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FABRICATIONANDEXPERIMENTALINVESTIGATIONOFPCMCAPSULESINTEGRATEDIN SOLARCABINET DRYER

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ABSTRACT

Solar dryer with heat storage material can reduce the drying time and assist to maintain thebetter quality of medicinal plant. Solar cabinet dryer integrated with thermal storage system byusing phase change material (PCM) for drying of tubular roots was designed, fabricated andtestedatDepartmentofUnconventionalEnergySourcesandElectricalEngineering,Dr.Panjabrao Deshmukh Krishi Vidyapeeth, Akola. The system consists of flat plate solar collector,transparent cover, absorber plate, insulation, drying chamber, chimney and heat exchanger withPCMcapsulesplaystostoreheatduringsunshinehoursandreleaseitduringnon-sunshinehours. In present heat storage units paraffin wax used as a PCM encapsulated of thirty fouraluminum cylindrical capsules were equally spaced at a distance of 2.5 mm. The inlet and outletairtemperatureandthermalstorageefficiencyofthesolardryersystemhasbeenstudied.Experimental results indicated that the average drying efficiency of solar dryer was 15.6 percentand 18.8 percent and the average thermal energy storage efficiency was 57.01 per cent and 57.20per centinsummer andwinter respectively.Itrevealsthattemperature of dryingchamberincreased by 12.64°C and 15.03°C over the average ambient temperature in summer and winterrespectively.Fromthestudyitisconcludedthattheheatstoragematerialstoredmaximum amountofheatduringsunshinehoursinsidetheairheaterthroughheatexchangeranddryingtakesplacemoreeffectively duringnon sunshinehoursforextended timeof4 to 5 hours.

Keyword: Solarcabinetdryer,Thermal energystorage,PCMcapsule, Tubularroots

INTRODUCTION

Solar energy is the most attractive alternative energy sources for the future. Utilization ofsolar energy for drying of various agricultural commodities/produce is in practice since timeimmemorable for preservation of food and agricultural crops (Al-Busoul 2017). Solar drying is a simple processof moisture removal from a product in order to reach the desired moisture content and is anenergy intensiveoperation(Gutti et al. 2018). The prime objective of dryingapartfromextended storage lifecan also be enhance quality, ease of handling, further processing and sanitation and is probablythe oldest method of food preservation practiced by humankind (Deshpande2018, Phadke et al. 2015, Tiwari, 2016). Drying involves theapplication of heat to vaporize moisture and some means of removing water vapor after itsseparation from the food products. It is thus a combined and simultaneous heat and mass transferoperation for which energy must be supplied (Zhang 2011, Ekechukwu 1999]. The removal of moisture prevents the growthandreproductionofmicroorganismslikebacteria,yeastsandmoldscausingdecayandminimizes many of the moisture-mediated deteriorative reactions (VanArsdel, 1965). Drying in earlier times wasdone primarily in the sun, now many types of sophisticated equipments and methods are used todehydrate foods(Shafiur Rahman).

Energystorageisnotonlyplaysanimportantroleinconservationofenergybutalso improves the performance and reliability of wide range of energy systems, and become moreimportant where the energy source intermittent such as solar (Alkilani et al. 2009). Energy storage process canreduces the rate mismatch between energy supply and energy demand (Dincer& Rosen 2007, Ermis&Findik 2020, Kuravi 2013]. The thermalenergystorageusedinplaceswherethereisavariationinsolarenergyorinareaswherethereis a high difference of temperature between day and night (Alkilani et al. 2011). There are many thermal energystorage (TES) materials available for solar thermal applications among which a few have beeninvestigated by experimental testing previously. Among these materials, the most commonmaterials are the rock beds, pebble beds, aluminum composites, water, and paraffin wax. Mostof the materials have a good capacity to store the heat and release this heat at a desiredtemperatureup to a longperiodduring offsunshinehours for aheating task(Saxena et al. 2012, Goyal et al. 1998 &Farid et al. 2004).

Amongst thermal heat storage techniques, latent heat thermal energy storage is particularlyattractive due to its ability to provide high energy storage density and its characteristicstostoreheatatconstanttemperaturecorrespondingtothephasetransition temperature of the PCM(Lane 1983, Abhat 1983). Latent heat storage is one of the most efficient ways of storing thermal energy (Mondal 2008).Latent TES system store energy in PCMs, with the thermal energy stored when the materialchanges phase, usually from a solid to liquid.A phase-change material (PCM) isa substancewith a high heat of fusion which on melting and solidifying at a certain temperature, is capable ofstoring and releasing large amounts of energy. Heat is absorbed or released when the materialchanges from solid to liquid and vice versa (Arun Kumar &Shukla 2015). As the source temperature rises, the chemicalbonds within the PCM break up as the material changes phase from solid to liquid (as is the casefor solid-liquid PCMs, which are of particular interest here). The phase change is a heat-seeking(endothermic) process and therefore, the PCM absorbs heat. Upon storing heat in the storagematerial,thematerialbeginstomeltwhenthephasechangetemperatureisreached.Thetemperatu rethen stays constant until the meltingprocess is finished (Sharma2005, Regin 2008, Sharma2009).

Selection of PCM is based on the application but the PCM to be use should possess thermophysical, kinetics and chemical properties and also availability and cost effectiveness of material(Himran et al. 2007, Lingayat 2013) The studies show that commercial grade paraffin wax and other pure paraffin's havestablepropertiesafter1000-2000cycles(Sharma 1999).Paraffinwaxdidnotshowregulardegradationinits thermal properties after repeated melting/freezing cycles. Paraffin waxes are safe and non-reactive (Buddhi 1994). They are compatible with all metal containers and easily incorporated into heatstoragesystems (Lane 1980).Paraffinwaxhavebeenwidelyusedforlatentheatthermalenergystorage system applications due to large latent heat and desirable thermal characteristics such as little ornosuper cooling,variedphase change temperature,lowvapour pressure inthe melt,goodthermal and chemical stability and self nucleating behavior (Pablo et al. 2012). The number of carbon atomspresent in the chains of paraffin wax which has melting temperatures between 30°C and 90 °Crangesfrom18to50(C18-C50).Thespecificheatcapacityoflatentheatparaffinwaxisabout 2.1 kJ/kg °C. Their melting enthalpy of waxes lies between 180 and 230 J/g which is quite highfororganicmaterials.Waxesarealsoreadilyavailableinmarketandinexpensive(Tan et al. 2009, Fan 2011).Utilization of PCM for thermal energy storage requires a proper heat exchanger system forchargingand dischargingthe thermal energy(Stella 2012).

Theaimofthepresentstudyisdevelopedsolarcabinetdryerwhichintegratedwith PCMs i.e. paraffin wax for drying of tubular roots and how much maximum amount of heat stored inheat storage material during sunshine hours inside the air heater and extended time takes fordrying effectively during non sunshine hours.The testing of solar dryer was carried out atDepartmentofUnconventionalEnergySourcesandElectricalEngineering,Dr.PanjabraoDeshmukh Krishi Vidyapeeth, Akola.

MATERIALSANDMETHODS

ExperimentalSetup

The optimum design of solar air heaters based on PCM assumptions are made such assimpleindesignandoperate,easytomaintain,performedinpoorambientconditions,inexpensiveandh aveimprovedefficiency,significantimprovementinproductquality,nocontaminationbyinsects,micro organismsandmycotoxin,reductionindryingtimeandextensionofdryingperiodduringnonsunshineho urs.Solarairheaterwithlatentstoragecollector using spherical capsules as a packed bed absorber for drying of 10 kg/batch tubularroots was designed and fabricated. The experiment for no-load and full-load test was undertakenfor drying of tubular crop. For evaluating the performance of solar dryer, full load test by usingtubular roots was conducted during summer and winter respectively. The design takes into muchconsiderationconcernwithsimplicityinconstruction,integratedwithPCMstorageunits,handling of PCM units, collector dimension are proposed accordance with Choudhury 1988, Fath1994 andEnibe2002.

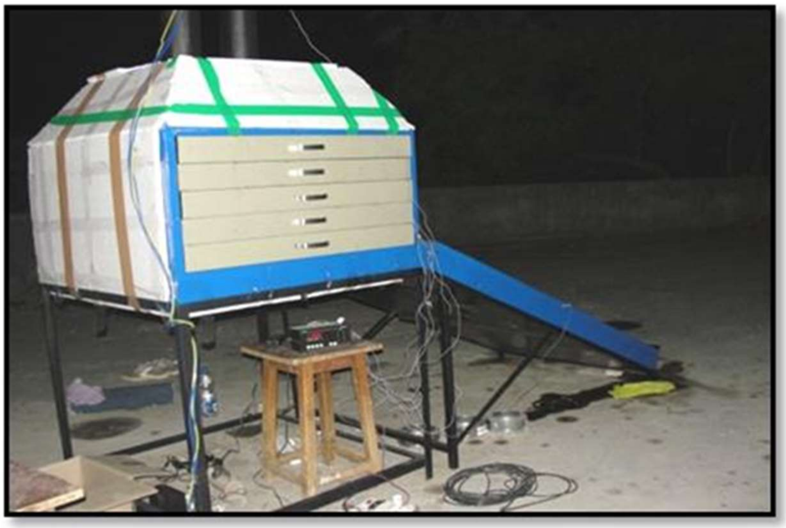


Fig1a:Experimentalset upofsolarcabinetdryer

Solarcabinetdryer

Thissystemconsistsof dryingchamber withheatexchanger andtwochimneys.Theinsulation of glass wool with thickness of 2.5 cm are sandwiched between absorber plate andouter cover of solar cabinet dryer. The size of solar cabinet dryer are 1800 x 1000 x 150 mmhaving number of drying tray is five. The absorber plate with thickness of 2 mm painted blackwith selective coating having high absorptivity. Slit with flap are provided at one side of solarcabinet dryer and other side was connected with drying chamber. The physical dimension of thissystem is given in Table A.1. The drying chamber is directly connected to solar air heater. Thedryingchamber consists offive drying trayswith two chimneys(FigureA.1).

TableA.1:Thermophysicaldimension oftestedsolarcabinetdryer

PARAMETER	VALUE
Sizeof solarcabinet dryer, mm	1800 x 1000 x 150
Numberofdrying trays,no.	05
Exhaustfans	12V, DC, 0.35 A
Constructingmaterialofairheater	GIsheet
Inclinationofthesolar airheaterwithrespecttohorizontal	27°
Globalradiation atAkola, (I_{SC}),Wm-2	700
Location	Dr.P.D.K.V.Akola
Longitude	77°10'̓E
Latitude	20°30̓N

FabricationofPCMcapsules

Heat exchanger unit consists of stand for aluminum capsules filled with phase changemedium i.e. paraffin wax. Thirty four (34) number of aluminum capsules spaced 2.5 mm apartwere placed centrally in between absorber plate and glass cover. The aluminum capsules werecoated with selective black paint and then placed in the collector, arranged in a single row acrossthe flow of air. Thethermo-physical propertiesofparaffinwaxweretestedat AnaconlabsPvt. Ltd. Nagpur given in Table A.2 while the physical dimension of capsules is in Table A.3.The storage unit consists of 65 kg paraffin wax encapsulated in the set of 50 cm diameteraluminumtubes. It wasused forproviding storedheat during offsunshine hours.

TableA.2:ThermophysicalpropertiesofParaffin waxphasechangematerial

PARAMETER	VALUE
WeightofParaffinwax	65 kg
Specificheat	2.50kJ/kgK
Thermalconductivity	0.28W/mK
Latentheatof fusion	201kJ/kg
Density	0.993 g/cm^3
Meltingpoint	52°C

TableA.3:Thermophysicalpropertiesofheatstoragesystem

PARAMETER	VALUE
Noofaluminumpipes ofheatexchanger	34
Diameterof aluminum pipe,mm	50
Lengthofaluminumpipe, mm	980
Spacingbetweenaluminumpipe,mm	2.5
Weightofaluminumpipe, kg	23
Sizeofaluminumabsorberplate, mm	1800 x 1000 x 2

The capsule ends were sealed by nylon caps fixed by screws and araldite.Theparaffinblocks were shredded into small pieces for easy melting then poured inside the tube via a bigscrewed hole made in order to reuse the capsule many times, such as if need to add someadditivestoenhance heat transfer or change the entire storage medium. The screw wasclosedwhenthetubewasfilledwithparaffinwaxinliquidphase,soastoreducethePCM pressureduringchargingprocess(FigureA.2).Alltheseprecautionsweretakentopreventanyleakageor expansion problems.

FigA.2:Capsulefillingprocesswithparaffin wax

Theoreticalbackground:ThermalEnergyStorageEfficiency(ηt)

During discharge process when no radiation and the PCM was initially at liquid phase.According to law of conservation of energy, energy stored in to the thermal storage unit is equaltoenergyextractedfromit.Thethermalenergystorageefficiencywascalculatedasfollows(Alkilani 2011)-

$$(T_{\square} - T_{out})C_a\acute{m} = 2\pi R_o l h\left(T_m - T_{sfc}\right) + \varepsilon A\sigma\left(T_{sfc}^4 - T_{sur}^4\right) \text{Eq.(1a)}$$

Where,

Tin =Airtemperaturebeforethecylinder(°C)
Tout =Airtemperatureafterthecylinder(°C)
Ca =Specificheatforair(kJkg -1°C -1)
m ´=Massflowrate(kgs-1)
Ro =Outsideradius(m)
l =Capsulelength(m)
h =Heattransfercoefficient(kJm-2s-1 °C-1)
Tsfc =Capsulesurfacetemperature(°C)
ε =Emissivity(-)
A =Capsulearea(m2)
σ =Stephan-Boltzmanconstant(kWm-2K-4)

Tsur =Surroundingtemperature(°C)
Tm =Meltingtemperature(°C)
The heattransfercoefficientofflownormaltobanksoftubesinlineapproximated(McAdams,1954):

$$h = \frac{K_a}{D_o} b_2 \Re^n \qquad \text{Eq. (2a)}$$

Where,

Ka= Thermal conductivity of air (kWm-1°C-1);
Do=Outsidediameter(m);
Re=Reynoldsnumber(-);
b2andη=Constantsequalto 0.3and 0.6respectively
The efficiency of thermal energy storage systems can be defined as the ratio of the energyextracted from the thermal storage unit to the energy stored into it. The following equation hasbeenused tocomputetheefficiency ofthermalenergystorage:

$$\eta = [(T_{in} - T_{out})\, C_a \acute{m}] \,/\, \{[(T_{in} - T_{out})\, C_a \acute{m}] + 2\pi R_o lh(T_m - T_{sfc}) + \varepsilon A \sigma (T_{sfc}^4 - T_{sur}^4)\}$$

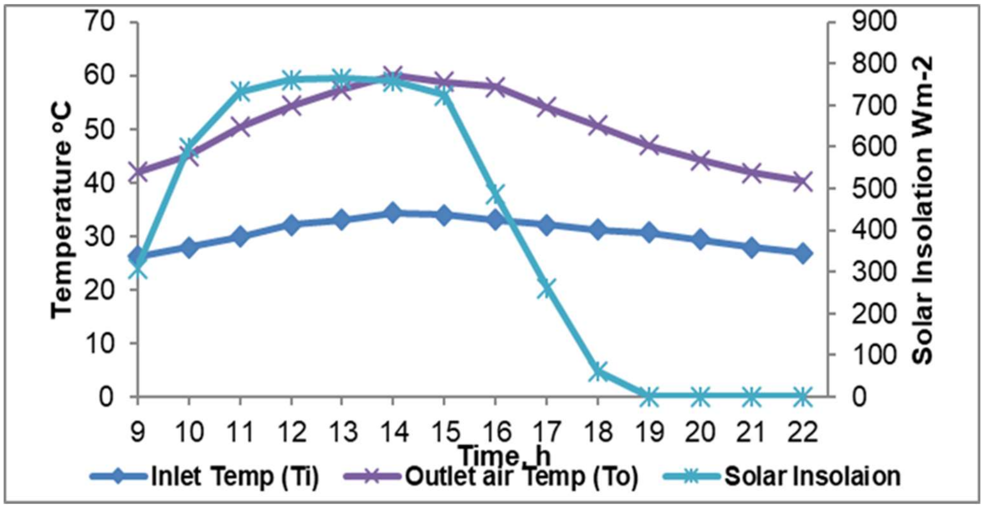
Eq.(4a)

(Tin -Tout) Cam ´=TESefficiency (%)
Qo =Heat retrievable from TES(kW)
QL=Heatlostto the environment(kW)
η = [(Tin -Tout) Cam ´] / {[(Tin -Tout) Cam ´] + 2π Ro lh(Tm- Tsfc) + ε A σ (Tsfc4 -Tsur4)}
Eq.(4a)

RESULTSANDDISCUSSION

The experiment were carried out in solar cabinet dryer during no load and full load test andevaluate the performance of solar dryer without product during summer and winter season. Thevariationintemperaturecorrespondingambienttemperature,solarradiationwererecorded.The temperaturedevelopedinairheateratitsinlet,andoutletwererecordedtoevaluatetheperformance of air heater integrated with thermal storage material i.e. paraffin wax in heatexchanger during summer and winter season.It was seen paraffin wax is used as PCM materialin solar air heater to conserve heat during day and can be used as a source of heat in night. Themelting of wax occurred during the study because maximum overheat above melting temperaturewasapproximately 18.5K.

No load test: The average inlet temperature in drying chamber was 47.58°C correspondingto ambient temperature 30.65°C and average solar isolation of 545.40 Wm-2 during no load test inwinter. Average inlet and outlet temperature developed in air heater was 30.63°C and 50.67°Cduring no load test in winter. It reveal that the average temperature difference of 19.94°C wasfound between inlet and outlet temperature in air heater and 16.94°C was found between inlettemperatureand averagetemperaturein drying chamber(Fig.A.3).



FigA.3:Averagetemperaturedevelopedin airheaterduringnoload testinwinterseason

The average inlet temperature in drying chamber was 47.84°C corresponding to ambienttemperature 34.72°C and average solar isolation of 602.62 Wm-2 during no load test in summer.Average inlet and outlet temperature developed in air heater was 34.74°C and 51.31°C during noload test in summer. It seen that average temperature difference of 16.57°C was found betweeninletandoutlettemperatureinairheaterandtemperature difference of 13.10°Cwasfoundbetweeninlettemperatureandaveragetemperatureindryingchamberduringsummer(Fig.A.4).

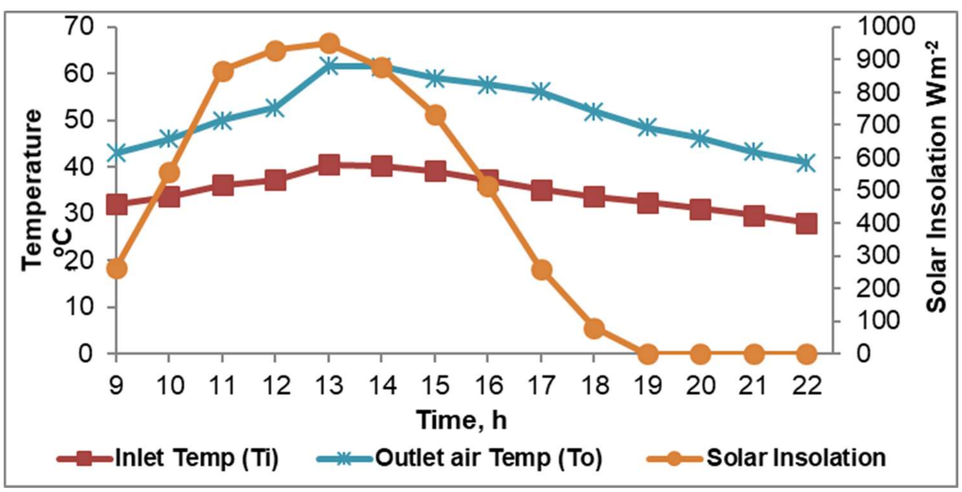
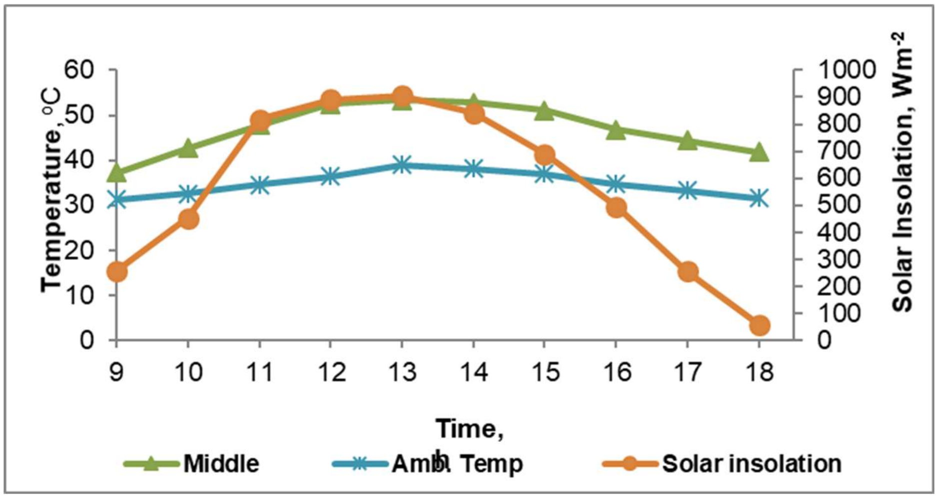


Fig.A.4:Averagetemperaturedevelopedin airheaterduringnoload testinsummerseason

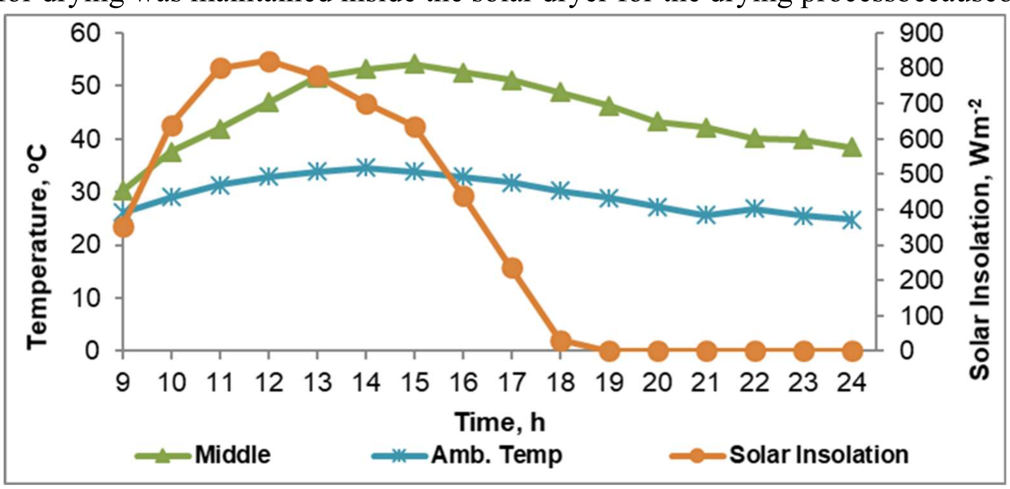
Full load test: Full load test of solar dryer wasconductedby drying fresh tubular roots insummer andwinterseason.

The average temperature inside the solar dryer and relative humidity was found 47.58°Cand 24.40 per cent corresponding to average ambient temperature, ambient relative humidity andsolar insolation were 34.84°C, 18 per cent and 566.61 Wm-2 respectively during load test insummer (Fig A.5).It is observed that the temperature of drying chamber was increased by12.64°C over the average ambient temperature,whereas average relative humidity was reducedby6.40 per cent than averageambient relative humidity.



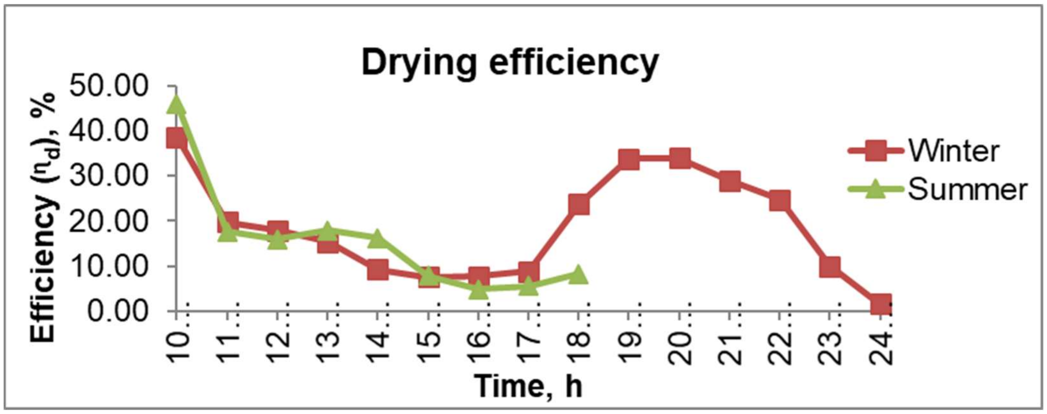
FigA.5:Averagevariationoftemperatureduringfull loadtestofdryerin summer

It is observed that the temperature of drying chamber and relative humidity was 44.74°Cand 19.38 per cent (Fig A.6). It reveals that temperature of drying chamber increased by 15.03°Cover the average ambient temperature, whereas average relative humidity was reduced by 12.06per cent than average ambient relative humidity in winter. The average ambient temperatures,relative humidity inside the dryer and solar insolation were 29.71°C, 31.19 per cent and 544.00Wm-2 respectively in winter. It was observed that the increase in temperature inside the dryingchamber correspondingly reduced the relative humidity to its lowest value attributed to the storedheat in the thermal heat storage system of air heater. It is revealed from the above results that thetemperature required for drying was maintained inside the solar dryer for the drying processbecauseofPCM.



FigA.6:Averagevariationoftemperatureduringfull loadtest ofdryerin winter

Theaveragedryingefficiencyofsolardryerwas15.6percentand18.8percentinsummerandwinterrespectively.Dryingefficiencyofsolardryerwashighestatinitialhoursi.e. 45.92percentinsummeranditwasmaximumi.e.38.68percentduringsunshinehoursand 33.93 per cent during non-sunshine hours in winter season. Thermal energy storage efficiencywas 70.18 per cent and 69.00 per cent in summer and winter respectively at 9:00 h and it reducedto 46.58 per cent at 16:00 h in summer and43.76 per cent at 14:00 h in winter, afterwardsthermal energy storage efficiency increased gradually to 72.29 per cent in summer and 72.76 percent in winter at 22:00 h (Fig A.7). The average thermal energy storage efficiency was 57.01 percent and 57.20 per cent in summer and winter respectively (Fig A.8). The heat storage materialstoredmaximumamountofheatduringsunshinehoursinsidetheairheaterthroughheat exchanger and drying takes place more effectively during non sunshine hours for extended timeof 4 to 5 hours. Similar type of thermal energy storage efficiency was reported by Krishnananth2013.



FigA.7:Variationin hourlydryingefficiencyduringsummerandwinter

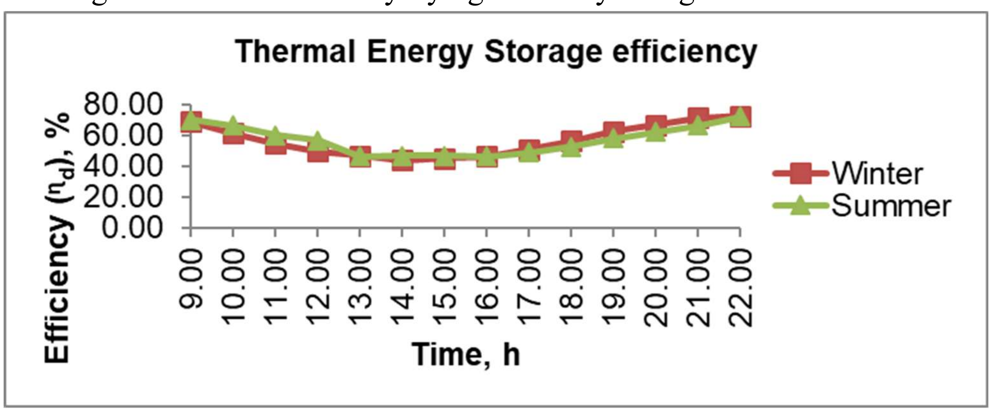


Fig A.8: Variation in hourly thermal energy storage efficiencyduringsummerand winter

CONCLUSION:

The temperature required for drying was maintained inside the solar dryer for the dryingprocessbecauseofphasechangematerial.Theaveragedryingefficiencyofsolardryerwas 15.6 percent and 18.8 percent and average thermal energy storage efficiency was 57.01 percent and 57.20 per cent in summer and winter respectively. Solar cabinet dryer integratedwithPCMwasfoundsuitablefordryingofmedicinalplantseffectivelyduringsummerand winter season.Itrevealsthattemperature of dryingchamberincreasedby12.64°Cand15.03°C over the average ambient temperature in summer and winter respectively.Heatstored in phase change material can be utilized during non-sunshine hours to extend dryingtime upto 5 hours.

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