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Research Article

Design and Construction of a Passive Solar Power Clothing Dryer

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Abstract: This manuscript presents the design and construction of the energy efficient, time saving, cost effective of passive solar powered clothes dryer. This manuscript begins with a derivation of mathematical model represents of solar dryer followed with an analysis of the elements necessary for successfully designing the various components of a solar dryer. The solar drying performance achieved an average drying rate of 0.35 kg/h and drying time of 3 h in a typical day, even under local low ambient humidity of around 35% and at moderate outdoor wind speed. Also, the computational fluid dynamic CFD of transient thermal behavior based on Navier-Stokes equations was used to demonstrate the prevailing temperature rises in the solar natural-ventilation system associated with the internal heat flux due to solar radiation and moisture removal. The efficiency of solar dryer was improved using Nano coating technology. The result showed good agreement between the computational solid simulation and the experimental measurements obtained from this system.

Keywords: Clothing, drying rate, nano coating, solar, solar dryer

INTRODUCTION

Solar drying is a process of using solar energy to dry substances as agricultural products, clothing by heat air and/or the products so as to achieve drying (Ekechukwu, 1999). The solar dryer technologies are basically characterized according to their heating modes, the way they capture, convert and distribute sunlight and how the solar heat is utilized as either passive solar (natural circulation) or active solar (forced convection). Active solar system depends on the using of photovoltaic panels, solar thermal collectors, with electrical or mechanical equipment, to convert sunlight into useful outputs. While the Passive solar system depends primarily on the way of orienting a building to the sun, selecting materials with efficient high storage of thermal energy or light scattering properties and designing spaces that naturally circulate air (Ekechukwu and Norton, 1999). After surveying the published studies, there is a positive trend in the amount of published studies about the subject, however, which describes the use of solar dryer technology for agricultural products especially fruit, vegetable, fish, pepper or crop drying (Sutherland, 1975; Kilkis, 1981; Condorí *et al*., 2001; Bala and Mondol, 2001). Few studies have been performed for cloth or textile drying. Furthermore, the cloth drying techniques were utilizing either in the form of steam by burner or waste heat from heat pump/air conditioning units. Van Deventer (1997) described a method of utilizing superheated steam for cloth drying with direct contact. Adnot (2000) discussed the adaptability of metal fiber burners to industrial paper and textile drying techniques. This method of drying of textiles involving evaporation and combustion require a careful control, high temperature chamber, typically around 600°C. Klöcker *et al*. (2002) reported a laboratory prototype laundry dryer equipped with CO_2 heat pump modified from a commercial hot air laundry dryer. Ameen and Bari (2004) described the utilization of the air conditioner waste heat for drying clothes. They found that the waste heat drying method took about 2 h compared to 2.5 h for a commercial dryer. While recovery technique using waste heat from heat pump or the condenser of air conditioning unit was feasible but the running cost of an air conditioner or heat pump itself was normally considered as expensive.

Torres-Reyes *et al*. (2002) described semi-empirical models for the thermal characterization of an experimental the result of which is an indirect modeling method, derived from the second law of thermodynamics. Gopalnarayanan and Radermacher (1997) described a simulation method for a closed loop pump assisted dryer for clothes drying.

This study will briefly investigate the using solar energy for both drying and ventilation to enhance the drying process of cloth in Jordan. Jordan is located 80 km east of the eastern coast of the Mediterranean Sea. Its location is between 29°11’ N and 33°22’ N and

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between 34°19’ E and 39°18’ E, with an area of 89329 km^2. The potentials of solar radiation in Jordan which it has ranges between 5 and 7 kWh/m^2 on a horizontal surface. This corresponds to a total annual value of 1600-2300 kW h/m^2 (Al-Salaymeh, 2006).

The structure of this manuscript starts by discussing the related research from the body of literature in section one, while the section two presents a derivation of mathematical model of solar dryer. The section three and four discusses the experimental approach and the 3-D thermal transient simulation model respectively. The section five presents the way to improve the efficiency of solar dryer using Nano coating technology. Section six presents the results and the discussion; while section seven summarizes the study findings through the conclusion.

SOLAR DRYER PROCESS-MATHEMATICAL MODEL

The clothing drying phenomenon can be modeled by introducing four factors which are clothing temperature, moisture content, outside temperature and relative humidity value if assuming the changes in the gas phase concentration are negligible compared with that of the solid phase changes (Pakowski and Mujumdar, 1995). To express mathematically of this system, four independent partial differential equations were needed. These four equations are: the drying rate equation, the mass balance equation on the drying air, the heat balance equation on the drying air and the heat balance equation on the cloth (Forson *et al*., 2007). In this model, the dryer walls were considered to be isothermal; these equations are explained below.

The rate of moisture removal from cloth was displayed using the solution of the diffusion equation for a slab-shaped (Okos *et al*., 1992):

$$\frac{M-M_e}{M_o-M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2 D\pi^2 t}{z^2}\right] \tag{1}$$

The diffusion coefficient (Igbeka, 1982):

$$D = \psi(-0.0274 - 5.74\times 10^{-6}\,M + 5.98\times 10^{-6}e^{M} + 0.0275\,e^{-\frac{1}{T}} + 2.23\times 10^{-6}[-2RH + 1.2) \tag{2}$$

where,

M = Average moisture content in the cloth at a particular time (%)
M_e = Equilibrium moisture content of the cloth (%)
M_o = The initial moisture content of the cloth (%)
D = The diffusion coefficient of the wet cloth (m^2/sec)
z = The thickness of the clothing bed (m)
t = The drying time (s)
ψ = A multiplying factor depends on the range of the moisture content of the cloth
RH = Relative humidity of drying air (%)
T = Temperature of drying air (K)

To relate the exchange of moisture between clothing being dried and the drying air, a conservation of mass of the drying air was applied and got a simplified equation (Forson *et al*., 2007):

$$G_a\frac{\partial\omega}{\partial z} = -\rho_P\frac{\partial M}{\partial t} \tag{3}$$

and

$$G_a = \frac{\dot{m}}{A_{dc}} \tag{4}$$

where,

G_a = The mass-flux of drying air ($\frac{kg}{m^2 s}$)
$\dot{m}$ = Mass flow rate of drying air ($\frac{kg}{s}$)
A_{dc} = The effective cross sectional area of the drying bed (m^2)
ω = The humidity ratio of the drying air ($\frac{kg_{water}}{kg_{air}}$)
ρ_P = The bulk density of the wet cloth ($\frac{kg}{m^3}$)

To find the average of the drying air temperature T (K), the energy balance was applied on the drying air:

$$\frac{\partial T}{\partial z} = \frac{1}{G_a(C_{pa}+C_{pw}\omega)} \times [h_v(T_{cl} - T) + \rho_p C_{pw}(T - Tcl\partial M\partial t{-}hvAwApT{-}Tw] \tag{5}$$

where,

C_{pa} = Specific heat capacity of air ($\frac{J}{kgK}$)
C_{pw} = Specific heat capacity of water ($\frac{J}{KgK}$)
h_v = The volumetric heat transfer coefficient ($\frac{W}{m^3 K}$)
T_{cl} = The average temperature of the drying cloth (K)
A_w = The total surface area of the drying (m^2)
A_p = The surface area of the drying bed (m^2)
T_w = The average temperature of the drying walls (K)

The volumetric heat transfer coefficient h_v was correlated to the mass-flux of air G_a by an expression derived by Bala (1983):

$$h_v = 175.07 G_a^{0.6906} \tag{6}$$

Now to find a mathematical expression for the average clothing temperature T (K), a heat balance equation on the wet clothing was applied (Forson *et al*., 2007):

$$\frac{\partial T_{cl}}{\partial t} = \frac{1}{\rho_p(C_{pg}+C_{p1}M)+C''m''}\Big[\alpha_p\tau_p\frac{\overline{H_s}}{\cos\beta} + \frac{h_v A_w}{A_p}(T - T_{cl}) + Ga\partial\omega\partial zCp1T{-}Tcl{+}Lt,cl{-}hr,pwAwAPTcl{-}Tw \tag{7}$$

where,

C_{pg} = The specific heat capacity of the dry matter content of the wet clothing ($\frac{J}{kgK}$)
C_{p1} = The specific heat capacity of moisture (liquid) in the wet clothing ($\frac{J}{kgK}$)
$C^{''}m^{''}$ = The volumetric heat capacity of the drying chamber ($\frac{J}{m^3K}$)
$\overline{H_s}$ = The insolation on the plane of the air-heater ($\frac{W}{m^2}$)
β = The angle of tilt
$L_{t,cl}$ = The enthalpy of vaporization of clothing moisture ($\frac{J}{kg}$)
$h_{r,pw}$ = The radiation heat transfer coefficient from product to the chamber walls ($\frac{W}{m^2K}$)

The enthalpy of vaporization of clothing moisture can be expressed according to correlation of Liley and Gambill (1973):

$$L_{t,cl} = R_v T_{cw} T_{bL} \ln\{\frac{P_{cL}}{10^5}\} \frac{(T_{cw}-T_{cl})^{0.38}}{(T_{cw}-T_{cl})^{0.38}} \quad (8)$$

where;
R_v = The gas constant for water vapor($\frac{J}{kgK}$)
T_{cw} = The critical temperature of water (K)
T_{bL} = The boiling point of water (K)
P_{cL} = the critical pressure of water ($\frac{N}{m^2}$)

Now the mass flow rate entering to dryer can be found using below equation (Adnot, 2000):

$$\dot{m} = \frac{H_e g(\rho_a-\rho_s)c_1\rho_1 A_{dc}}{h_L} \quad (9)$$

where,
$\dot{m}$ = The mass flow rate of drying air ($\frac{kg}{s}$)
H_e = The minimum height between inlet and exit of air heater (m)
g = The gravity acceleration ($\frac{m}{s^2}$)
ρ_a = The density of ambient air ($\frac{kg}{m^3}$)
ρ_s = The average density of air inside the above dryer ($\frac{kg}{m^3}$)
c_1 = Constant and its equal 0.465 for cassava
ρ_1 = The average air density at exit ($\frac{kg}{m^3}$)
h_L = The depth of the drying (m)

EXPERIMENTAL METHODOLOGY

Design consideration: The direct solar and ventilation gains are two crucial parameters should be taken to design of the enclosure of the cloth solar dryer. Direct solar gain through transparent elements is estimated by the following equation (Stoecker and Jones, 1982; Howel *et al*., 1998):

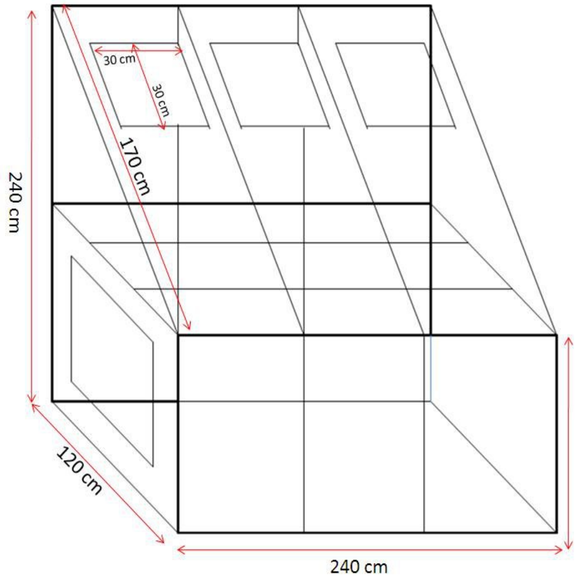


Fig. 1: 3-D schematic diagram of the clothing solar dryer with its basic dimensions

$$Q_s = G \times A \times sgf \quad (10)$$

where,
Q_s = The total direct solar gain (Watt)
G = The total solar ration on the dryer ($\frac{W}{m^2}$)
A = The surface area of dryer (m^2)
sgf = The solar gain factor and it is a function of the type of material and represents the amount of direct radiation that actually makes it through the element into the dryer

The total ventilation gain in watt (Q_v) can be estimated from below equation:

$$Q_v = 20 \times N \times V \times \Delta T \quad (11)$$

where, the value 20 results from the fact that moist air has volumetric heat capacity of 1200 $\frac{J}{m^3K}$ and the flow rate is given as a factor of air changes per minute. Hence, as Watt ($\frac{J}{s}$), then (1200 ($\frac{J}{m^3K}$) / (60 min) = 20 $\frac{J}{m^3K\ min}$, N is the number of air changes per h within the dryer zone, V is the total internal volume of the dryer zone (m^3) ΔT is the temperature difference between inside and outside.

Design description: The frame of clothes dryer is made from aluminum due to its rigidity and light weight. The dryer wall is composed of isolated foam between two layers of tin plastic sheet. Figure 1 displays the 3-D schematic diagram of solar clothing dryer with basic dimension. Figure 2 represents the front and side

Table 1: Specification of the experimental equipment were used

Equipment	Parameter	Photo	Accuracy
Digital thermometer type C	Temperature		±1%°C
Laboratory balance	Weight		±2%
Digital hygro-thermometer (commercial name LAM880D)	Relative humidity		±3% 25°C

Front view Side view

Fig. 2: Front and side views of clothing solar dryer

view of inside solar dryer. The total capacity of the dryer is about 20 clothes. The front and the diagonal surfaces of the enclosure are transparent to maximize the quantity of sunlight absorption.

Experimental setup: A passive solar powered clothes dryer had been successfully built and tested. A series of experiments were carried out in Mutah university, karak, south of Jordan (31°26’ North, 35°44' East) on April 20, 2013. All tests were conducted outdoor on sunny days, low relative humidity within range 30-35% and normal wind speed within range of 3-5 m/sec. The average weight of moisture clothe before dryer around 300 and 150 g after dryer process. The experimental work is set according to the following protocol; during the dryer process, the temperatures, clothing weight and the relative humidity are continuously measured. The inside dryer temperature and ambient temperature were recorded using digital thermometer type C with in accuracy ±1%. The weight of the clothes was recorded using a laboratory balance within accuracy ±2%. And the relative humidity was measured by a digital Hygro-thermometer (commercial name LAM880D) within accuracy ±1% RH. The readings were recorded hourly. All specifications of previous apparatus were used in out experiments are tabulated in Table 1.

CFD-thermal transient simulation: We used the commercial CFD package “Solid Works” (SolidWorks, 2010) to simulate the temperature gradient inside the clothing dryer using the data collected during our experimental measurements. This program was most efficient and accurate in describing the temperature and velocity within the clothing dryer. The air flow tracing and temperature gradient was modeled using Flovent Software Manual (2004) and Siegal and Howel (1992) by solving the classic Navier-Stokes equations through superimposing many hundreds or thousands of grid cells which describe the physical geometry of the air flow and heat transfer as:

$$\frac{\partial}{\partial t}(\rho\varphi) + \nabla\left(\rho v\varphi - \psi^{\varphi}\nabla_{\varphi}\right) = S^{\varphi}$$

[Transient] + [convection] -
[diffusion] = [heat source] (12)

The simultaneous equations are solved iteratively for each one of these cells to produce a solution which satisfied the conservation law of conservation of mass, momentum and energy. As a result, the flow in any part of the cloth dryer can be simultaneously traced using color changes according to change parameters such as temperature and heat flux.

The boundary surfaces conditions were used in the present study are:

- Smooth, zero slip wall
- Pressure-based inlets

The water vapor is modeled as a contaminant in air with molecular diffusivity of 2.6×10^{-5} m^3/sec and its density follows ideal gas law. An initial study based on the above finite volume method coupled with radiation-ventilation module was employed to simulate the internal airflow of the dryer. In this manuscript the following are considered, namely:

- Mass flow and heat transfer
- Solar radiation
- Transient state simulation

Nano-coating technology:

Technology definition and classifications: The Nanotechnology defined as a material becomes more and more finely divided it reaches a point whereby the physical properties that the bulk material possesses begin to differ significantly and it is basically depend on the nano-scale (Singh *et al*., 2004b; Clark *et al*., 1997). The Nano crystalline materials can be classified into three categories depending on the number of dimensions; which are:

Table 2: Classification of nano-crystalline materials

Dimensionality	Designation	Typical method (s) of synthesis
One-Dimensional (ID)	Layered (lamellar)	Vapor deposition Electro deposition
Two-Dimensional (2D)	Filamentary	Chemical vapor deposition Gas condensation
Three-Dimensional (3D)	Crystallites (equiaxed)	Mechanical alloying/milling

- Layered or lamellar structures is a one-Dimensional (1-D) nanostructure in which the magnitudes of length and width are much greater than the thickness
- Filamentary structures is two dimensions
- Equiaxed nano structured materials is three dimensions

The Table 2 presents the three types of nanostructure classification.

1-D nanostructure crystallites can be prepared using electro deposition method by utilizing the interference of one ion with the deposition of the other. Electro deposition yields grain sizes in the nanometer range when the electro deposition variables (e.g., bath composition, pH, temperature, current density, etc.) are chosen such that nucleation of new grains is favored rather than growth of existing grains (Singh *et al*., 2004b; Clark *et al*., 1997). This can be achieved by using high-deposition rates, formation of appropriate complexes in the bath, addition of suitable surface-active elements to reduce surface diffusion of ad atoms and so forth. Electro deposition techniques can yield porosity-free finished products that do not require subsequent consolidation processing. Further, the process requires low initial capital investment and provides high-production rates with few shape and size limitations. In this section two electrochemically were prepared using Nano-coating technology.

Experimental study: Electro deposited Cadmium sulfide CdS films were prepared in a classical double wall, three-electrode cell under nitrogen using a 0.2 M Cadmium Chloride $CdCl_2$ solution on Indium Tin Oxide (ITO) coated glasses as the substrates (Singh *et al*., 2004a; Clark *et al*., 1997). Solutions were prepared using water purified by a Millipore-Mili-Q filtration system. ITO coated glasses were cleaned with a special detergent in an ultrasonic bat 50000 EUh and rinsed and then ultrasonically cleaned with water. As the reference and counter electrodes, saturated calomel and glassy glass electrodes were used, respectively. The pH was changed from 2 up to 4 by using either Hydrochloric acid HCl or Sulfuric Acid H_2SO_4. The Sodium Thiosulfate $Na_2S_2O_3$ concentration was varied between 0.01 and 0.05 M. All chemicals were Aldrich analytical grade. Deposition was performed applying a potential of -0.6V/SCE at 80 and 90°C. Electrochemical experiments were performed using a Voltalab impedance spectroscopy (Singh *et al*., 2004a; Clark *et al*., 1997).

RESULT ANALYSIS

The hand-squeezed clothes were successfully dried in the cloth solar dryer within 3 h, compared to about 5 to 7 h needed for the conventional cloth lines drying under local conditions.

Clothing solar dryer experimental results: The variation of inside natural ventilation of clothing solar dryer temperature and ambient or outside air temperature with time is displayed in Fig. 3, which indicates that as time passes, the outside temperature increases until reaches maximum at 14:00 beyond which it starts to decrease. The temperature range of the internal drying air is around 30-42 °C and the higher inside dryer temperature was occurred at 14:00 due to maximum amount of solar radiation. After that a little deceases of internal dryer temperature. The variation of Relative Humidity (RH) inside the dryer for natural ventilation versus time is depicted in Fig. 4, which indicates that as time passes, the RH decreases until reaches minimum beyond which it starts to decrease due to continuously change of inside dryer temperature and clothing moisture. The variation of clothes weight and moisture removal during drying period is shown in Fig. 5. As shown in this figure, a maximum moisture removal has been occurred during 13:00-17:00 witch have a maximum internal dryer temperatures. The insufficient amount of air change retarded moisture removal through the solar dryer and the clothes' surface ultimately lead to slow moisture removal. So, the potential difference thus speeds up the separation process in between the moisture and the cloth surface through enhancement of evaporation, convection and diffusion. Therefore, higher percentage of water vapor escaped quickly forms the boundary surface of the cloth due to relatively lower concentration of moisture. This causes higher internal humidity in the dryer initially as shown in Fig. 4 and 5. However, these escaped moisture or vapor continuously removes from the dryer by natural-ventilation. As a result, total cloth drying time is reduced.

A review on the past work has shown that the present drying method assisted with natural-ventilation poses equivalent average moisture removal rate (0.35 kg/h) compared to that reported by Ameen and Bari (2004) where waste heat from air conditioning (average moisture removal rate = 0.42 kg/h) and a commercial cloth dryer were used for drying respectively, as shown in Table 3. Nevertheless, present study took longer complete drying time of 3 h compared to 2 and 2.5 h by waste heat and the commercial dryer respectively. Waste heat drying method has the advantage of higher removal rate at initial testing period and shorter drying time; this further confirms that result from the present study could be possibly improved by increasing the

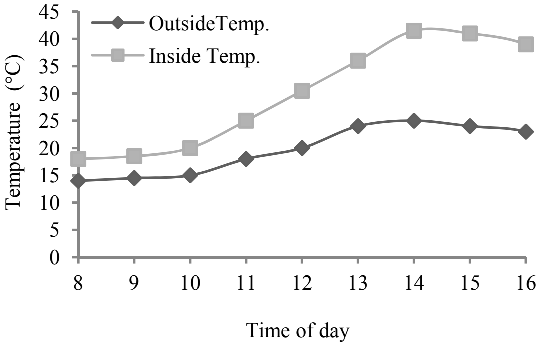


Fig. 3: The variation of inside natural ventilation of clothing solar dryer temperature and ambient or outside air temperature versus time

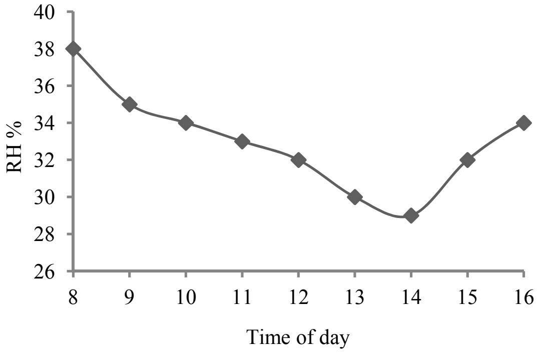


Fig. 4: The variation of inside natural ventilation of clothing solar dryer relative humidity versus time

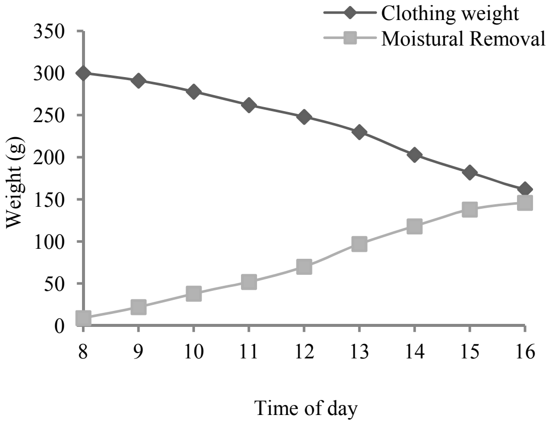
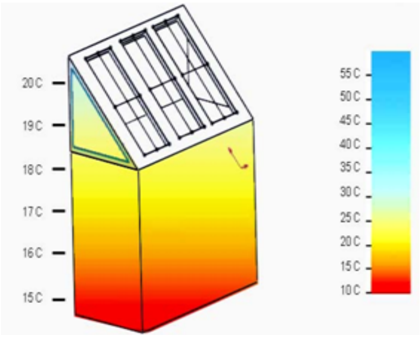


Fig. 5: The variation of clothes weight and moisture removal during dryer period

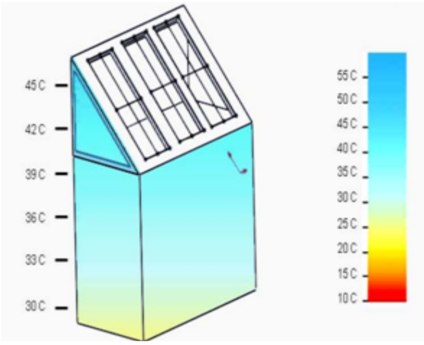
Table 3: Comparison of drying menthods performance

Drying method	Average drying rate, kg/h	Total drying time, h
1. Waste heat from air conditioning	0.42	2.0
2. Commercial cloth dryer	0.52	2.5
3. Present study	0.35	3.0

internal temperature and amount of moisture removal, particularly at initial drying period.



@ time = 10 min



@ time = 180 min

Fig. 6: Temperature profile simulated at (a) time = 10 min; (b) time = 180 min

Simulation results: The simulation of temperature distribution inside the clothing dryer using commercial CFD package "Solid Works" after time passes of 10 and 180 min are shown in Fig. 6a and b, respectively. The figure shows that at t = 10 min, the initial temperature profile was not much different with that of the ambient temperature profile Fig. 3, which has an average temperature around 17°C. The highest temperature (yellowish) region, initially only found at the upper portion of the dryer. But gradually the temperature was buildup with time. After 180 min, about 60% of the upper portion of the attire area was having a temperature of around 40-50°C or more due to heat flux generation, as shown in Fig. 6b.

The simulation results obtained from the natural-ventilation study came close to that of the experiment works. As shown in the previous experimental results the moisture removal or cloth drying prediction was found fairly well-matched to that of the experimental works, although the experiment result has somewhat lower drying efficiency performance after approximately 30 min or 1 h.

Nano-coating technology results: The effect of using Nano coating technology on the drying process is illustrated in Fig. 7 and 8, which indicates that the improvement on the drying process, efficiency of the

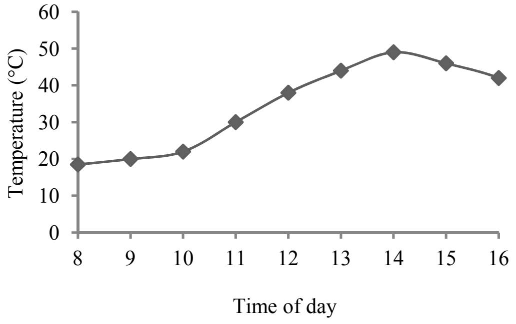


Fig. 7: The variation of inside natural ventilation of clothing solar dryer temperature versus time using nano coating technology

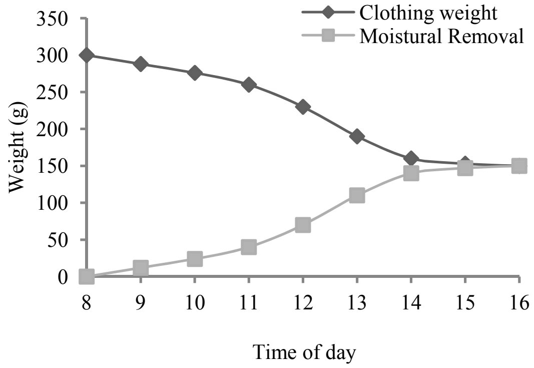


Fig. 8: The variation of clothes weight and moisture removal during dryer period using nano coating technology

system and reduced the drying time due to Increase the amount of solar absorption and reduced the radiation reflected from the outside surfaces.

In general, the Nano-structured layers in thin film solar cells offer three important advantages (Singh *et al*., 2004b; Kadırgan, 2000):

- **Firstly:** Due to multiple reflections, the effective optical path for absorption is much larger than the actual film thickness.
- **Secondly:** The light of electrons and holes generated will need to travel much shorter path and will lead to reduce losses As a result, the absorber layer thickness in Nano-structured solar cells can be as thin as 150 nm instead of several micrometers in the traditional thin film solar cells.
- **Finally:** The energy band gap of various layers can be tailored to the desired design value by varying the size of Nano-particles. This allows for more design flexibility in the absorber and window layers in the solar cell. So, the our objective is to make a porous structure of CdS, deposit an absorber material like, copper indium dieseline, copper sulfide or cadmium telluride into the pores.

CONCLUSION

We elucidated in great detail our optimal design strategy using the different components of our passive solar power clothing dryer. We conducted these experimental investigations to study the temperature, relative humidity and moisture removal variation inside the clothing solar dryer and effect on the system performance. We also used our CFD to simulate the performance of clothing solar dryer, particularly the temperature profile inside the dryer. This study results can be usefully summarized into following points:

- The natural ventilation solar drying performance achieved an average drying rate of 0.35 kg/h and drying time of 3 h in a typical day, under local low ambient humidity of around 35% and at moderate outdoor wind speed.
- It can be deduced that more airflow and heat flux is important especially in the early stages of drying to further remove free moisture around the clothes' surface.
- Both experimental and simulation work conducted has shown that cloth drying rate increases with temperature rise, heat flux and moisture removal.
- The efficiency of solar dryer was improved using Nano coating technology.

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