases}$$

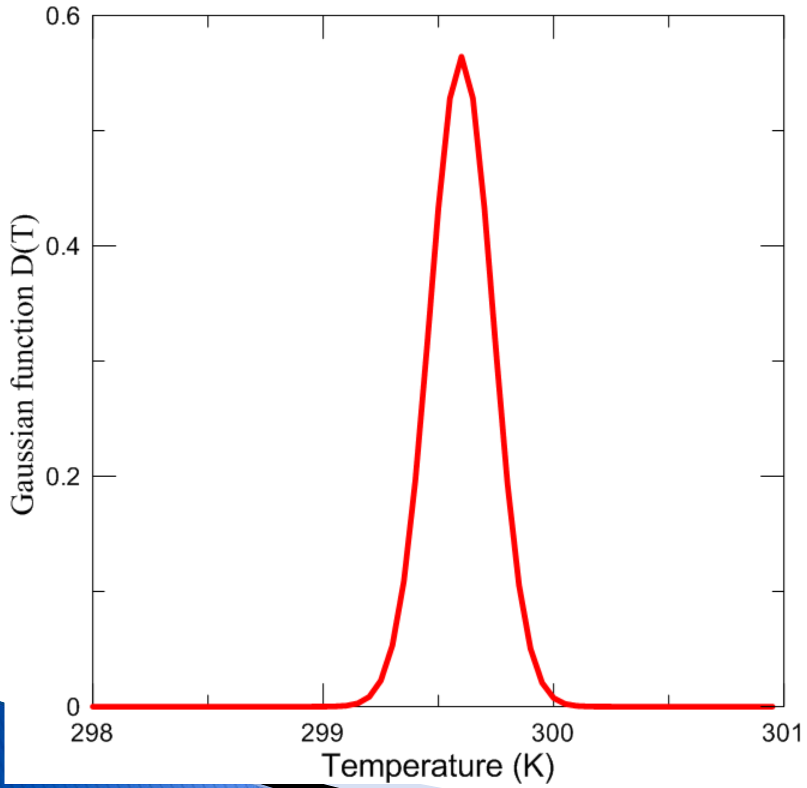
It accounted for the viscosity of the liquid PCM in the melted region and forced the solid PCM to remain fixed by having a solid viscosity of 10^6

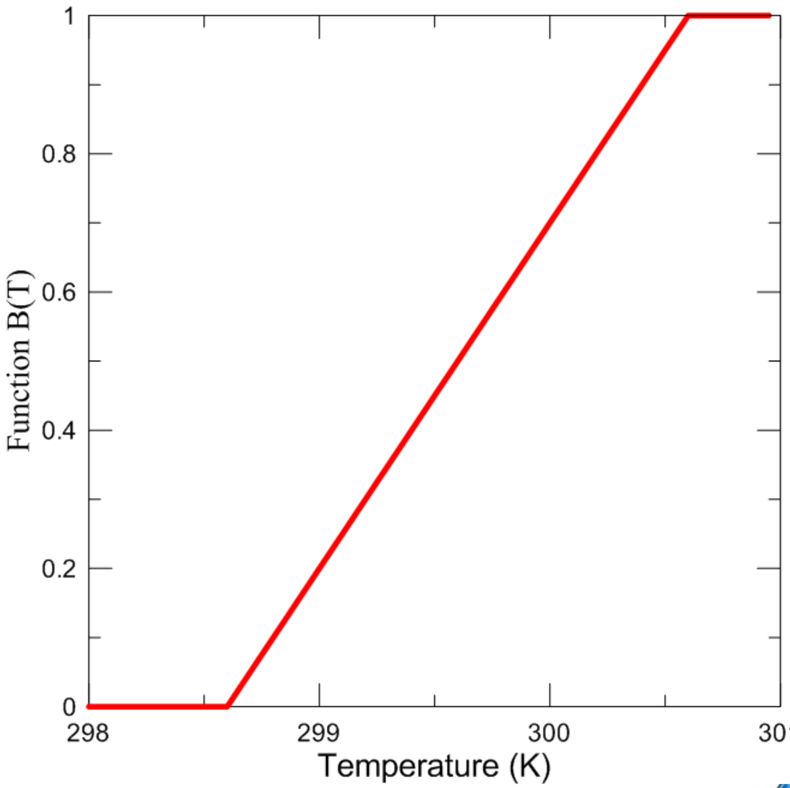


2nd: Defined functions

$$D(\mathrm{T}) = e^{\frac{-(T-T_m)^2}{\Delta T^2}} \Big/ \sqrt{\pi \Delta T^2}$$

$$B(\mathrm{T}) = \begin{cases} 0, & T < (T_m - \Delta T) \\ \dfrac{T - T_m + \Delta T}{2\Delta T}, & (T_m - \Delta T) < T < (T_m + \Delta T) \\ 1, & T > (T_m + \Delta T) \end{cases}$$





2nd: Modified C_p

$$C_p = C_{p,s} + (C_{p,l} - C_{p,s})B(T) + L \cdot D(T)$$

$C_{p,s}$ = Solid phase C_P
= 1.8 kJ/kg

$C_{p,l}$ = Liquid phase C_P
= 1.8 kJ/kg

L = Latent heat of fusion
= 232 kJ/kg

ΔT = Melting Temperature range
= 1 K

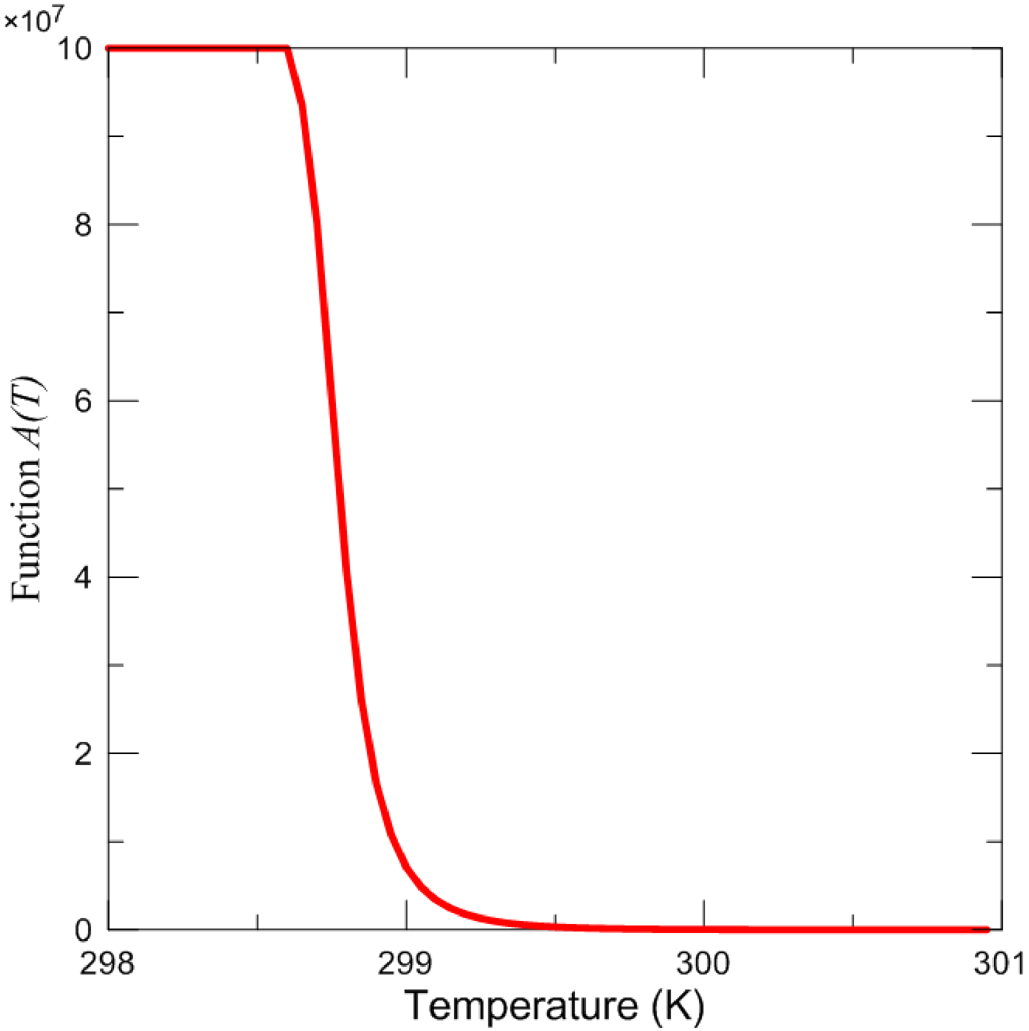
2nd: Modified μ

$$\mu(\mathrm{T}) = \mu_l\left(1 + A(T)\right)$$

with

$$A(T) = \frac{C(1 - B(T))^2}{(B(T)^3 + q)}$$

where C and q are arbitrary constants
$C = 10^5$
$q = 10^{-3}$



Buoyancy Forces

Both methods use the Boussinesq approximation to account for the buoyancy forces in the melted PCM.

This force is added into the model via the volumetric force in the fluid physics interface:

$$\vec{F}_b = \vec{g}\rho_l \beta (T - T_m)$$

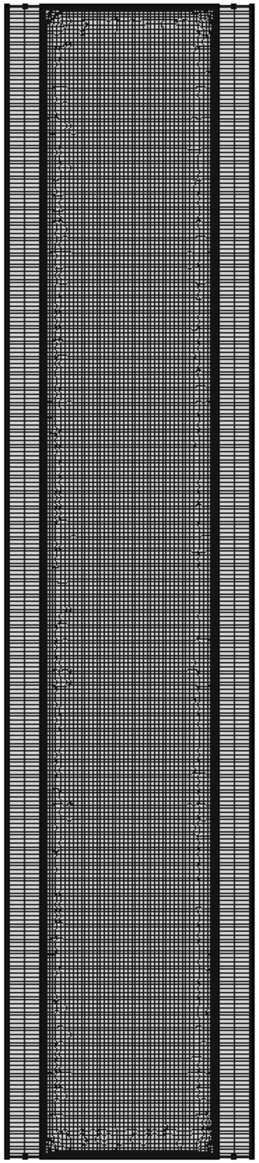
2nd: Modified Navier-Stokes

$$\rho\frac{\partial\vec{u}}{\partial t}+\rho\left(\vec{u}\cdot\nabla\right)\vec{u}-\mu\nabla^{2}\vec{u}=-\nabla P+\vec{F}_b+\vec{F}_a$$

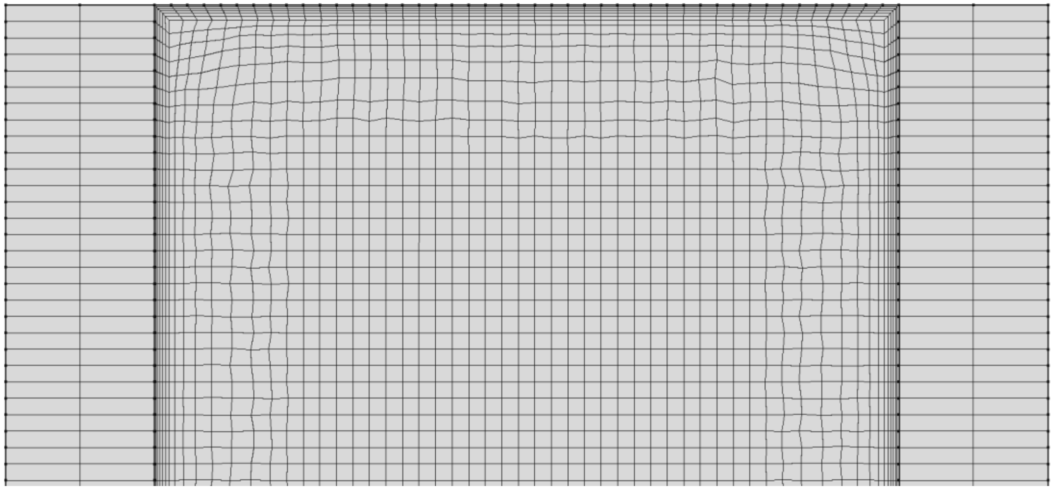
with $\vec{F}_a=-A(T)\cdot\vec{u}$

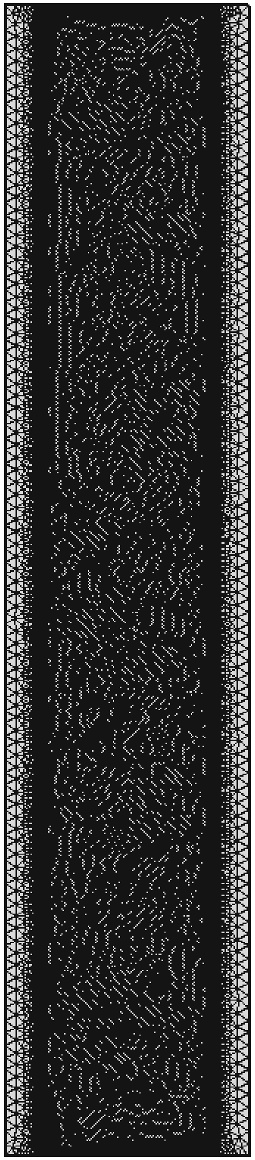
The impact of $\vec{F}_a$ is to dominate every other force terms in the momentum equations when the PCM is solid, speeding up the calculation and effectively forcing a trivial solution of $\vec{u}=0$ in the solid.

Mesh 1



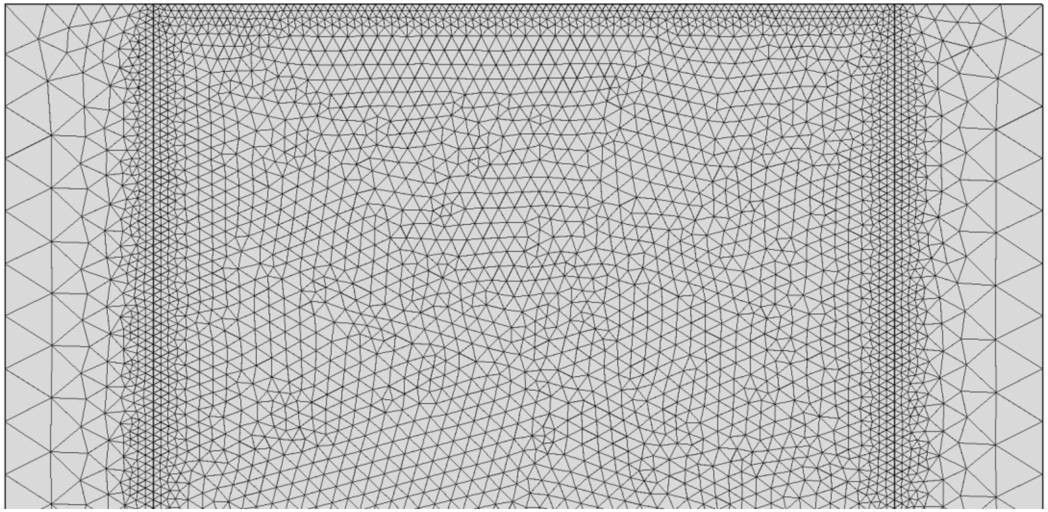
- 2D quadrilateral elements;
- 9200 or 18840 elements were selected (any more elements required simulation longer than a week!);
- Both linear and quadratic elements where used.
- Simulations took an average of 5 to 7 days to run in a Xeon QuadCore.





Mesh 2

- 2D free triangular elements;
- 53 679 elements were selected;
- Only linear elements where used.
- Simulations took an average of 5 to 7 days to run in a Xeon QuadCore.

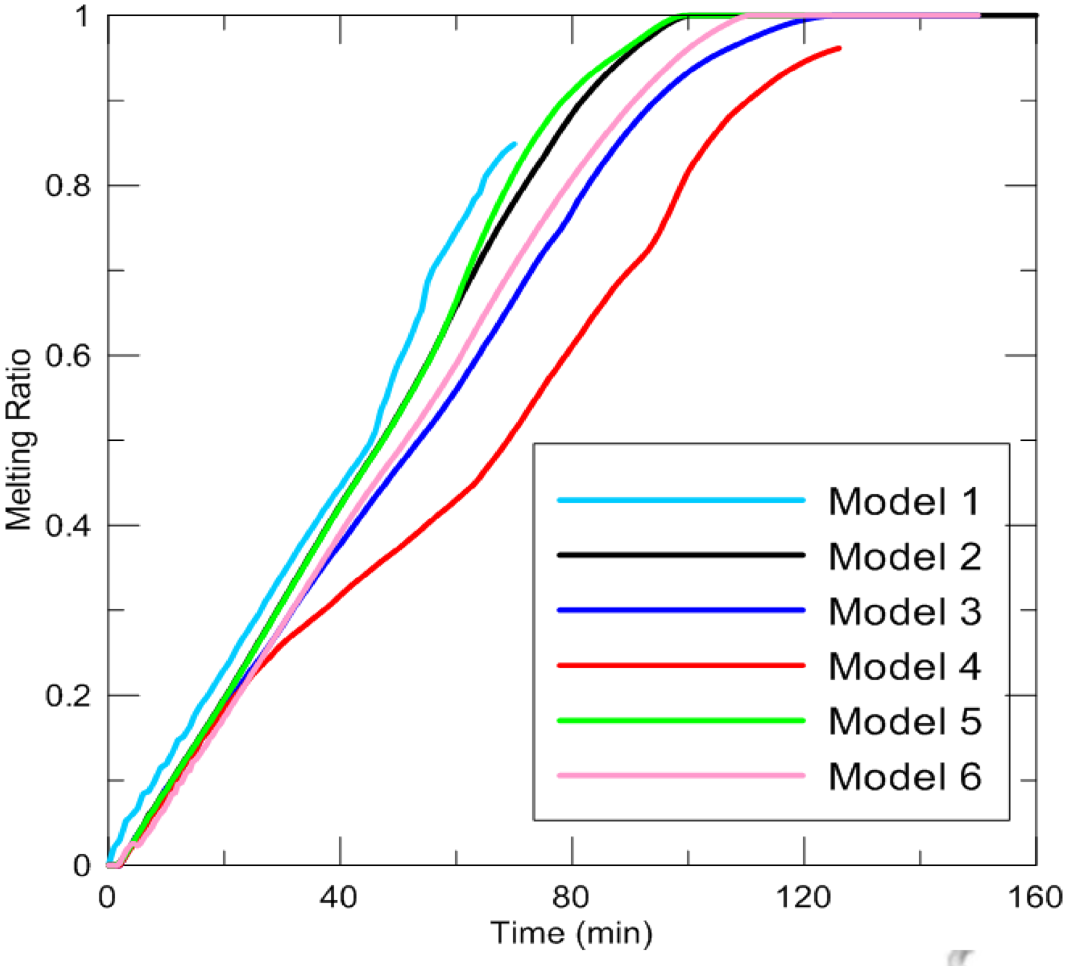


Results

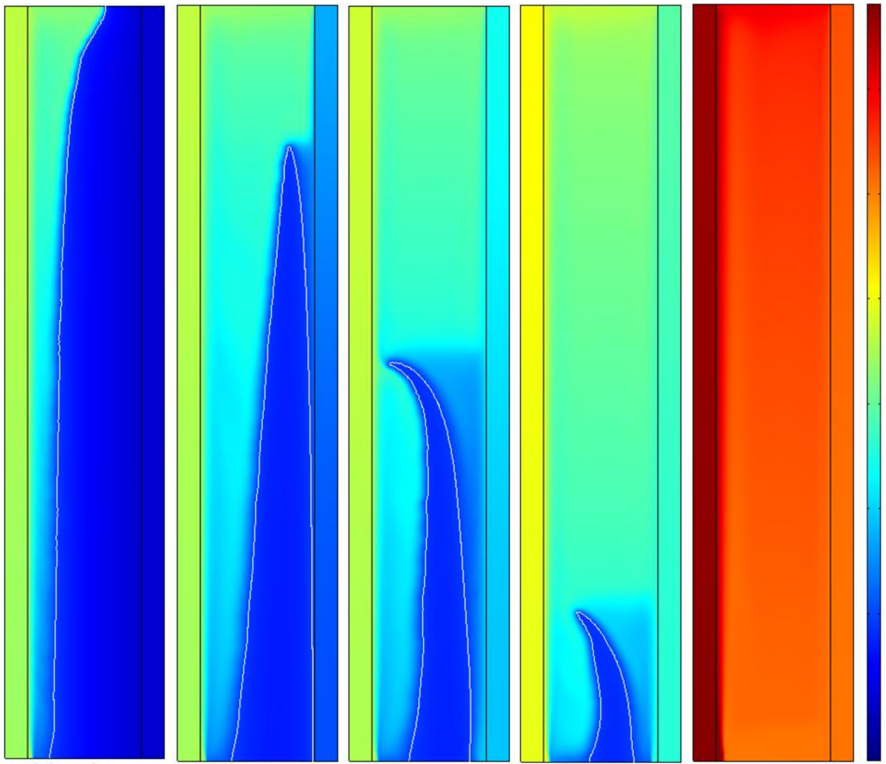
- Comparison

Simulations

Model Number	Brief Description	Temperature Discretization	Number of Elements
~~1~~	~~1st Method~~	~~Linear~~	~~53924~~
2	2nd Method	Linear	53678
3	2nd Method	Quadratic	9200
4	2nd Method	Linear	9200
5	2nd Method ($F_a = 0$)	Linear	53678
6	2nd Method	Quadratic	18840

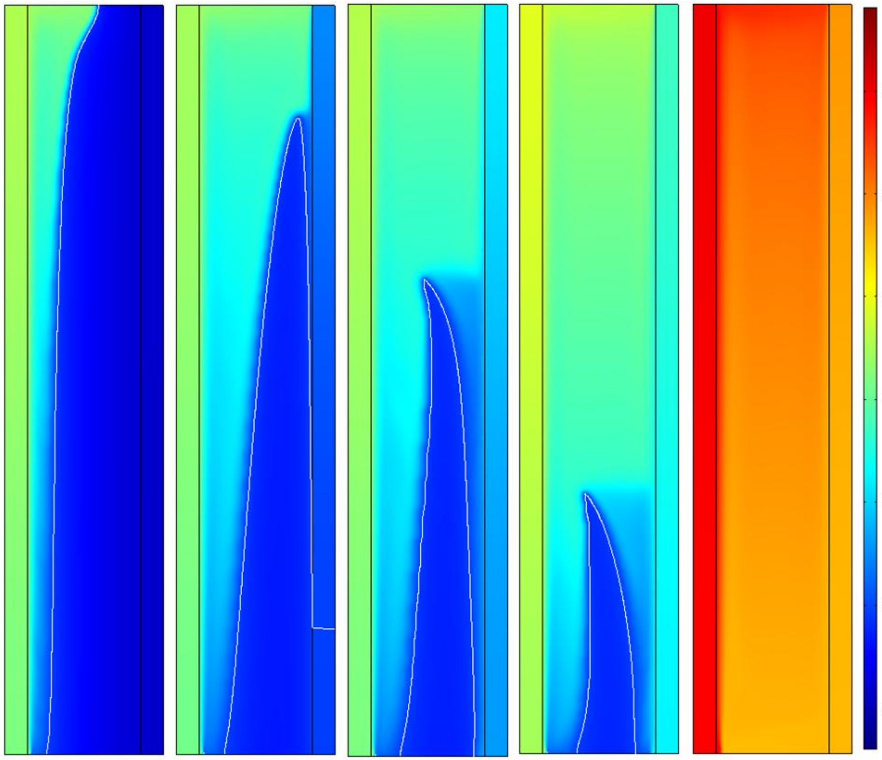


Temperature Profile



30 min 60 min 75 min 90 min 120 min

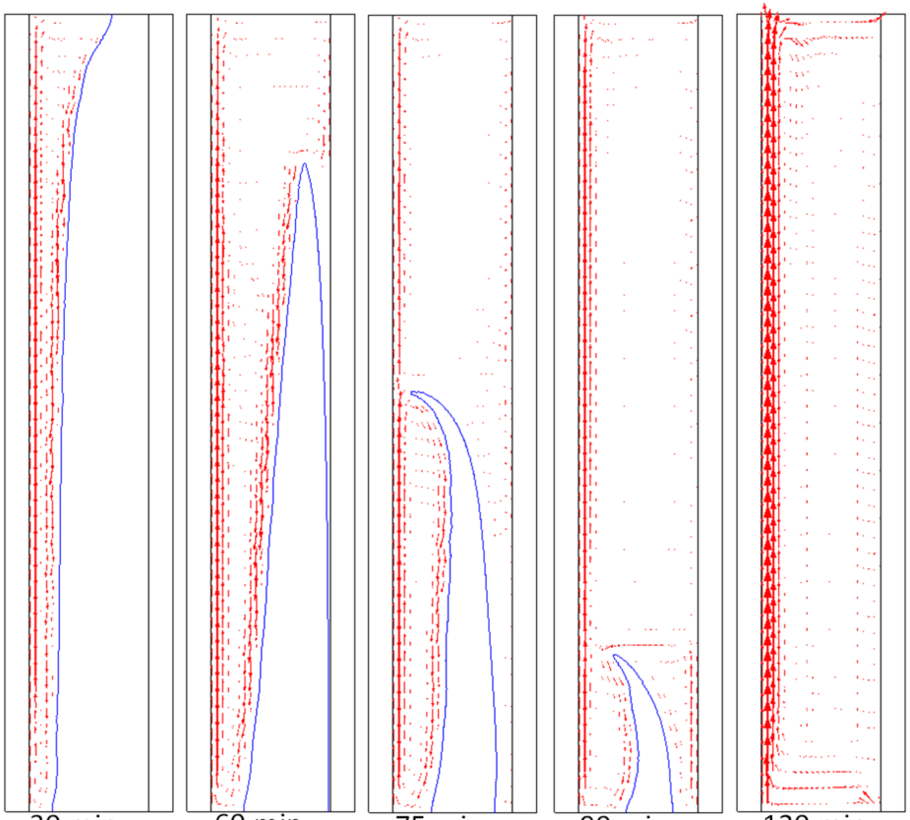
Model 2



30 min 60 min 75 min 90 min 120 min

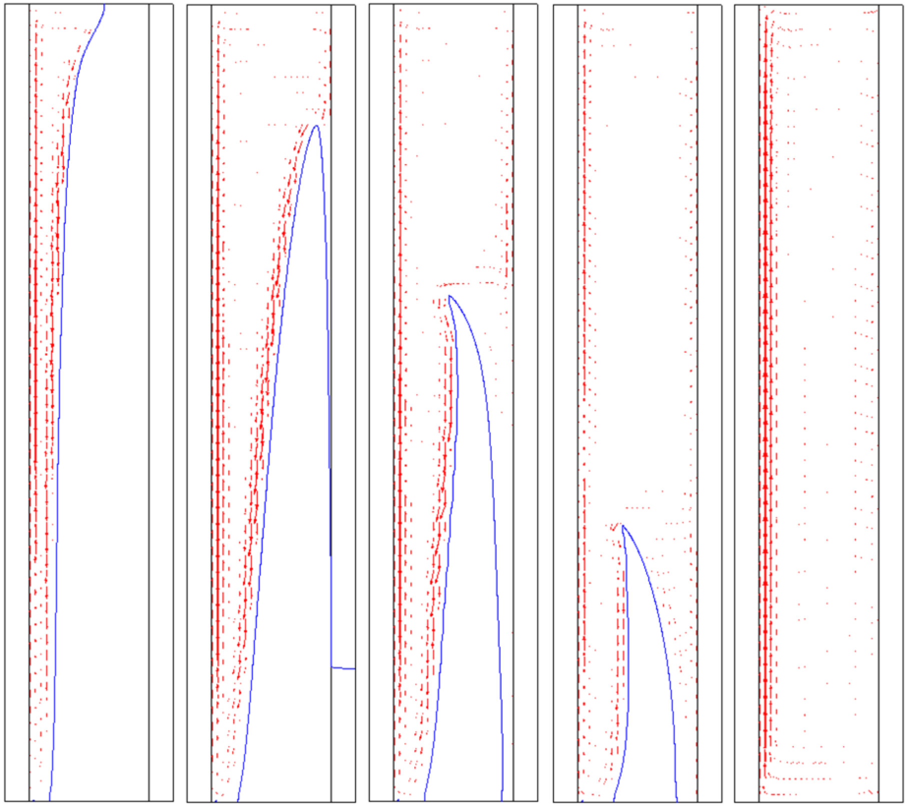
Model 6

Velocity Profile



30 min 60 min 75 min 90 min 120 min

Model 2



30 min 60 min 75 min 90 min 120 min

Model 6

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;

- Between the two methods presented, **the second**, having a more thorough mathematical treatment, with better defined functions, specific heat, viscosity and volume force in the Navier-Stokes equation, provides a more robust method;

- However, the effect of the mesh, and some extra terms incorporated with the 2nd method are still not clearly understood and will require **experimental work** to clearly be understood.