Design of Solar Thermal Dryers for 24-Hour Food Drying

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Abstract: Solar drying is a method that has been adopted for many years as a food preservation method. To this date, significant advancements have been made in this field with the adoption of a multitude of solar thermal dryer designs for single-layer and multi-layer drying of fruit and vegetables e.g. cabinet, tunnel and chimney dryers. However, the ability to dry overnight, thus drying over a 24-hour period, to enhance efficiency and productivity, has continued to plague the agricultural community. One solution is the incorporation of phase change materials as heat storage mechanisms. Under the appropriate conditions, phase change materials can be an invaluable resource in food drying. In this work we have utilized the COMSOL 5.0 Heat Transfer Module to simulate the temperature profiles for solar cabinet dryers, composed of materials with different optical properties and under various conditions, to identify suitable phase change materials for solar thermal dryers.

Keywords: solar thermal dryers, optical properties, phase change materials, temperature

1. Introduction

Solar dryers have great potential in developing countries. Typically, drying in these regions and part of the United States consists of open-air drying. Open-air drying is a practical method for drying fruits such as grapes, plums, tomatoes, etc. The process can span several days to weeks, depending on the desired end moisture content and type of fruit. However, there are many drawbacks to this technique e.g. lack of environmental control, birds and other animals can eat produce, and insects can destroy crops. During nocturnal times when solar radiation is not present, the lack of a heat source prevents continued dehydration. Therefore, in agricultural processes such as solar drying, short-term thermal energy would be beneficial: thermal energy could be stored during the day and then harnessed in the evening with solar radiation is limited or during overcast weather conditions. A potential source of energy is phase change materials (PCM). A dryer designed to protect against environmental factors, constructed in an economical way, and efficient with a source of energy or heat during these times, would be an invaluable asset to the agricultural community.

Most of the published articles in the literature provide insight on the performance of solar dryers in service but with little information on the selection process or material attributes that allow them to be selected as candidates in solar thermal dryers. Furthermore, limited information on dryer performance is available prior to dryer design and implementation.

While a multitude of phase change materials are available; in order to capitalize on the heat storage mechanism of such materials the optimal conditions must be met. In this work, simulations have been employed using COMSOL 5.0 to assess the temperature profiles for multi-layer solar thermal cabinet dryers fabricated using materials with different optical properties.

2. Design of the Dryer

The solar dryer cabinet consisted of a simple box design as shown in the sketch of Figure 1. The specifications for the cabinet are as follows: 40.6 (W) x 43.1 (D) x 50.8 (H) cm. The radiation is captured via a transparent cover configured at the top of the dryer. For cost effectiveness, aluminum was chosen as our structural material. The heat transfer fluid selected for this model was air, which acted as a vehicle to transfer heat into the cabinet via the sun, the external radiation source.

COMSOL simulations were conducted using the same thermal properties but different optical properties- solar absorptivity and surface emissivity- for the transparent acrylic. Temperature profiles for the different parameters were simulated based on the solar traverse in the Albany, CA, U.S.A. (37.88N 42’, -122.30W 18’ 16.0”) region using the following equation:

$$27+3*\cos\left(2*pi*\left(x-14\right)/24\right) \quad (1)$$

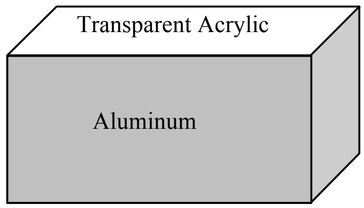

Figure 1. Sketch of the solar dryer cabinet.

3. COMSOL Multiphysics Modeling

3.1 Governing Equations

The Heat Transfer Module, with Surface-to-Surface Radiation, was employed to solve the conduction and radiation equations. The equation for a system with heat transfer including conduction, convection, and surface-to-surface radiation is:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathrm{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \quad (2)$$

where ρ is the density of the material (kg/m^3), C_p is the specific heat capacity of the material (J/kg·K), T is temperature (K), $\mathbf{u}$ is the 3-dimensional bulk velocity vector (m/s), k is the thermal conductivity of the material (W/m·K), and Q is the source term for radiative heating (W/m^3).

Neglecting convection and radiation heat transfer within the mass of air inside the cabinet, the equation for the conductive heat transfer within the mass of air is simplified from (2) to:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \quad (3)$$

Assuming thermal insulation between the air inside the cabinet and the aluminum sides of the cabinet, the relevant boundary condition is described as:

$$-\mathbf{n} \cdot (k \nabla T) = 0 \quad (4)$$

while the convective heat flux at the interface between the top surface of the cabinet lid and the ambient environment is described as:

$$-\mathbf{n} \cdot (k \nabla T) = h \cdot (T_{ext} - T) \quad (5)$$

where h is the convective heat transfer coefficient (W/m^2·K) and T_{ext} is the ambient temperature (K).

The bottom surface of the cabinet is assumed to remain constant at T_0 and governed by the following equation:

$$T = T_0 \quad (6)$$

where T_0 is the ambient temperature of 20^{o}C.

3.2 Simulation Parameters

Material properties data for aluminum and acrylic were provided by COMSOL Material Browser as shown below in Table 1. These parameters were the same across simulations; however, the optical properties, as seen in Table 2 were the variables in this study.

Table 1. List of material properties used in model.

	Units	*Acrylic*	*Aluminum*
α_{th}	1/K	7.0E-5	2.3E-5
C_p	J/kg·K	1470	900
ρ	kg/m^3	1190	2700
k	W/m·K	.18	238
E	Pa	3.2E9	70E9

where α_{th} is the coefficient of thermal expansion and E is Young's modulus.

Table 2. Optical properties employed in simulation.

Study	*Units*	*O*	*H*	*R*
SS1				
Solar Spectral Band: ε_{B1}		0.2	0.5	0.8
Ambient Spectral Band: ε_{B2}		0.8	0.5	0.2
Heat Transfer Coefficient	*W/m^2·K*	20	20	20
SS2				
Solar Spectral Band: ε_{B1}		0.94	0.94	0.94
Ambient Spectral Band: ε_{B2}		0.76	0.76	0.76
h	*W/m^2·K*	20	20	20

where O signifies original, H is half-half, R is reverse, SS is surface-to-surface radiation, ε_{B1} is solar absorptivity, and ε_{B2} *is* surface emissivity.

4. Results and Discussion

Temperature profiles recorded at 9:00, 12:00 and 18:00 hours are presented in Figure 2. The profile was simulated for a random date in the year 2014. The highest temperature of 330 K (57^{o}C) was observed for an acrylic with absorptivity and emissivity values of 0.8 and 0.2, respectively. Peak temperatures within the range of 30-45^{o}C was observed for the other 2 acrylic types – original and half-half. Similar temperature trends were observed for the minimum temperatures in all three cabinet types, with the lowest temperature value of 297 K (24^{o}C) observed in this study.

Based on the temperature profiles observed in order to incorporate phase change materials the material must possess a phase transition temperature of 57^{o}C or less.

Given that storage space is a limiting factor for the implementation of solar thermal dryers, latent heat PCMs are a much desirable choice in comparison to sensible heat PCMs, which require a larger surface area. Thus, suitable candidates consist of Glauber's salt and low transition temperature paraffin wax.

5. Conclusions

A 3D model for a solar cabinet dryer using COMSOL Multiphysics® 5.0 software was developed to simulate the temperature profiles of a transparent acrylic material with various

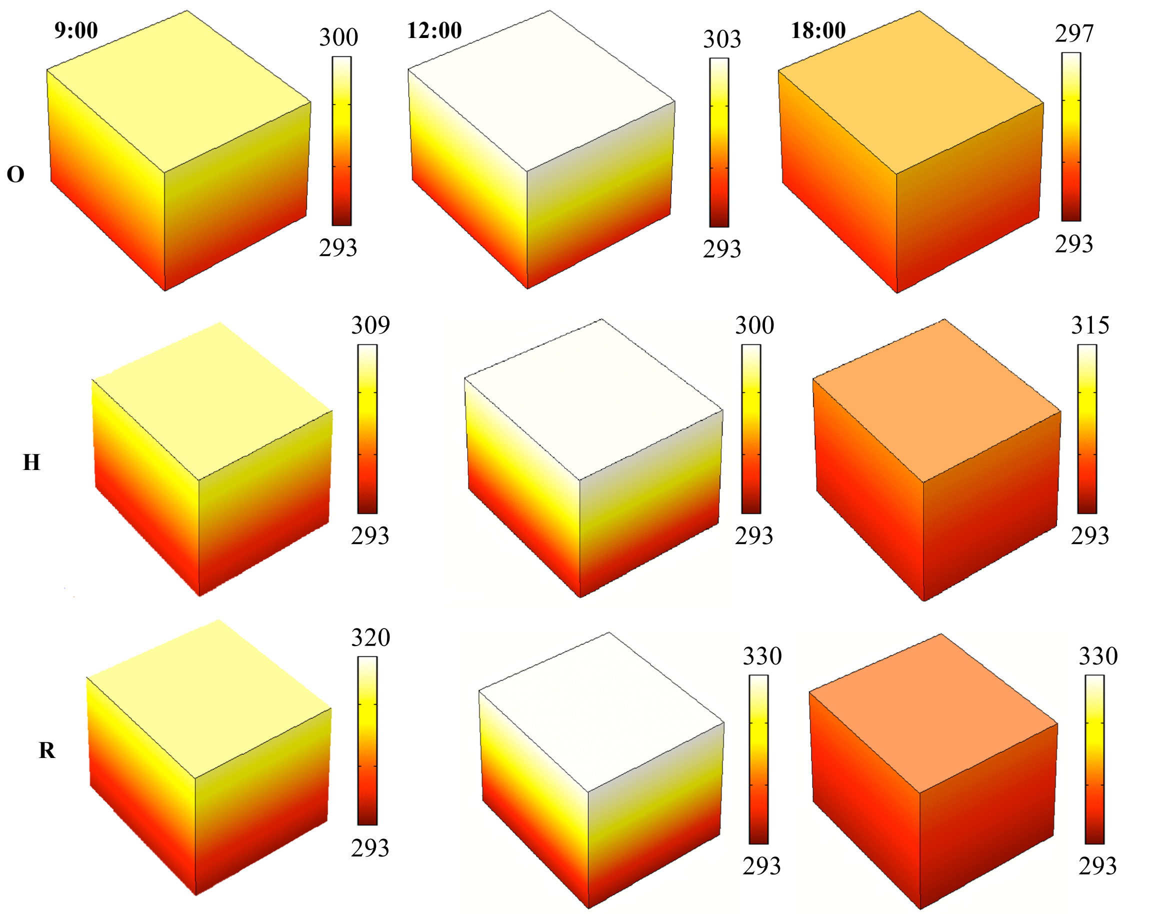

Figure 2. Temperature profiles for the solar cabinet simulated based on the emissivity and absorptivity values for the original (O), half-half (H), and reversed (R) conditions at 9:00, 12:00, and 18:00 hours.

optical properties e.g. absorptivity and emissivity. The results reveal that an acrylic material with an absorptivity and emissivity value of 0.8 and 0.2, respectively would be the best candidate for solar thermal cabinet dryers. Based on this work, appropriate materials can be identified and incorporated into the design process in order to enhance the efficiency of in-field testing and development of solar thermal dryer units. Furthermore, ideal phase change materials can be identified given that the peak temperatures found in this work was 57^{o}C. Thus, only crops that require overnight drying at conditions less than 57^{o}C are optimal choices for this current dryer design.

6. References

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10. Acknowledgements

The authors would like to thank the United States Department of Agriculture (USDA) for their financial support.