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Temperature Stabilization and Value Addition in Solar Drying of Arid Area Horticulture Products with Phase Change Materials and High Heat Capacity Materials

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Abstract: Arid and desert areas are home to priceless medicinal plants and horticulture produce. Scattered production, absence of preservation technology and specialized transportation facility has hindered economic exploitation of these produce. Family size solar dryer in the required temperature range is best suited for these regions. Decentralized mode of solar drying of horticulture produce and easy transportation has immense potential to contribute in the development of the region. In this paper, a typical solar dryer is designed and experimentally evaluated using a combination of High Heat Capacity Material (HHCM) and Phase Change Material (PCM). The result show that high storage density, with small temperature swing of PCM in the HHCM-PCM combine, allows the produce to dry in a single day without loss of vitamins and/or changes in taste and odor.

Keywords: Arid horticulture, Latent heat storage system, Phase change material, Solar drying

1. Introduction

Aid areas are worst hit by global climate changes. Options of sustainable development have shrieked at a faster pace than expected. Ecosystems are under stress and mass migration of local people has become common. Arid areas are also home to priceless medicinal and horticulture produces, rich in vitamins, essential minerals and medicinal values; and high solar insolation. Seasonal horticulture produces are either consumed locally in the season itself or sent to the bigger market immediately after harvest causing instant and short-lived slumps in prices. Transportation of these products is also difficult and a large part gets rotten before they reach market. Cost-effective preservation technology at local and small scale levels for these produces is hardly visible at local level due to their scattered production.

Solar drying at very small scale (family size) has many advantages (Choudhary *et al*., 2005, 2006). Decentralized drying in hygienic manner (without any application of insecticide) and value addition is possible. Dried produces can be preserved and transported without fear of degradation. Single day drying is most suitable for these produces. However, most of the horticulture produces need to be dried in particular temperature range to preserve vitamins, color and taste. Controlling temperature variation by increasing thermal mass increases drying time and therefore loss during off sunshine hours. Latent heat storage in a Phase Change Material (PCM) is very attractive option to overcome this lacuna because of its high storage density with small temperature swing.

Phase Change Materials (PCM) is latent heat storage material. When the source temperature rises, the chemical bonds within the PCM break up as the material changes phase from solid to liquid (as is the case for solid-liquid PCMs which are of particular interest here). The phase change is a heat-seeking (endothermic) process. Upon storing heat in the storage material, the material begins to melt when the phase change temperature is reached. The temperature then stays constant until the melting process is finished. The heat stored during the phase change process (melting process) of the material is called latent heat. The effect of latent heat storage has two main advantages; (a) It is possible to store large amounts of heat with only small temperature changes and therefore to have a high storage density, (b) Because the change of phase at a constant temperature takes some time to complete, it becomes possible to smooth temperature variations. They store 5 to 14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock.

Phase change materials themselves cannot be used as heat transfer medium. Latent heat energy storage

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system must, therefore, posses at least three properties: (1) a suitable PCM with its melting point in the desired temperature range; (2) a suitable heat exchange surface; and (3) a suitable container compatible with the PCM. The theoretical process of heat exchange in PCM is explained in the next section.

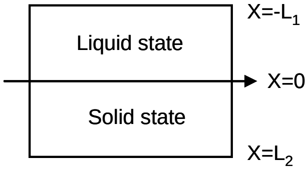

Fig. 1. Phase Change

2. Energy Balance Equations: Thermal Analysis

Heat gain and loss from Phase Change Material (PCM) is a non-linear and complex process. Let X= 0 be the heat retrieval plane with X = -L_1 and X = L_2 as liquid and solid boundaries of the PCM respectively. Total heat exchange q is given by,

$$q = \dot{m}C(T_o - T_i); \quad \dot{m} \text{ in kg/sec}$$

Heat gain by the phase change material gives rise to temperature gain at different boundaries, governed by the following equation,

$$(\alpha\tau)_{eff}\ I(t) = -K_1 \left.\frac{\partial T_1}{\partial x}\right|_{x=-L_1} + U_t (T_{x=-L_1} - T_S)$$

and,

$$T_I(X = 0) = T_S\ (X = 0) = T_0$$

Where, $(\alpha\tau)_{eff}$ is effective gain of solar radiation *I(t)*. U_t is heat loss coefficient from phase change material to the environment and,

$$-K \left.\frac{\partial T_1}{\partial x}\right|_{x=0} = -K_S \left.\frac{\partial T_S}{\partial x}\right|_{x=0} + q$$

$$-K \left.\frac{\partial T_S}{\partial x}\right|_{x=L} = h_2\ (T_{S|x=L_2} - T_S)$$

The average temperature $\overline{T}_P$ of the PCM can be obtained as,

$$\overline{T}_P = \frac{1}{(L_1 + L_2)}\left[\int_{-L_1}^{0} T_1\,(x)\,dx + \int_{0}^{L_2} T_S\,(t)\,dx\right]$$

The effective thermal property of the PCM can be given by,

$$C_P = C_S + \left(\frac{H_O}{\overline{T}_P} - T_a\right)\left(\frac{L_1}{L_2}\right)$$

C_P is effective specific heat of the PCM, C_S is specific heat material in solid phase. Now energy balance for the cabinet solar dryer with phase change and high heat capacity material inside the system is given by,

$$(\alpha\tau)_{eff}\, I(t)\ A_b = (M_r C_r + M_p C_p)\,\frac{dT_{CSD}}{dt} + U_s\ (T_{CSD} - T_a)\ A_b$$

and,

$$M_f\ C_f\,\frac{dT_{CSD}}{dt} = M_r\ C_r\,\frac{dT_r}{dt} + M_P\ C_P\,\frac{d\overline{T}_P}{dt}$$

A_b is area of the base of the solar dryer. M_r, M_P and M_f are the thermal mass of the high heat capacity material, phase change material and thermal load kept for drying, respectively. Similarly, C_r, C_P and C_f are the specific heat capacity of the high heat capacity material (HHCM), phase change material (PCM) and thermal load kept for drying, respectively. T_{CSD} and T_r are the transient temperatures of Cabinet Solar Dryer (CSD) and HHCM kept inside the CSD.

3. Materials and Methods

Family size passive solar dryer was designed by optimizing various parameters for remote areas and scattered rural population of North Bihar. The dryer achieved 90 degree Celsius during peak summer and dried even high water and sugar content horticulture products in a single day (12-14 Hrs). One of the main objectives was to make it simple for local production. Field experience showed that the design lacked at

Table 1. List of PCMs for drying application.

Material	M.P. (°C)	L. heat (kJ/Kg)	Density (Kg/m³)
Inorganic PCM			
$H_4P_2O_6$	55	213	--
$SO_3(\gamma)$	62.1	331	--
Paraffins PCM			
n- Docosane	44	249	763
n- Tricosane	47.6	234	769
n- Tetracosane	51	255	766
n- Pentacosane	54	238	769
n- Hexacosane	56	257	770
n- Heptacosane	59	236	773
n- Octacosane	61	255	765-910
n- Nonacosane	64	240	765-910
n- Triacotane	65	252	765-910
Non – Paraffins PCM			
Methyl Eicosanate	45	230	851
3-Heptadecanone	48	218	--
2-Heptadecanone	48	218	--
Camphene	50	238	842
9-Heptadecanone	51	213	--
Methyl Behanate	52	234	--
Hypophosphoric acid	55	213	--
Trymyristin	33-57	201-213	862
Arachic acid	76.5	227	
Fatty Acid PCM			
Myristic acid	49-51	205	861
Palmitic acid	64	185.4	850
Stearic acid	69	202.5	848
Salt Hydrates			
$Fe(NO_3)_2 .9H_2O$	47	155-190	1684
$Na_2S_2O_3.5H_2O$	48	209	1600
$MgSO_4.7H_2O$	48.4	202	168
$CH_3COONa. 3H_2O$	58	270-290	145
$LiC_2H_3O_2.2H_2O$	58	251-377	--
$MgCl_2.4H_2O$	58	178	--
$NaOH.H_2O$	58	272	--
$NaAl(SO_4)_2.12H_2O$	61	181	--
$FeSO_4.7H_2O$	64	200	1893
$LiCH_3COO.2H_2O$	70	150-251	--
$Na_2P_2O_7.10H_2O$	70	186-230	--
$Ba(OH)_2.8H_2O$	78	265-280	1937

Fig. 2. Mango pulp drying in prototype solar dryer.

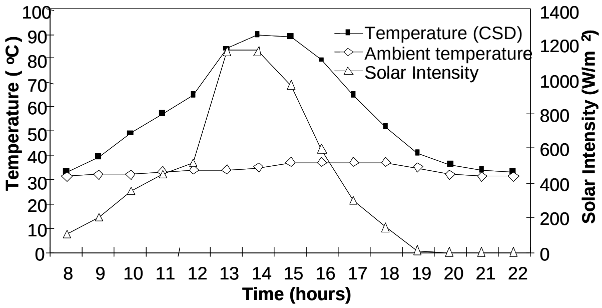

Fig. 3. Variation of solar intensity, ambient temperature and temperature inside the dryer.

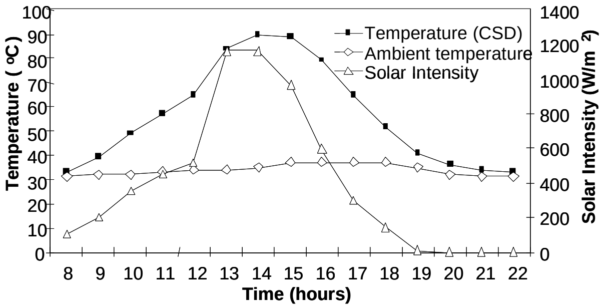

Fig. 4. Variation of temperature inside the dryer with different combinations of HHCM and PCM ($NaOH. H_2O$).

three fronts, (1) temperature range control mechanism needed manual intervention with small PV operated fans and/or opening the vents, which was unpopular; (2) Variation in temperature (>5 degree C) more than required range for drying made products brittle, sticky and even changed their colour, taste, odour and food value; and (3) Operation after off-sunshine hours increased loss of thermal energy due to local construction. Strict control on heat loss cannot be possible by local construction. It also highlighted reduction in the amount of HHCM for early temperature gain, which increased further temperature variation. The situation worsened in partly cloudy sky.

Dryer with four compartments is designed (**Fig. 2**), which uses PCMs in combination with HHCMs for temperature control. PCMs allow temperature inside the dryer to rise faster in the early sunshine hours as compared to HHCMs. **Table 1** show the list of PCMs, which are nontoxic and are in middle temperature range (45-75 ˚C). Latent heat of fusion, Melting Point, Density and thermal conductivity are most important parameters in selection of PCMs (Sharma *et al.*, 2004; Grigoriov and Mulikhov, 1995).

Experiments on drying of mangoes, Litchi, Aonla, Jamun and plants were conducted with Sodium Hydroxide ($NaOH.H_2O$), Sodium Thiosulphate Penta Hydrate ($Na_2S_2O_3.5H_2O$), and Acetamide, which are easily available and have low price. Numerical analysis and a series of experiments were undertaken to stabilize temperature inside the dryer for different temperature ranges.

4. Results and discussion

It allows longer period of slow and continuous drying, suitable for bulky fruits. **Fig. 3** shows the variation of solar intensity, ambient temperature and temperature inside the dryer without any HHCM and PCM thermal mass. A large variation in temperature is found with maximum temperature rising to 90˚C. This is not good for horticulture drying. **Fig. 4** shows a typical result of HHCM (boulders) and PCM ($NaOH.H_2O$) combine. Pick of the temperature curve is curtailed and thermal energy is preserved for longer period of time with increase in PCM. At the same time, initial rise in temperature improves with PCM use. **Fig. 5** shows the variation in weight with time for *aegle marmelos.* It clearly shows that PCM application increases initial rate of drying and therefore, reduces thermal energy loss in off sun-shine hours.

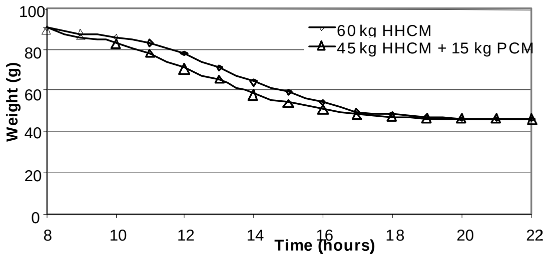

Fig. 5. Variation of dried weight of aegle marmelos with PCM

Sodium Hydroxide is best suited for temperature stabilization at 58˚C and good for medium size fruits. $Na_2S_2O_3.5H_2O$ is found good for slow drying process of fish and fruit pulp. Fast drying changes color of the produce. Acetamide (stabilization at 81˚C) is good for quick drying of small fruits. The whole drying process requires no chemicals or any pesticides for preservation up to six months. The system is simple to operate and convenient for rural people particularly in developing countries.

5. Conclusion

Appropriate solar drying designs with options of a combination of high heat capacity material and PCMs can be one of the main planks of rural development, economic prosperity in remote areas as well as support food security. Results indicate that a combination of high heat capacity material combined with PCMs can stabilize temperature in the desired range. The CSD design can be used for drying of horticulture products in (a) desired range of temperature and (b) single day optimized drying.

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