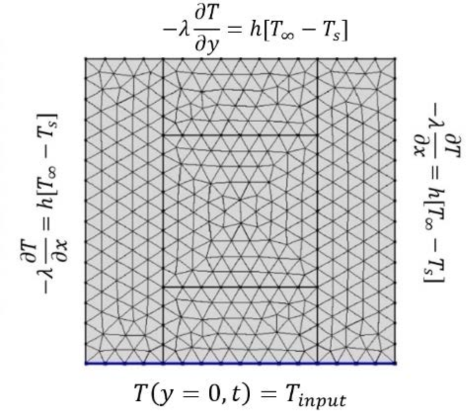
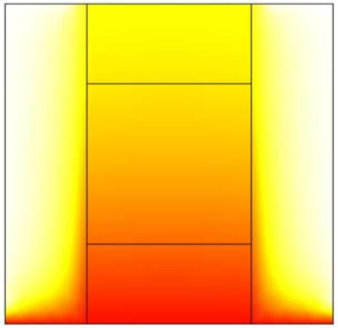
COMSOL Modeling of Temperature Changes in Building Materials Incorporating Phase Change Materials

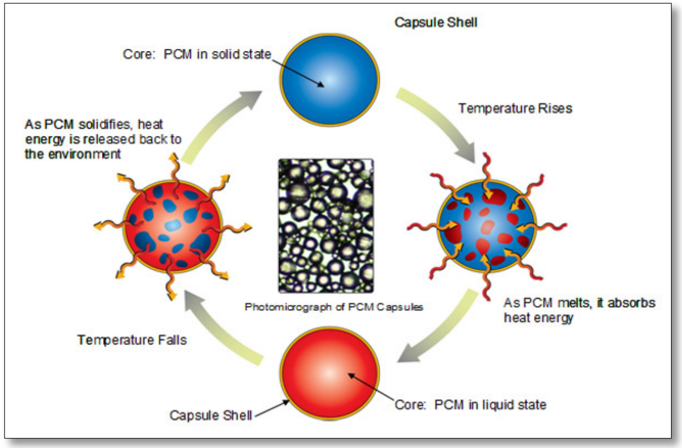




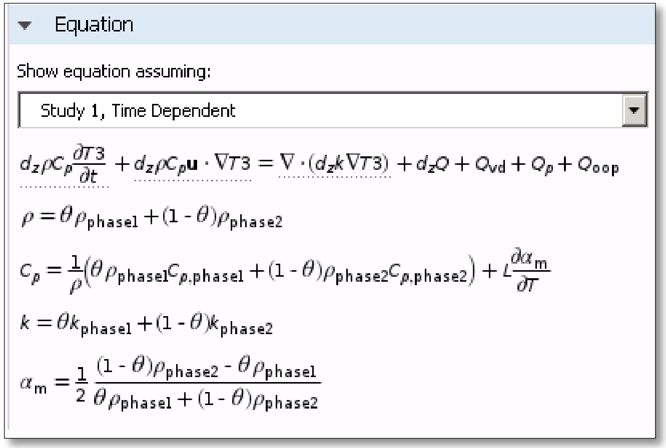
Naser P. Sharifi, Ahsan A. N. Shaikh, Aaron R. Sakulich

Overview

1- PCMs



2- COMSOL Modeling



Show equation assuming:

Study 1, Time Dependent

$$d_z\rho C_p\frac{\partial T3}{\partial t} + d_z\rho C_p\mathbf{u}\cdot\nabla T3 = \nabla\cdot(d_z k\nabla T3) + d_z Q + Q_{\mathrm{vd}} + Q_p + Q_{\mathrm{oop}}$$

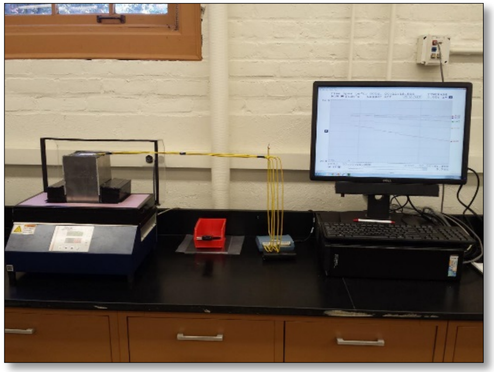
$$\rho = \theta\rho_{\mathrm{phase1}} + (1-\theta)\rho_{\mathrm{phase2}}$$

$$C_p = \frac{1}{\rho}\left(\theta\rho_{\mathrm{phase1}}C_{p,\mathrm{phase1}} + (1-\theta)\rho_{\mathrm{phase2}}C_{p,\mathrm{phase2}}\right) + L\frac{\partial\alpha_{\mathrm{m}}}{\partial T}$$

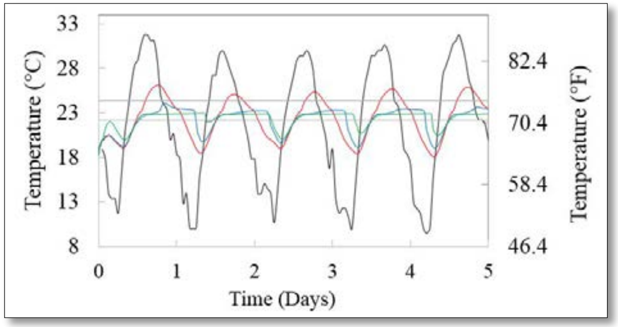
$$k = \theta k_{\mathrm{phase1}} + (1-\theta)k_{\mathrm{phase2}}$$

$$\alpha_{\mathrm{m}} = \frac{1}{2}\frac{(1-\theta)\rho_{\mathrm{phase2}} - \theta\rho_{\mathrm{phase1}}}{\theta\rho_{\mathrm{phase1}} + (1-\theta)\rho_{\mathrm{phase2}}}$$

3- Model Validating



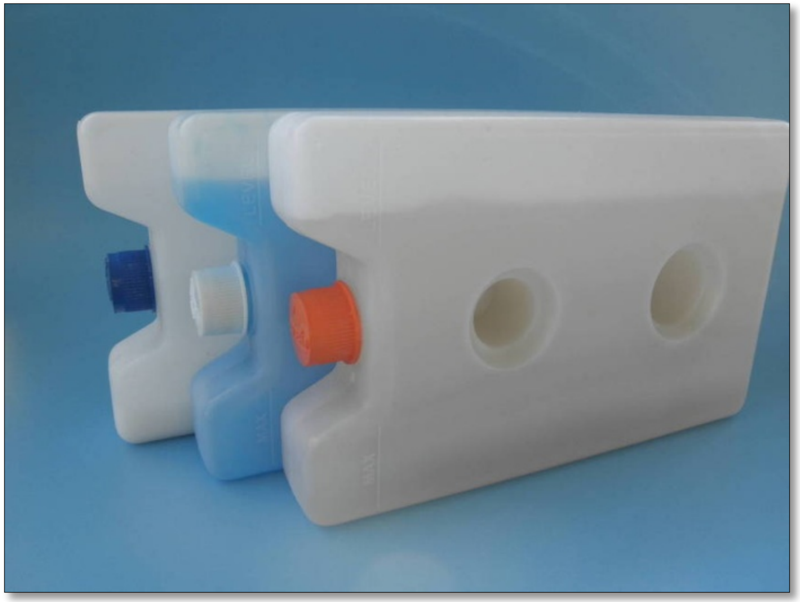
4- Actual Results



1- Phase Change Materials

- Phase Change Materials:
  - Specific melting point
  - High latent heat of fusion

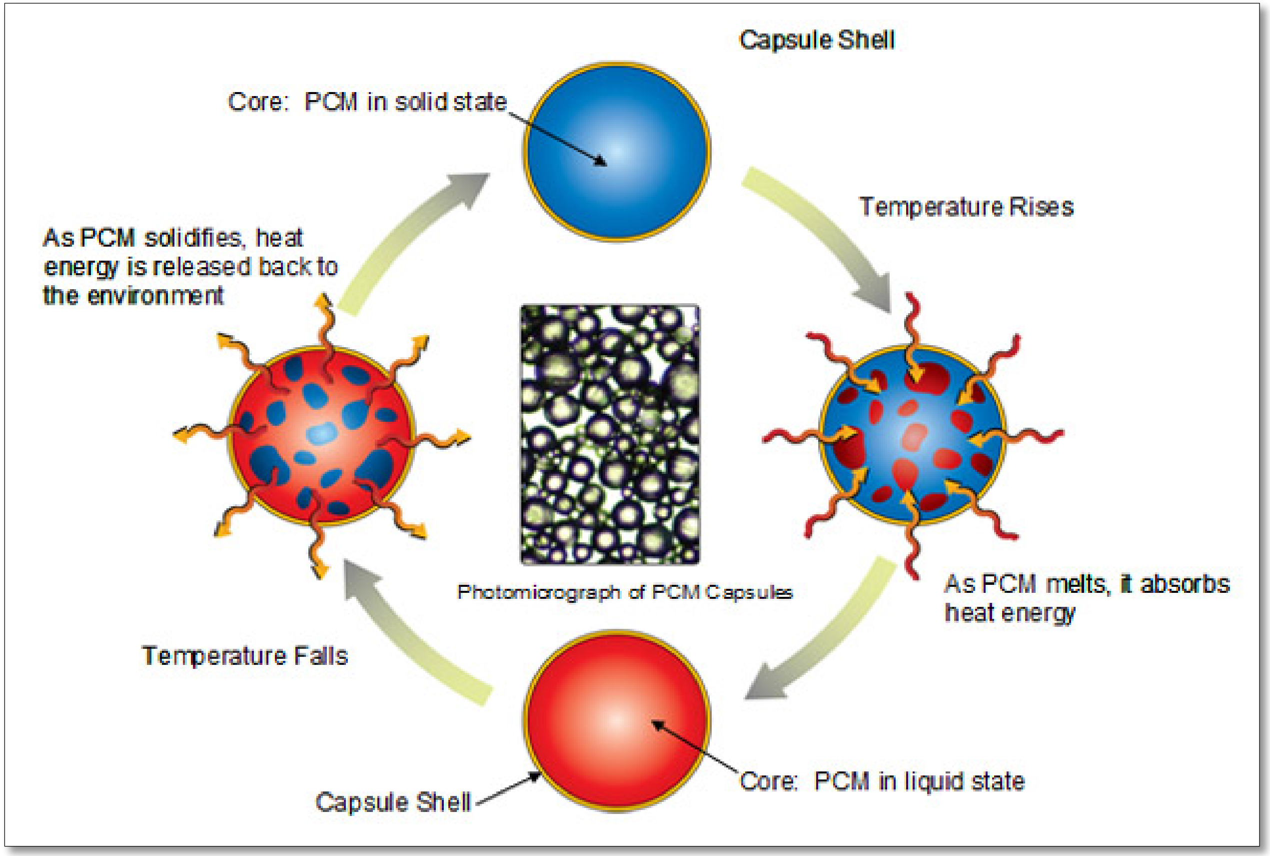
http://www.pcmproducts.net



http://www.thomasnet.com

1- Phase Change Materials

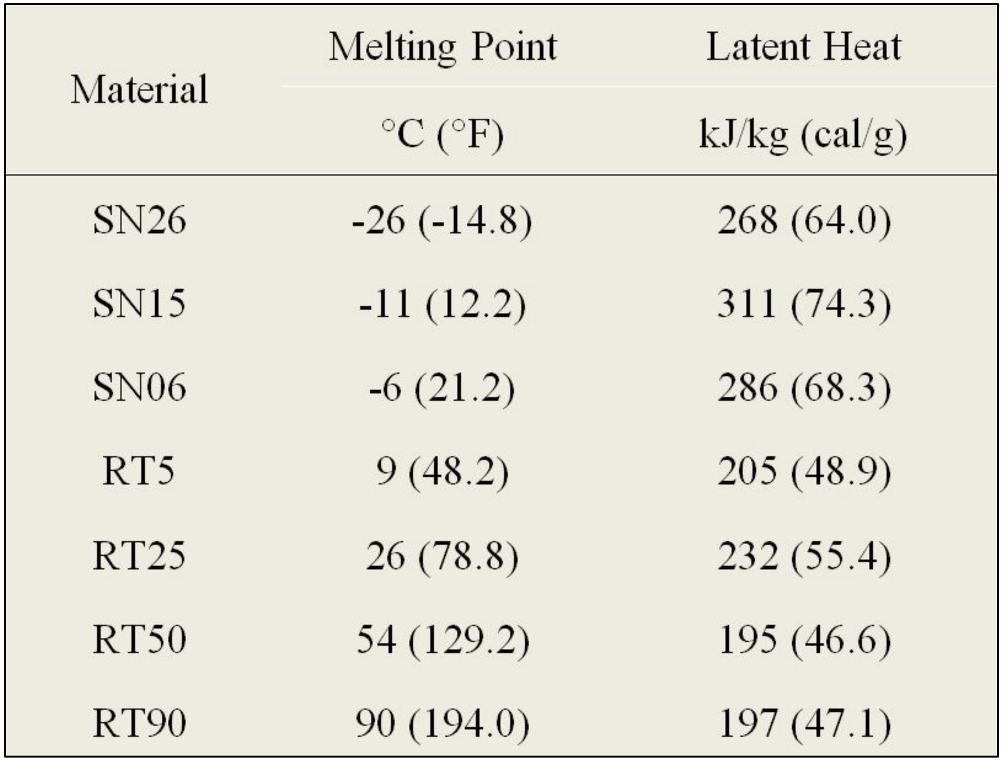
- Absorbs heat; Temperature remains constant



http://musingsonentropy.wordpress.com

1- Phase Change Materials

- PCMs are passive interior heat energy storage units



Material	Melting Point °C (°F)	Latent Heat kJ/kg (cal/g)
SN26	-26 (-14.8)	268 (64.0)
SN15	-11 (12.2)	311 (74.3)
SN06	-6 (21.2)	286 (68.3)
RT5	9 (48.2)	205 (48.9)
RT25	26 (78.8)	232 (55.4)
RT50	54 (129.2)	195 (46.6)
RT90	90 (194.0)	197 (47.1)

1- Phase Change Materials

- Desire for more energy efficient buildings
- Increase occupant comfort
- Environmentally friendly construction

http://www.drlanguell.com

2- COMSOL Modeling

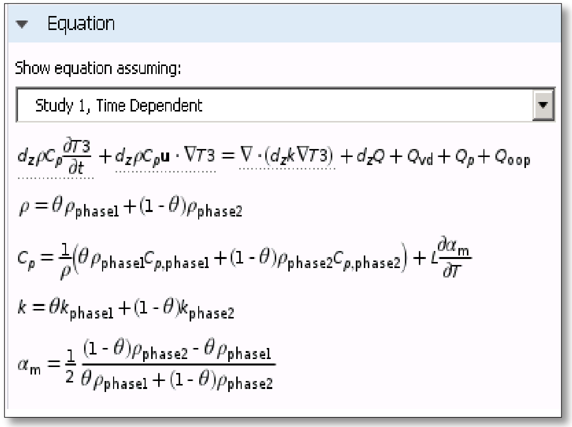
The question is:

- What is the best Melting Temperature for buildings that are located in different cities?
- What is the optimum PCM percentage?
- How effective is the PCM?
- How much energy of HVAC system will be saved?

2- COMSOL Modeling

Using COMSOL to model temperature changes in structural elements

Step 1: Modeling porous media and PCM



Show equation assuming:

Study 1, Time Dependent

$$d_z \rho C_p \frac{\partial T3}{\partial t} + d_z \rho C_p \mathbf{u} \cdot \nabla T3 = \nabla \cdot (d_z k \nabla T3) + d_z Q + Q_{\mathrm{vd}} + Q_p + Q_{\mathrm{oop}}$$

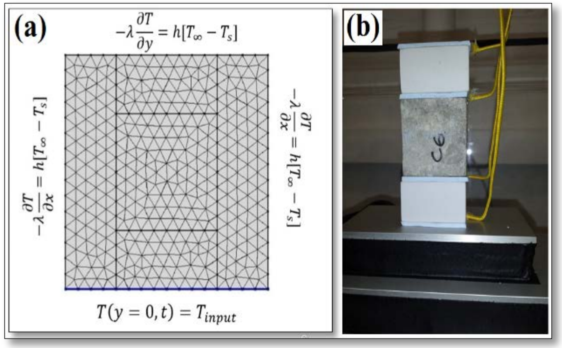
$$\rho = \theta \rho_{\mathrm{phase1}} + (1 - \theta) \rho_{\mathrm{phase2}}$$

$$C_p = \frac{1}{\rho}\left(\theta \rho_{\mathrm{phase1}} C_{p,\mathrm{phase1}} + (1 - \theta) \rho_{\mathrm{phase2}} C_{p,\mathrm{phase2}}\right) + L \frac{\partial \alpha_{\mathrm{m}}}{\partial T}$$

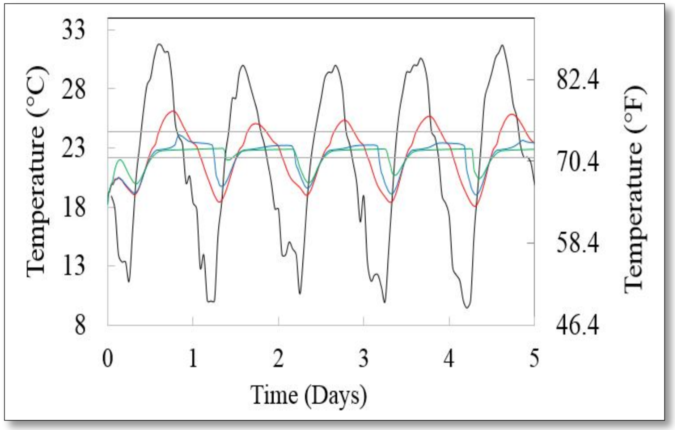
$$k = \theta k_{\mathrm{phase1}} + (1 - \theta) k_{\mathrm{phase2}}$$

$$\alpha_{\mathrm{m}} = \frac{1}{2} \frac{(1 - \theta) \rho_{\mathrm{phase2}} - \theta \rho_{\mathrm{phase1}}}{\theta \rho_{\mathrm{phase1}} + (1 - \theta) \rho_{\mathrm{phase2}}}$$

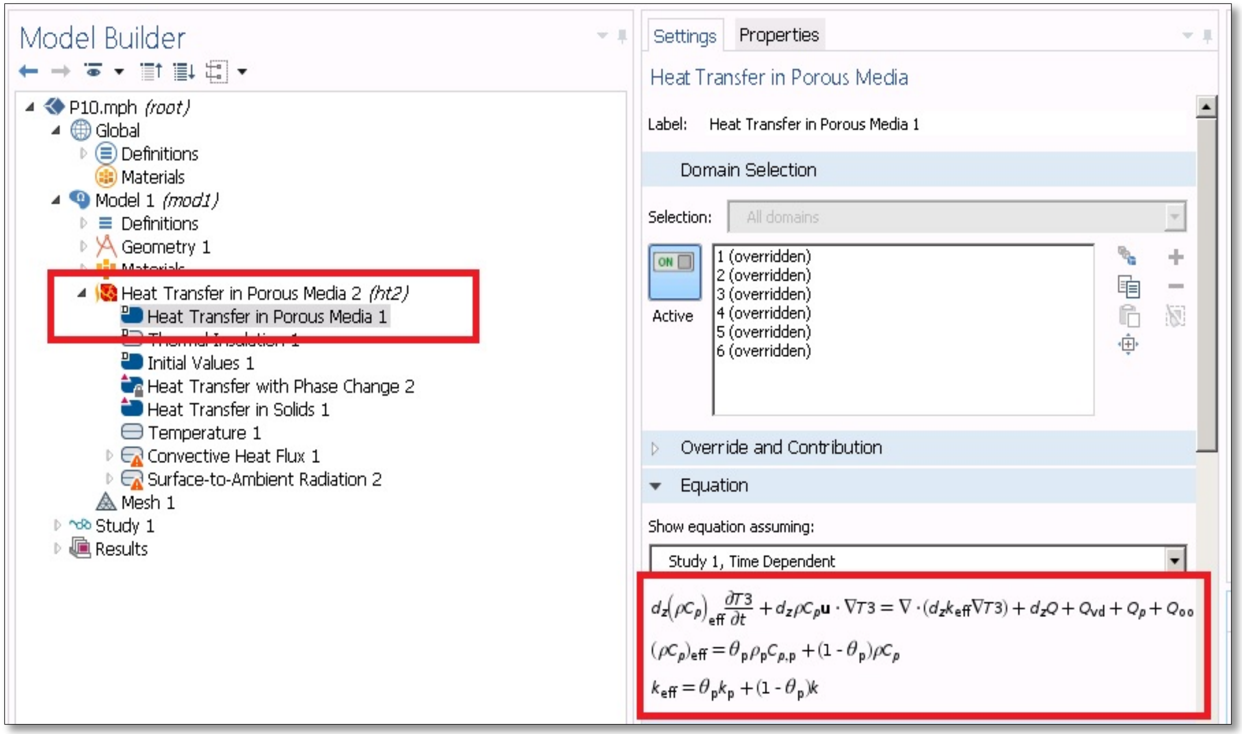
Step 2: Validating the Model



Step 3: Using real temperature profiles of different cities



Porous Media



Heat Transfer in Porous Media

Label: Heat Transfer in Porous Media 1

Selection: All domains

1 (overridden)
2 (overridden)
3 (overridden)
4 (overridden)
5 (overridden)
6 (overridden)

Show equation assuming: Study 1, Time Dependent

$$d_z(\rho C_p)_{\mathrm{eff}}\frac{\partial T3}{\partial t} + d_z\rho C_p\mathbf{u}\cdot\nabla T3 = \nabla\cdot(d_z k_{\mathrm{eff}}\nabla T3) + d_z Q + Q_{\mathrm{vd}} + Q_p + Q_{\mathrm{oo}}$$

$$(\rho C_p)_{\mathrm{eff}} = \theta_{\mathrm{p}}\rho_{\mathrm{p}}C_{p,\mathrm{p}} + (1-\theta_{\mathrm{p}})\rho C_p$$

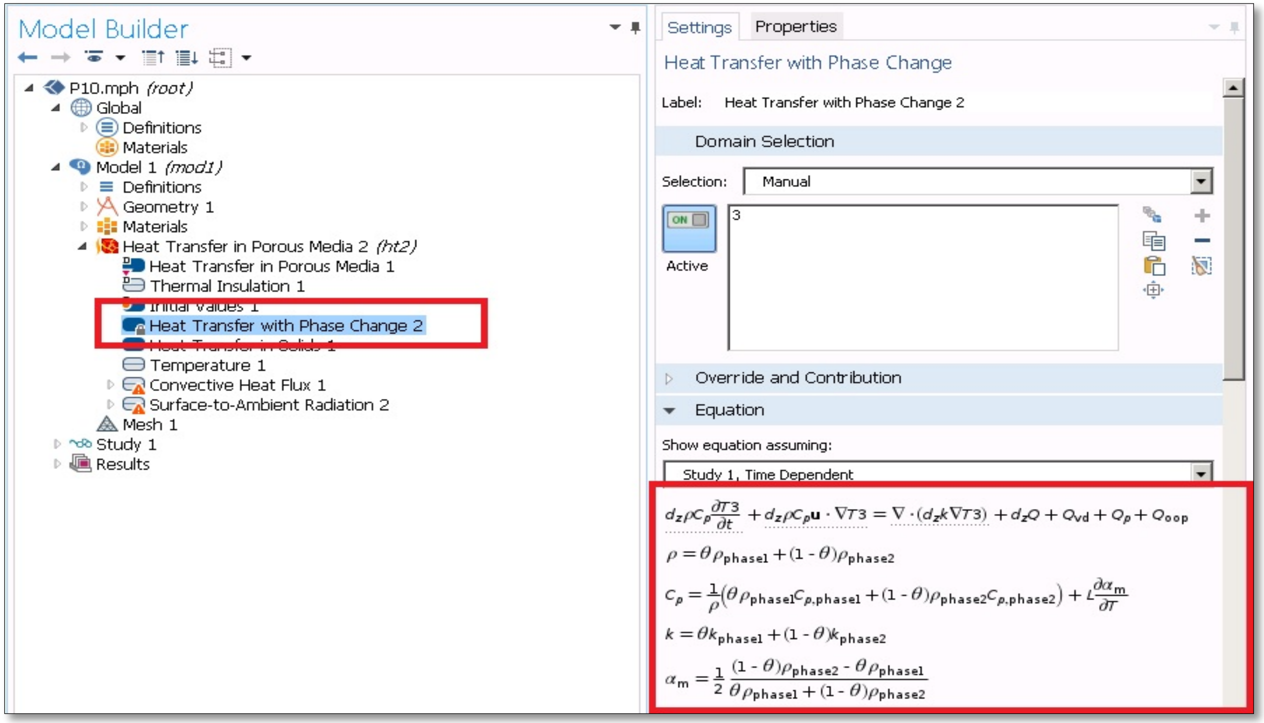
$$k_{\mathrm{eff}} = \theta_{\mathrm{p}}k_{\mathrm{p}} + (1-\theta_{\mathrm{p}})k$$

θ_m: Volume fraction of mortar

$(1-\theta_m)$: Volume fraction of the porosity (the volume fraction filled with PCM)

$$\lambda_{eff} = \lambda_m\theta_m + \lambda_{PCM}(1-\theta_m) \qquad \left(\rho C_p\right)_{eff} = \rho_m C_{p,m}\theta_m + \rho_{PCM}C_{p,PCM}(1-\theta_m)$$

Phase Change



Heat Transfer with Phase Change

Label: Heat Transfer with Phase Change 2

Domain Selection

Selection: Manual

3

Show equation assuming: Study 1, Time Dependent

$$d_z\rho C_p\frac{\partial T3}{\partial t}+d_z\rho C_p\mathbf{u}\cdot\nabla T3=\nabla\cdot(d_zk\nabla T3)+d_zQ+Q_{\mathrm{vd}}+Q_p+Q_{\mathrm{oop}}$$

$$\rho=\theta\rho_{\mathrm{phase1}}+(1-\theta)\rho_{\mathrm{phase2}}$$

$$C_p=\frac{1}{\rho}\left(\theta\rho_{\mathrm{phase1}}C_{p,\mathrm{phase1}}+(1-\theta)\rho_{\mathrm{phase2}}C_{p,\mathrm{phase2}}\right)+L\frac{\partial\alpha_{\mathrm{m}}}{\partial T}$$

$$k=\theta k_{\mathrm{phase1}}+(1-\theta)k_{\mathrm{phase2}}$$

$$\alpha_{\mathrm{m}}=\frac{1}{2}\frac{(1-\theta)\rho_{\mathrm{phase2}}-\theta\rho_{\mathrm{phase1}}}{\theta\rho_{\mathrm{phase1}}+(1-\theta)\rho_{\mathrm{phase2}}}$$

β: Volume fraction of PCM at phase 1

(1-β): Volume fraction of PCM at phase 2

$$\rho_{PCM}=\rho_{phase1}\beta+\rho_{phase2}(1-\beta)$$

$$\lambda_{PCM}=\lambda_{phase1}\beta+\lambda_{phase2}(1-\beta)$$

$$C_{p,PCM}=\frac{1}{\rho_{PCM}}(\rho_{phase1}C_{p,phase1}\beta$$

$$+\rho_{phase2}C_{p,phase2}(1-\beta))+L\frac{\partial\alpha_m}{\partial T}$$

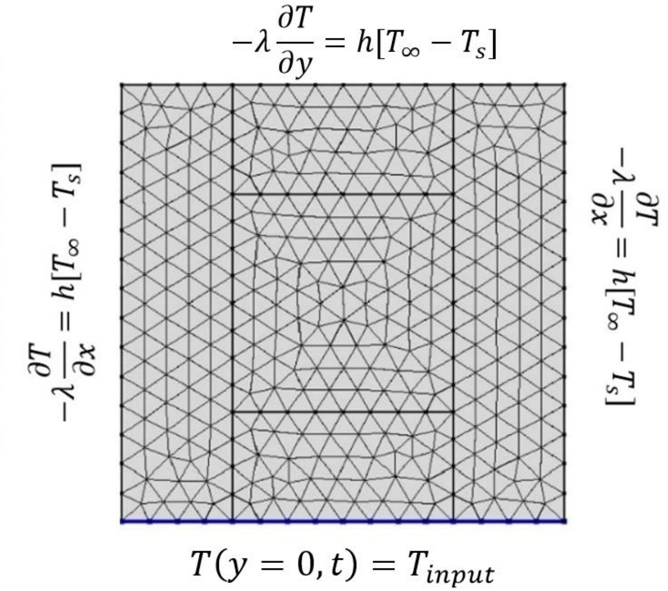
2- COMSOL Modeling

Conduction Heat Transfer: $$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=\frac{\rho C_p}{\lambda}\frac{\partial T}{\partial t}$$

Boundary Condition: $$\begin{cases} -\lambda\dfrac{\partial T}{\partial x}=h[T_\infty - T_s] \\ -\lambda\dfrac{\partial T}{\partial y}=h[T_\infty - T_s] \end{cases}$$

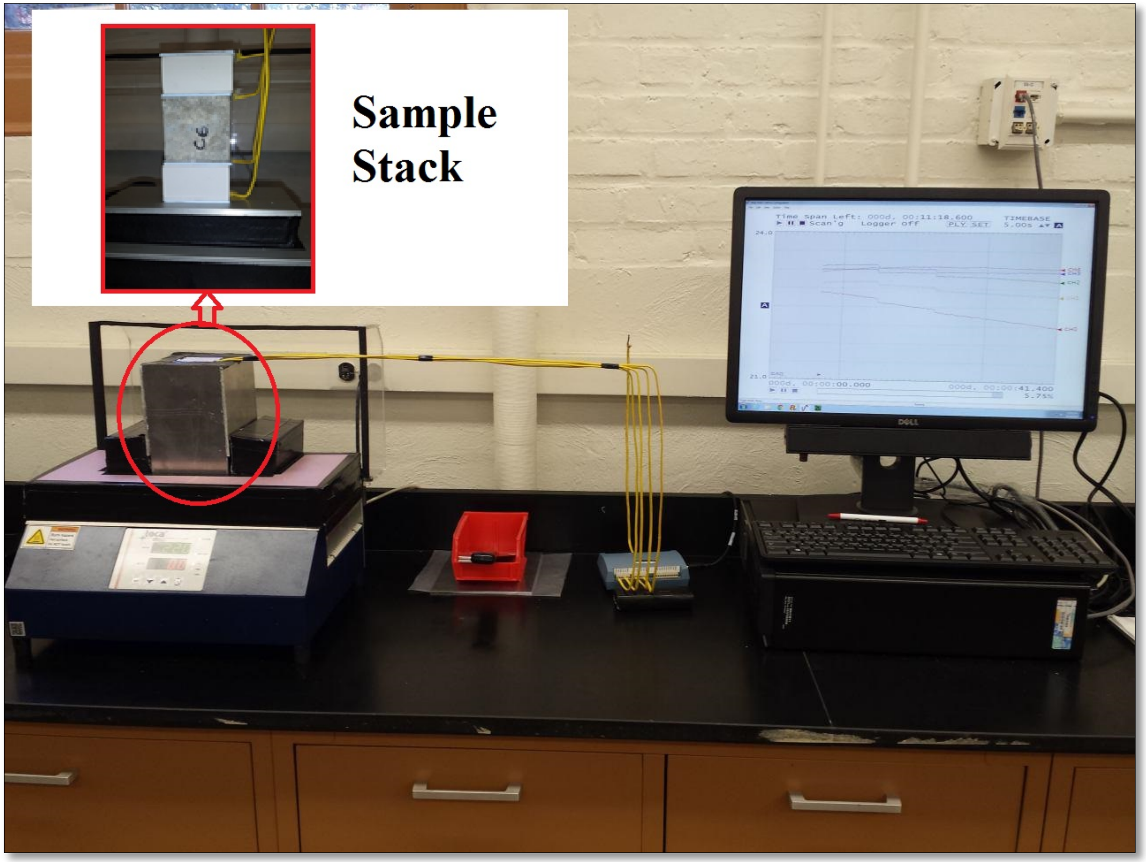
Initial Condition: $T(x,t=0)=T_R$

Applying Temp.: $T(y=0,t)=T_{input}$

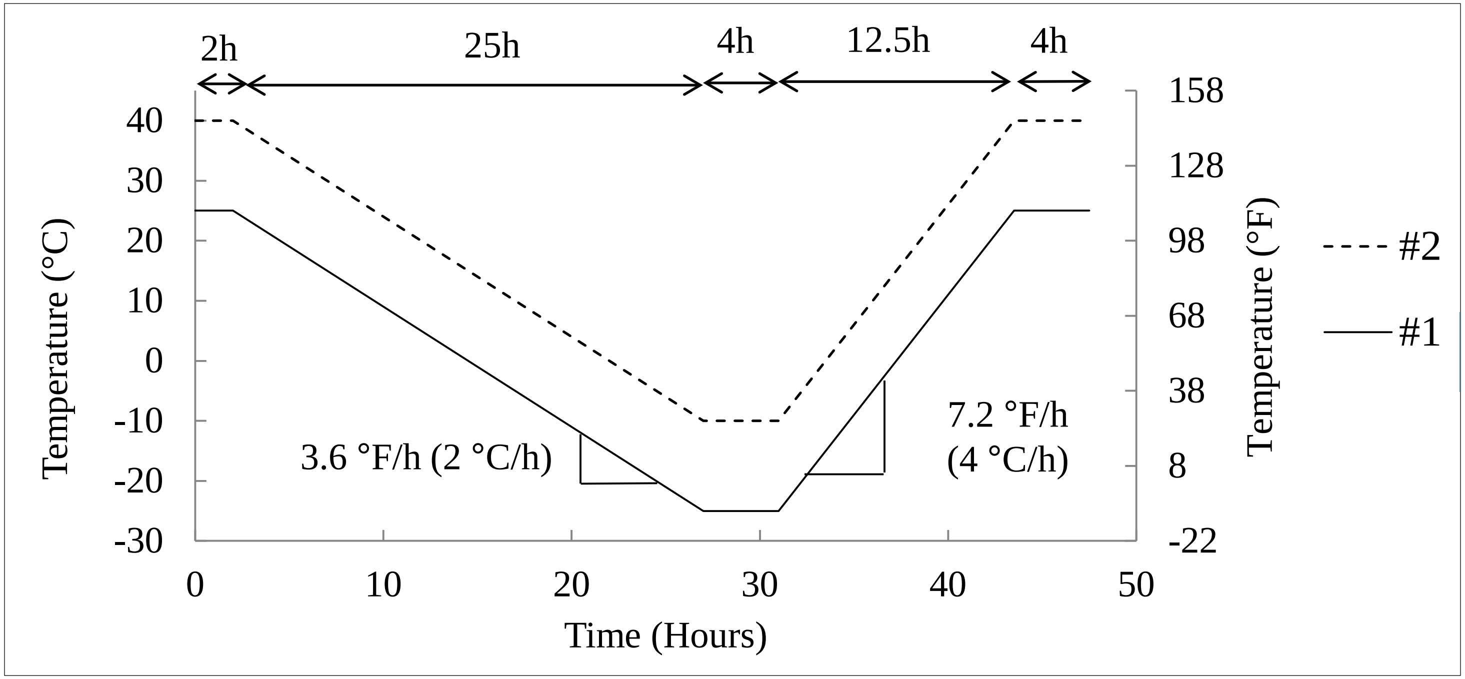


Guarded Longitudinal Calorimeter

- Cold Plate
- Sample Stack
- Insolation
- Thermocouples
- Data Acquisition
- Computer

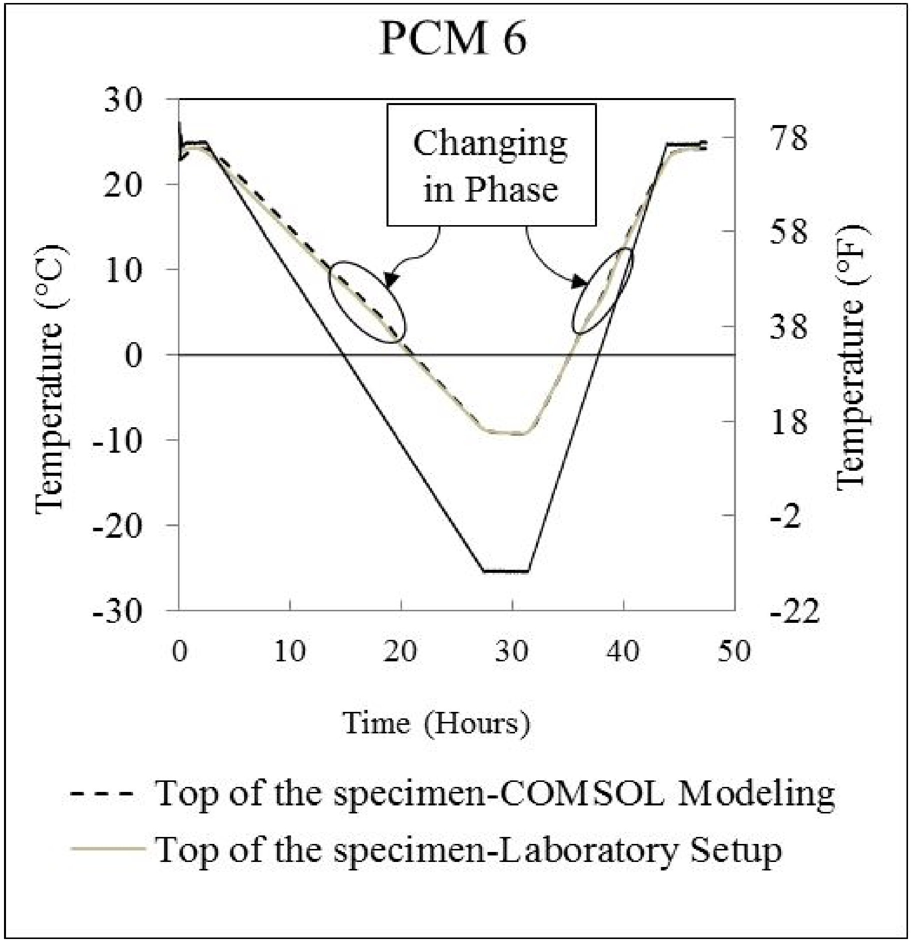


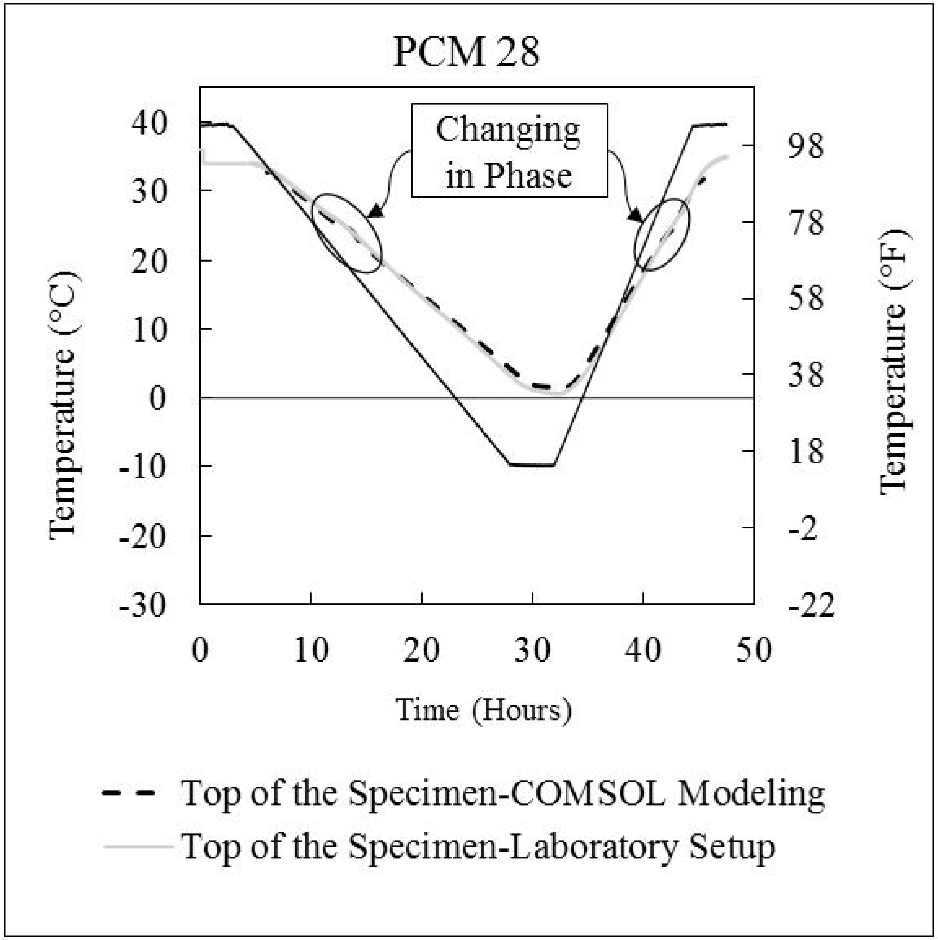
Applied Temperature Profiles



Number 1 for sample with PCM 6
Number 2 for sample with PCM 28

Comparing COMSOL simulation and laboratory experiment

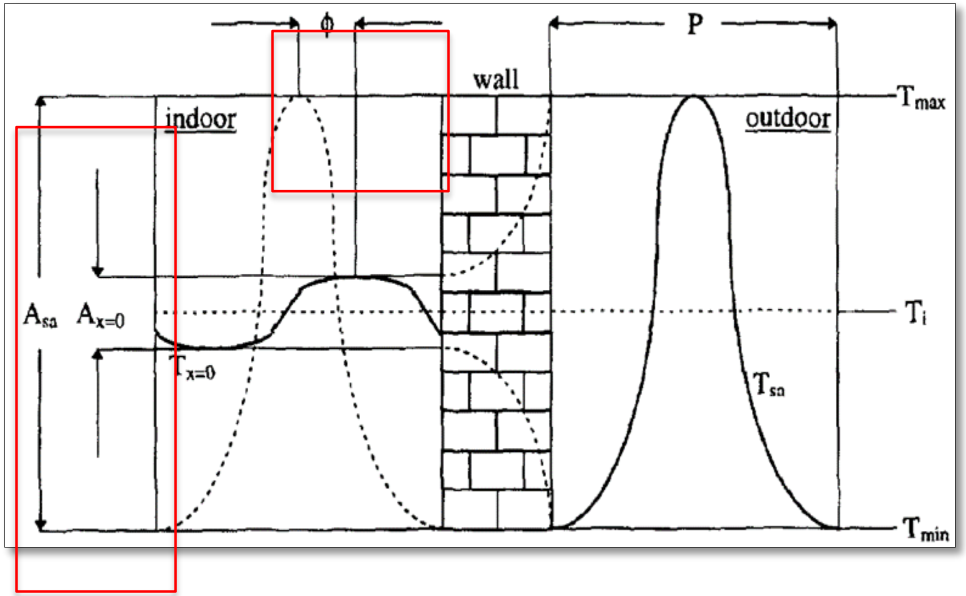




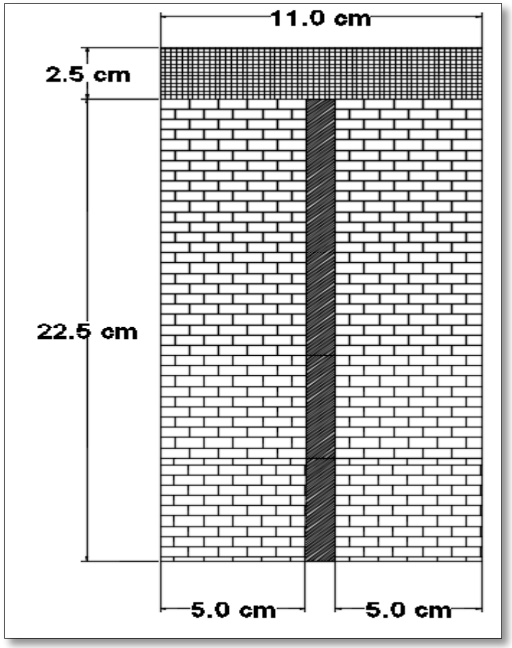
4- Actual Results

Effect of different PCM percentages on the:

1) Time Lag 2) Decrement Factor (f)



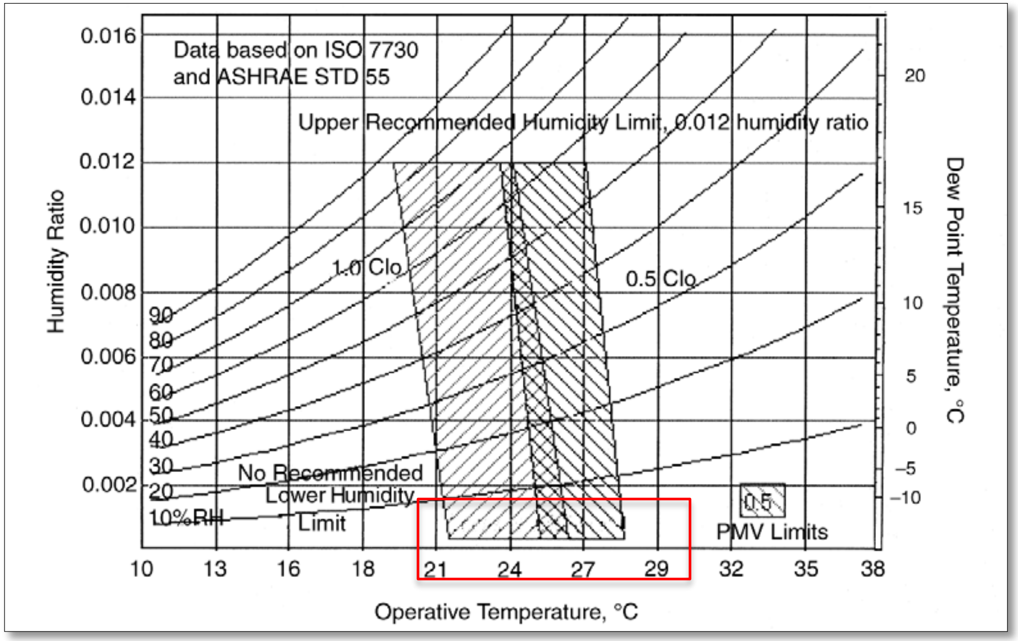
$$f = \frac{A_{x=0}}{A_{sa}}$$



Wall Cross Section

4- Actual Results

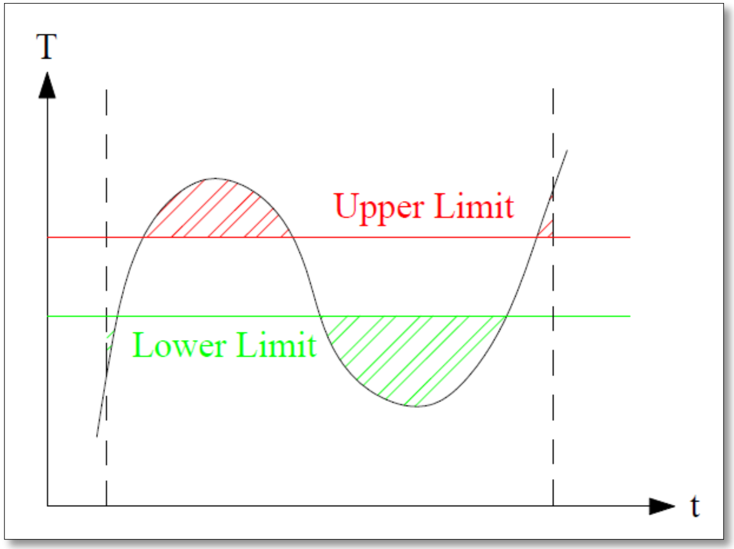
3) Duration of being in comfort zone



Comfort Zone:

22 °C to 26 °C (71.6 °F to 78.8 °F)

4) Energy required by HVAC

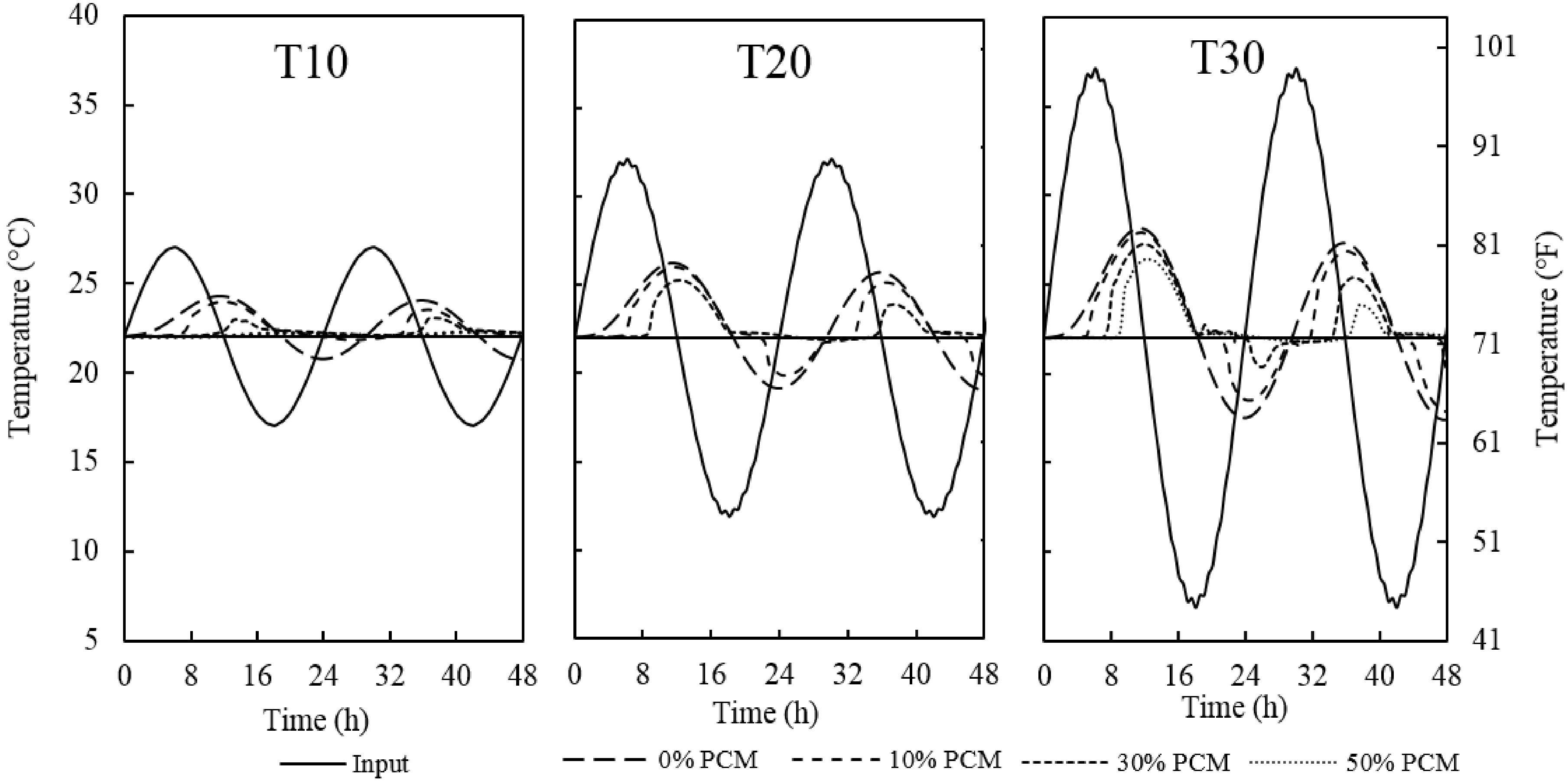


$$\frac{dQ}{dt} = hA(T_R - T_s) \rightarrow$$

$$Q = hA\int_{t_1}^{t_2}(T_R - T_s)dt$$

4- Actual Results

Sine Functions



4- Actual Results

Comfort duration and the area out of the comfort zone for Sine functions

Input	PCM %	Percentage increase in the comfort time duration		Percentage decrease in the area out of comfort zone	
		22 ± 1.5 °C	22 ± 3.0 °C	22 ± 1.5 °C	22 ± 3.0 °C
T10	10	29	0	82	100
	30	41	0	100	100
	50	41	0	100	100
T20	10	69	18	43	63
	30	181	29	88	95
	50	202	33	98	100
T30	10	75	26	26	35
	30	208	97	73	84
	50	323	118	92	93

4- Actual Results

Real Temperature Changes of Different Cities

City	Time	PCM %	Percentage increase in the comfort time duration	Percentage decrease in the area out of comfort zone
Seattle, Washington	Second week Aug. 1996	10	8	16
		30	18	27
		50	32	39
San Diego, California	Second week Sep. 2004	10	4	9
		30	31	29
		50	38	42
San Antonio, Texas	Second week Aug. 1990	10	1	5
		30	2	7
		50	4	10
Miami, Florida	Third week May 2000	10	2	6
		30	3	8
		50	5	12
Minot, North Dakota	Second week Jun. 1980	10	8	17
		30	23	39
		50	28	43
Denver, Colorado	Second week Jul. 2004	10	15	28
		30	24	39
		50	27	48

Conclusion and Future Works

- COMSOL Multiphysics® software can accurately simulate changes in temperature in porous media, such as gypsum boards, and can accurately take the effects of phase transition of PCMs into account.

- Under sine function inputs, depending on the percentage of the PCM, the inside peak temperature can be delayed by up to 7 hours and be decremented by up to 80%.

- For the real changes in temperature of different cities, the comfort duration was increased by up to 40% and almost half of the energy required by HVAC systems was reduced.

- **Future Works:**

More studies should be conducted to find the optimum percentage and melting temperature of PCM for different cities. Furthermore, cost analysis should also be conducted to compare the efficiency of PCMs to alternative methods.

References

- 1. Chwieduk, D., Towards sustainable-energy buildings, *Applied Energy*, **76**(1–3), 211-217 (2003)
- 2. Papadopoulos, A.M., T.G. Theodosiou, and K.D. Karatzas, Feasibility of energy saving renovation measures in urban buildings: The impact of energy prices and the acceptable pay back time criterion, *Energy and Buildings*, **34(5),** 455-466 (2002)
- 3. Laustsen, J., Energy efficiency requirements in building codes, energy efficiency policies for new buildings, *International Energy Agency,* (2008)
- 4. Kong, X., et al., Numerical study on the thermal performance of building wall and roof incorporating phase change material panel for passive cooling application, *Energy and Buildings* (2014)
- 5. Raoux, S. and M. Wuttig, *Phase change materials: science and applications*, Springer (2009)
- 6. Kuznik, F. and J. Virgone, Experimental assessment of a phase change material for wall building use, *Applied energy*, **86**(10), 2038-2046 (2009)
- 7. Baetens, R., B.P. Jelle, and A. Gustavsen, Phase change materials for building applications: a state-of-the-art review, *Energy and Buildings*, **42**(9), 1361-1368 (2010)
- 8. Sharifi, N.P. and A. Sakulich. Application of Phase Change Materials in Structures and Pavements, *Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering*, (2013)

References

- 9. Sharifi, N.P. and A. Sakulich, Application of Phase Change Materials to Improve the Thermal Performance of Cementitious Material, Energy and Buildings (2015)
- 10. Zwanzig, S.D., Y. Lian, and E.G. Brehob, Numerical simulation of phase change material composite wallboard in a multi-layered building envelope, *Energy Conversion and Management*, **69**(0), 27-40 (2013)
- 11. Biswas, K. and R. Abhari, Low-cost phase change material as an energy storage medium in building envelopes: Experimental and numerical analyses, *Energy Conversion and Management*, **88**(0), 1020-1031 (2014)
- 12. Evers, A.C., M.A. Medina, and Y. Fang, Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salt phase change materials using a dynamic wall simulator. *Building and Environment*, **45**(8), 1762-1768 (2010)
- 13. Incropera, F., *Introduction to Heat Transfer*, Fifth ed.: John Wiley & Sons (2005)
- 14. Sharifi, N.P., G.E. Freeman, and A.R. Sakulich, Using COMSOL Modeling to Investigate the Efficiency of PCMs to Modify the Temperature Changes in Cementitious Materials, Case Study, Submitted to *Construction and Building Materials* (2015)
- 15. Asan, H. and Y. Sancaktar, Effects of wall's thermophysical properties on time lag and decrement factor, E*nergy and Buildings*, **28**(2), 159-166 (1998)
- 16. *ASHRAE Standard* 55, Thermal Environmental Conditions for Human Occupancy (2004)

THANKS FOR YOUR ATTENTION!

npourakbarsharif@wpi.edu