

Thermal Modelling on Solar-Absorbing Metamaterial Microencapsulation of Phase Change Materials for Smart Textiles

William Tong^{1*} and Alan Tong²

¹Illinois Mathematics and Science Academy, Aurora, IL 60506, USA

²Neuqua Valley High School, Naperville, IL 60564, USA

Abstract

This paper will present a novel concept to design solar-absorbing metamaterial encapsulation of phase change materials (PCM) incorporated with thermo-regulated smart textiles for coats or garments especially for outdoor wear in cold weather. The metamaterial is a periodically nanostructured metal-dielectric-metal thin film and can acquire surface plasmons to trap or absorb solar energy at subwavelength scales. This kind of metamaterial microencapsulation is not only able to take advantage of latent heat that can be stored or released from the PCM over a tunable temperature range, but also has other advantages over conventional polymer microencapsulation of PCMs, such as enhanced thermal conductivity, improved flame retardant, and extra solar power resource. The thermal modelling for this metamaterial encapsulation has been done and will provide a guideline for future design of the integrated thermos-regulated smart textiles.

Keywords: Metamaterial; Microcapsulation; Phase change material; Thermo-regulated textile; Thermal modeling

Introduction

The incorporation of PCM microcapsules into textile structure to improve their thermal performance have been studied since the early 1980s [1]. The forming process for microcapsules is called microencapsulation, which, in this case, is usually carried out by coating individual PCM particles with a continuous film to produce capsules a micrometer to a millimeter in size [2]. Microencapsulation of PCMs is an effective technique for enhancing their thermal conductivity, preventing possible interaction with the surroundings and preventing leakage during the melting process [3]. The thermo-regulated fibers and textiles can then be made through two different processes [1]: (a) PCM microcapsules are integrated inside the fiber itself by adding them to a polymer solution prior to fiber extrusion; (b) PCM microcapsules are attached onto the fiber surface or incorporated into the textile matrix through coating, lamination, finishing, melt spinning, bi-component synthetic fiber extrusion, injection molding, the foam techniques, and so on. Conventionally, microencapsulated phase change materials consist of two main parts [3]: a PCM as core and a polymer or inorganic shell as the PCM container. This paper will provide a new concept for using three-layer nanostructured metal-dielectric-metal metamaterial thin film as the shell of a PCM microcapsule; meanwhile the metamaterial shell acts as a solar thermal resource for heating up the PCM. Compared to conventional polymer microencapsulation of PCMs, the metamaterial encapsulation can also provide largely enhanced thermal conductivity, improved flame retardant and extra solar power resource for effectively thermo-regulating fibers and related smart and interactive textiles.

Solar-absorbing Metamaterial Selection

By exciting plasmonic resonances at particular wavelengths inside the material structures [4], solar absorbing metamaterials used for the PCM microencapsulation can selectively absorb solar radiation in three different wavelength regions, including the visual region from 0.4-0.7 μm ; the solar region from 0.3-3.0 μm ; and the thermal region with wavelengths larger than 2 μm [5]. One of such metamaterials is shown in Figure 1 [6]. It is made of nanostructures with subwavelength tungsten planar stack on a tungsten film separated by a silica dielectric

spacer. Between the tungsten planar stack and the tungsten film, strong electromagnetic coupling could occur at selected wavelengths due to electric and magnetic responses of the metamaterial. The left insert of Figure 1 illustrates a unit cell of the metamaterial with double-sized tungsten patches of different widths w_1 and w_2 . The patches with the same width are arranged diagonally such that the structure behaves exactly the same at normal incidence for either TE or TM waves. Each patch is centered in its quadrant, and the period $\Lambda' = 2\Lambda$ [6]. The absorptance of the metamaterials with single-sized and double-sized tungsten patches, using the same geometric parameters of $\Lambda=600$ nm, $h=150$ nm and $t=60$ nm but different patch widths $w_1=250$ nm and $w_2=300$ nm, respectively [6]. Comparably, the double-sized metamaterial is more preferable to use for PCM encapsulation because of its broader absorption band than the single-sized one with $w_1=250$ nm, and higher absorbance than the single-sized one with $w_2=300$ nm. The calculated solar energy conversion efficiency is over 85% for these metamaterials [7], and would be used for thermal analysis of the PCM encapsulation in this paper.

Microencapsulation and its Thermal Modeling

The tungsten-silica- tungsten metamaterial can be coated on PCM using closed field magnetron sputtering (CFM), which can be carried out at room temperature allowing different layer materials such as tungsten and silica to be coated even in the same batch [8]. Figure 2 illustrates the tungsten-silica-tungsten metamaterial microencapsulation of PCM (Figure 2a), and its potential applications [7]: coated on the surface of fibers or textiles (Figure 2b) and embedded in fibers/textiles (Figure 2c). If neglecting the temperature variation in the coated metamaterial shell, and/or assuming the temperature

***Corresponding author:** William Tong, Illinois Mathematics and Science Academy, Aurora, IL 60506, USA, Tel: 509 331-6516; E-mail: ironwilliam1@gmail.com

Received March 18, 2015; **Accepted** March 30, 2015; **Published** April 30, 2015

Citation: Tong W, Tong A (2015) Thermal Modelling on Solar-Absorbing Metamaterial Microencapsulation of Phase Change Materials for Smart Textiles. J Textile Sci Eng 5: 190. doi:10.4172/2165-8064.1000190

Copyright: © 2015 Tong W, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

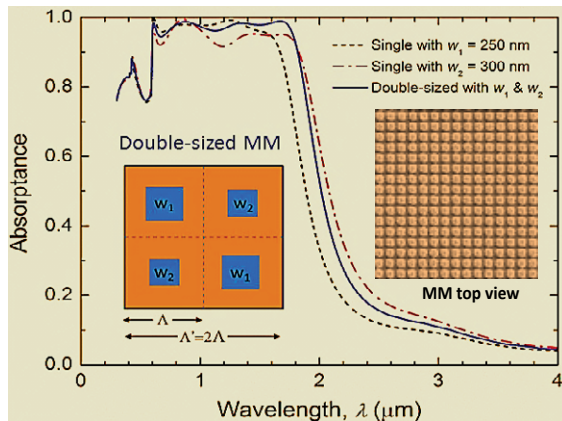


Figure 1: Schematic of solar absorbing metamaterials [6]: Double-sized tungsten patches of different widths w_1 and w_2 , and period $\Lambda = 2\Lambda$. The patches with the same width are arranged diagonally and each patch is centered in its quadrant. Spectral normal absorbance in the spectral region from $0.4 \mu\text{m}$ to $4 \mu\text{m}$ for solar absorbing metamaterials with tungsten patch widths of $w_1 = 250 \text{ nm}$ and $w_2 = 300 \text{ nm}$, in comparison with that of single-sized with w_1 or w_2 . $\Lambda = 600 \text{ nm}$, $h = 150 \text{ nm}$, and $t = 60 \text{ nm}$.

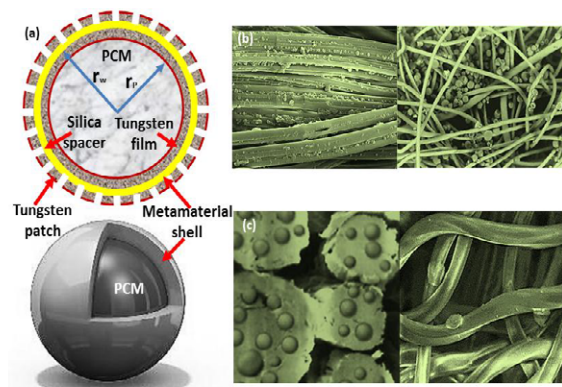


Figure 2: Illustration of metamaterial microencapsulation of PCM (a) and its potential applications [7]: coated on the surface of fibers or textiles (b) and embedded in fibers/textiles (c).

distribution in the base tungsten film around the PCM sphere surface is relatively uniform since the thermal conductivity of tungsten is much higher than that of the PCM, a thermal equilibrium between the metamaterial solar thermal absorption and the temperature increase of the PCM can be expressed as

$$4\pi r_w^2 J_s t_d \eta \alpha = m [C_{sp} (T_m - T_i) + \alpha_m \Delta h_m + C_{lp} (T_f - T_m)]$$

$$= \frac{4}{3} \pi r_p^3 [d_{sp} C_{sp} (T_m - T_i) + d_{lp} \alpha_m \Delta h_m + d_{lp} C_{lp} (T_f - T_m)]$$

When $T_f > T_m$, the PCM final temperature T_f could be induced from Eq. (1):

$$T_f = T_m + \frac{3r_w^2 J_s t_d \eta}{2r_p^3 d_{lp} C_{lp}} - \frac{d_{sp} C_{sp} (T_m - T_i)}{d_{lp} C_{lp}} - \frac{\alpha_m \Delta h_m}{C_{lp}} \quad (2)$$

Where r_w is radius of the outside surface of the base tungsten film in the metamaterial shell; r_p is radius of the PCM particle; J_s is standard

solar radiation at the earth's surface, 1000 W/m^2 [9]; t_d is working hours per day of the solar absorbing metamaterial shell; η is thermal efficiency of the solar absorbing metamaterial shell, 85%; α is sunlight acceptance coefficient of the metamaterial shell, which is mainly influenced by the light acceptance angle and the light transparency of the medium around the metamaterial PCM microcapsules (here it is taken as 0.5, assuming half of the metamaterial shell surface can accept the sunlight and the medium around it is totally light-transparent); α_m is the fraction of PCM that is melted, taken as 1; Δh_m is heat of fusion per unit mass PCM (J/kg), 189,000 J/kg for Paraffin $C_{13}-C_{24}$ [10]; m is mass of PCM (kg); d_{lp} is density of liquid Paraffin $C_{13}-C_{24}$, 760 kg/m^3 [10]; d_{sp} is density of solid Paraffin $C_{13}-C_{24}$, 900 kg/m^3 [10]; C_{sp} is average specific heat of Paraffin $C_{13}-C_{24}$ between T_i and T_m (kJ/kg K), 2.9 [11], C_{lp} is average specific heat of Paraffin $C_{13}-C_{24}$ between T_m and T_f (J/kg K), 2.1 [11]; T_i is initial temperature of PCM ($^{\circ}\text{C}$); T_m is melting temperature of Paraffin $C_{13}-C_{24}$ ($^{\circ}\text{C}$), 23°C [10]; T_f is final temperature of PCM ($^{\circ}\text{C}$).

The calculation results according to Eq. (2) are shown in Figures 3 and 4 for metamaterial microcapsules of Paraffin $C_{13}-C_{24}$, the PCM

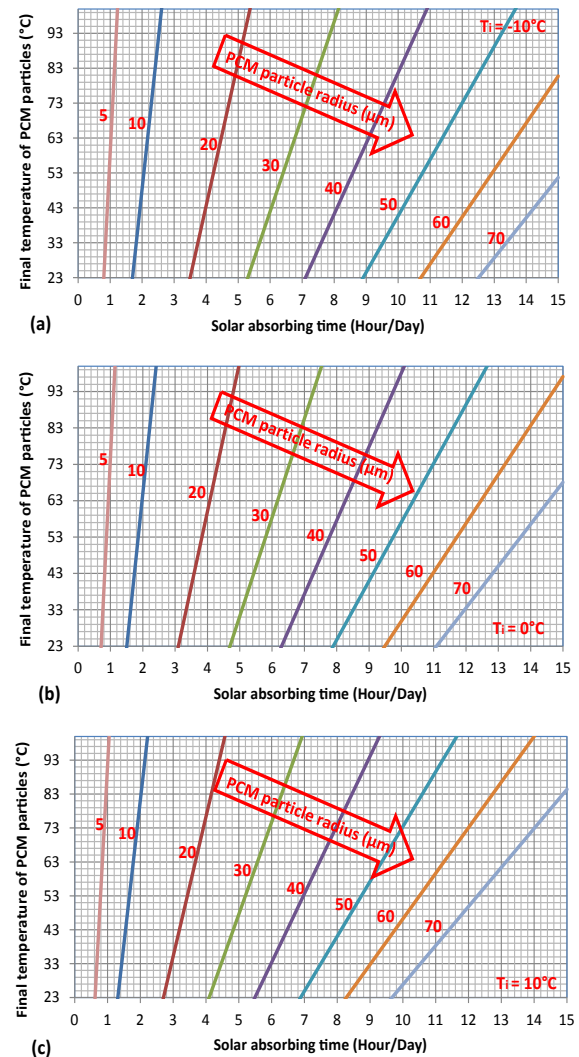


Figure 3: For metamaterial microcapsules of Paraffin $C_{13}-C_{24}$ when the PCM particle radius is $5 \mu\text{m}$ and over, the PCM final temperature varies with solar absorbing time for different PCM particle sizes under different initial temperatures: (a) -10°C ; (b) 0°C ; and (c) 10°C .

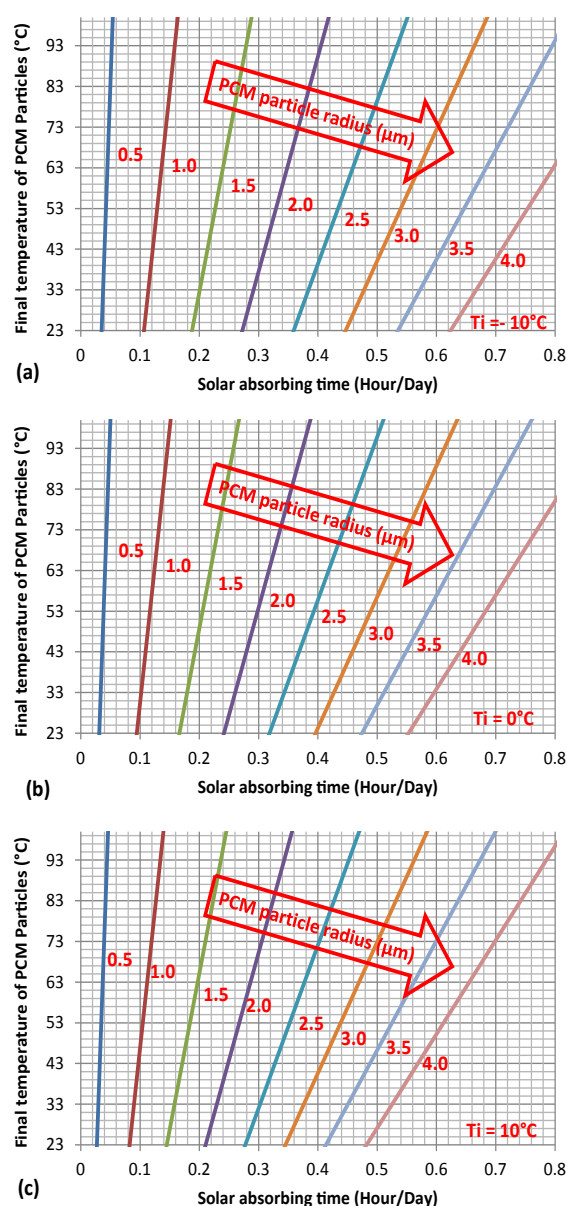


Figure 4: For metamaterial microcapsules of Paraffin C13–C24 when the PCM particle radius is less than 5 μm , the PCM final temperature varies with solar absorbing time for different PCM particle sizes under different initial temperatures: (a) -10°C ; (b) 0°C ; and (c) 10°C .

final temperature varies with solar absorbing time for different PCM particle sizes under different initial temperatures: (a) -10°C ; (b) 0°C ; and (c) 10°C . For example, for a typical PCM particle radius range of 15–45 μm , the metamaterial microcapsules need to be exposed under the sunlight for 2 to 9 hours to bring the PCM final temperature above the PCM melting point of 23°C (Figure 3). As shown in Figure 4, however, if the capsule radius can be shrunk to 5 μm down to 0.5 μm , the sunlight exposure time can be reduced to less than 0.7 hours or even under 0.05 hours to raise the PCM final temperature over its melting point, 23°C , although this may create some fabrication challenges in present. This analysis would provide basic guidelines for designing thermo-regulated smart textiles incorporated with the

metamaterial microcapsules for coats or garments intended especially for outdoor wear in cold weather.

In addition, the PCM metamaterial microencapsulation may have great potential in overcoming the problems or challenges facing conventional PCM smart textiles [1] with exceptional advantages, such as:

- Significantly enhanced thermal conductivity of PCM, because the thermal conductivity of tungsten film (173 W/mK) or silica spacer (1.1 W/mK [12]) is much higher than that of polymer microencapsulation of PCM (about 0.21 W/mK [10]).
- Excellent flame retardant, because of the extremely high melting temperature of tungsten ($3,422^\circ\text{C}$) and silica (over 1600°C) and their inertness.
- The metamaterial microencapsulation can directly provide solar thermal power and incorporate with micro/nano-scale thermoelectric modules to generate electrical power for smart textile structures.

Conclusion

A novel concept has been presented and demonstrated through thermal analysis for designing solar-absorbing metamaterial encapsulation of phase change materials (PCM) incorporated with thermo-regulated smart textiles for coats or garments. The needed sunlight exposure time of the metamaterial microencapsulation to raise the PCM temperature is closely dependent on the radius of microencapsulates under certain weather environments. The metamaterial encapsulation not only can take advantage of latent heat that is stored or released from a PCM over a tunable temperature range, but also has potential to overcome problems of the conventional polymer microencapsulation by enhancing thermal conductivity, improving flame retardant, and providing solar power resource. The potential applications of this metamaterial encapsulation incorporated textiles may cover highly complex life support and healthcare systems, life-saving military uniforms, and performance sportswear.

References

- Mondal S (2008) Phase change materials for smart textiles – An overview. Appl Therm Eng 28: 1536–1550.
- Tyagia VV, Kaushika SC, Tyagib SK, Akiyamac T (2011) Development of phase change materials based microencapsulated technology for buildings: a review. Renew Sustain Energy Rev 15: 1373–1391.
- Jamekhorshid A, Sadrameli SM, Farid M (2014) A review of microencapsulation methods of phase change materials (PCMs) as a thermal energy storage (TES) medium. Renew Sustain Energy Rev 31: 531–542.
- Watts CM, X Liu, WJ Padilla (2012) Metamaterial electromagnetic wave absorbers. Adv Mater 24: OP98–OP120.
- Voss K, Platzer W, Robinson P (2014) Education of architects in solar energy and environment -Advanced glazing.
- Wang H, Wang L (2013) Perfect selective metamaterial solar absorbers. Optics Express 21: 1078–1093.
- Bendkowska W, Tysiak J, Grabowski L, Blejzyk A (2005) Determining temperature regulating factor for apparel fabrics containing phase change material. Int J Clothing Sci Tech 17: 209–214.
- Gibson DR, Brinkley I, Hall GW, Waddell EM, Walls JM (2006) Deposition of multilayer optical coatings using closed field magnetron sputtering.
- Green MA, Emery K, Hishikawa Y, Warta W (2011) Solar cell efficiency tables (version 37). Prog Photovolt Res Appl 19: 84–92.

10. Abhat A (1983) Low temperature latent heat thermal energy storage: heat storage materials. Solar Energy 30: 313-332.
11. Zhoua D, Zhaob CY, Tiana Y (2012) Review on thermal energy storage with phase change materials (PCMs) in building applications. Applied Energy 92: 593-605.
12. Kleiner MB, Siemens AG, Munich, Kuhn SA, Weber W (1995) Thermal conductivity measurements of thin silicon dioxide films in integrated circuits. Electron Devices 43: 1602-1609.