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Design and experimental evaluation of a mixed-mode continuous solar dryer for plaster molds †

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Abstract

This work aimed to develop and evaluate a mixed-mode continuous solar dryer for plaster molds for the local craft ceramics industry to reduce the drying time during the pottery manufacturing process. This novel design reduces time and movements in the manufacturing line. Indirect solar energy is used to complement direct solar energy; such a combination allows the continuous drying process to meet the energy requirements and optimize solar energy expenses. The experimental results show that the average evaporation rate is 0.7 kg/hr, the average energy consumption is 2.57 MJ/kg-H_2O-evaporated, and the drying time is 4 days. The actual drying time represents 20% to 29% of the total foregoing time employed by Morelos-México craft potters. This finding indicates that the dryer continuously works using 66.4% indirect and 33.6% direct solar energy, thereby entailing lower expenses than traditional continuous drying processes.

Keywords: Mixed-mode solar dryer; Plaster molds; Continuous operation; Solar dryer; Dryer system; Experimental evaluation

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1. Introduction

One of the current, most promising forms of renewable energy is solar heating [1, 2]. Solar drying at less than 50°C can greatly contribute to energy sustainability worldwide [3]. Solar drying applications are very extensive [4-8]. However, interruptions or fluctuations in the energy supply during long working periods restrict some applications, such as direct solar drying [9] and most cases of indirect solar drying, which require working periods of days or weeks.

Most solar thermal applications are facilitated by a continuous supply of energy. This continuous supply is commonly required by industrial processes, and energy interruptions greatly reduce the manufacturing performance. Therefore, a continuous supply of energy is necessary for most industrial processes.

Indirect solar dryers enable better and faster drying, thereby reducing damage to products during the process. Nevertheless, these kinds of dryers considerably increase the initial investment and operating cost as opposed to direct solar drying. Several types of indirect solar dryers were mainly developed to improve the quality of food products in terms of color, texture, or taste. Other indirect dryers were developed to optimize the drying time and achieve better efficiency for short periods [10-14]. An example of an indirect dryer is a mixed dryer, which is mainly used for food preservation. This dryer generally comprises a solar collector system and a drying chamber. Mixed dryers have been studied to increase energy gains and reduce solar energy expenses, but their operation is only possible during daytime [15-17]. Consequently, the use of this kind of solar dryer to achieve continuous drying for several days has not yet been fully investigated. However, combinations can enhance the drying time, lessen the cost of energy (direct solar energy costs less than indirect solar energy), and avoid the fast degradation of products due to weathering [13, 18-21].

In the craft potter ceramic manufacturing process, drying usually limits the production capacity because the molds are dried outdoors or almost outdoors, or by placing them near high-temperature ovens with little temperature control. Consequently, there is no drying homogeneity and the relative humidity during the drying phase becomes uncertain. As recommended by plaster manufacturers, the goal during the drying process is to dry a material below 50°C to avoid mold calcinations [22, 23]. Attributes such as low relative humidity, good batch homogeneity, high air velocity, and low drying time are desirable because all of them enable maximum profitability in terms of the best cost benefit [16, 24]. The quality of dried molds is reflected in the moisture content (about 7%), mold batch homogeneity, and long mold lifetime.

The craft ceramic process usually involves nine steps, and

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eight of them can be accomplished only in hours. However, mold drying by the traditional drying techniques takes weeks. An example is the case of Morelos-México craft potters, where drying is completed between 14 and 21 days [25]. The drying of the plaster molds can be enhanced by minimizing adverse outdoor conditions and realizing continuous drying for several days. The drying kinetics and energy consumption of drying plaster molds was reported only for specific drying conditions [23] that can be achieved only with specialized ovens, which are not affordable to the local craft industry.

This study aimed to develop and evaluate a mixed continuous solar dryer that can work day and night for several days using low-cost solar energy. The dryer allows the current timeline of the craft pottery process to be reduced, and employs a desirable temperature of less than 50°C to extend the useful life of plaster molds. The dryer is tested in the manufacturing process of Morelos-México craft pottery industry, which is similar to many other potters worldwide [26].

2. Materials and method

The dryer was evaluated in terms of the drying kinetics (drying time), efficiency, and solar energy expenses. Solar energy was assessed according to the fraction of direct energy that can be used to achieve continuous drying.

2.1 Experimental design

The adequate moisture content in the dry and wet molds was determined by measuring two batches of 50 molds each provided by the local potters. Based on the experience of the workers, one batch was labeled as dry and ready for ceramic manufacturing. The other was considered wet and not ready for ceramic manufacturing. The measured moisture contents of each batch were 7.0% ± 1.0% (wb) for the molds ready for manufacturing and 24.0% ± 1.0% (wb) for those considered still wet. The average mold sample size was 21.0 × 17.5 × 19.0 cm^3, which is considered a medium size by Cuernavaca-México potters [25]. A maximum of 50°C drying temperature was employed to avoid mold calcination, as recommended by the plaster manufacturer [23]. Before each test, 32 molds (416 kg) were soaked in water for 24 h. They were then placed and distributed uniformly into the chamber on the work table. The tests were duplicated for comparison during sunny and cloudy days in the semi-warm, semi-humid climate of Cuernavaca, Morelos, México.

The dryer operates when the solar water heater works with the solar energy irradiance Q_{s1} and supplied heating Q_{whs} to the heat exchanger to achieve air flux with lower relative humidity. The solar air heating Q_{ahs} is a heating complement that supplies energy to provide continuity during the drying process throughout day and night. The drying chamber receives Q_{ahs} and Q_{s2} to remove water content from the molds, and then expends Q_{ds} to evaporation (Fig. 1).

The thermal performance of the dryer was analyzed by the drying kinetics and calorimetry, taking into account the drying constant, drying time, dryer efficiency η_{ds}, solar water heating efficiency η_{whs}, and air heating efficiency η_{ahs}. The latter was used to determine the performance of the dryer independently of the kind of power supply. The direct and indirect solar energy consumption per kilogram (MJ/kg-H_2O evaporated) was evaluated to obtain the fraction of direct energy (f_{dd}) used.

The drying kinetics is given by Eq. (1):

$$dM/dt = -k\left[M_{db} - M_e\right] \tag{1}$$

where the dry basis moisture content M_{db} is the ratio of the weight of moisture present in the product over the dry weight unit of matter in the product, as shown in Eq. (2):

$$M_{db} = \frac{m_{wet} - m(t)}{m_{wet}} \tag{2}$$

where m_{wet} is the weight of the wet product (kg) and $m(t)$ is the weight of the product to be dried (kg). The drying constant is calculated for the falling drying rate period $M = M_o \exp(-kt)$, as shown in Eq. (3) [9]:

$$k = ln\left[\frac{M(t)}{M_o}\right]^{-1/t}. \tag{3}$$

The standard error of the estimate was calculated by Eq. (4):

$$E = \sqrt{\frac{\sum\left(M_{measured} - M_{calculated}\right)^2}{N-1}}. \tag{4}$$

The thermal efficiency of the solar drying, air heating, and water heating were calculated by Eqs. (5)-(7), respectively.

$$\eta_{ds} = \frac{Q_{ds}}{Q_{s1} + Q_{s2} + Q_{ST}} \tag{5a}$$

$$\eta_{ds} = \frac{\int_0^{t_f} \dot{m}_{rem}\, h_{fg}(T_C)dt}{A_{sc}\int_0^{t_f} Gdt + A_d\,\tau \int_0^{t_f} Gdt + m_{ST}Cp\left[T_{ST}(0) - T_{ST}(t_f)\right]} \tag{5b}$$

$$\eta_{ahs} = \frac{Q_{ahs}}{Q_{s1}} = \frac{\int_0^{t_f} \dot{m}_{ex}Cp\left[T_a - T_{amb}\right]dt}{A_{sc}\int_0^{t_f} Gdt} \tag{6}$$

$$\eta_{whs} = \frac{Q_{whs}}{Q_{s1}} = \frac{\int_0^{t_f} m_{ST}Cp\frac{dT_{ST}}{dt}dt}{A_{sc}\int_0^{t_f} Gdt} \tag{7}$$

where A_d is the dryer surface projected on the horizontal sur-

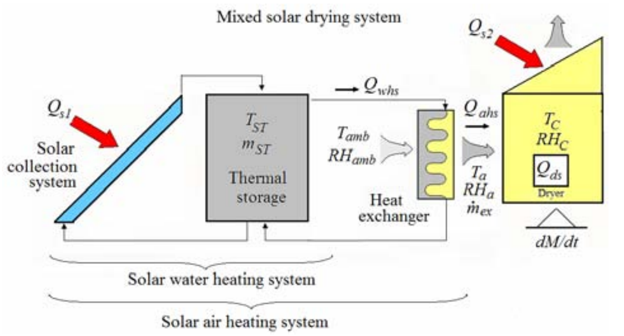


Fig. 1. Solar drying system.

face and τ is the daily cover transmittance on the horizontal surface.

To determine the percentage of less expensive solar energy used in the manufacturing process, a new factor is proposed in Eq. (8) to show the fraction of direct solar energy over the solar energy required to dry the molds. This fraction corresponds to the percentage of cheaper solar energy that can be used in the process.

$$f_{dd} = \frac{Q_{ar\_sh}}{\left[Q_{ar\_slh} + Q_{ar\_sh}\right]} \tag{8}$$

where Q_{ar_sh} and Q_{ar_slh} are the drying energies required during the operation with and without sufficient direct solar radiation, respectively. The uncertainty of each figure of merit is determined considering the general law of error propagation [27].

2.2 Experimental design

The dryer was designed using the structured design methodology considering the need statement, main constraints, main functions, design condition, critical parameters, and functional alternatives. Many of these factors were collected from a representative group of Cuernavaca-México potters. The design conditions considered drying continuity in cycles of several days, optimization of movements and time, and low solar energy expenses, among others. The proposed functional alternatives were run individually using an abstraction cycle design method [28-30].

The solar dryer equipment starts to operate when the air is warmed by direct solar energy through the translucent cover and/or by the storage water heater using the heat exchanger. Therefore, the dryer works with direct and indirect solar heating. Direct energy is supplied when it is available and indirect heating is complementary. The drying system is shown in Fig. 1.

The dryer was manufactured and installed at Centro Nacional de Investigación y Desarrollo Tecnológico (Cuernavaca, México). Fig. 2 shows the experimental setup. The dryer system consists of a drying chamber, a heat exchanger, and a storage solar water heater. In the drying chamber, we utilized a drying work table, a translucent cover, an air supply duct, and two fans to drain the wet air. The translucent cover har-

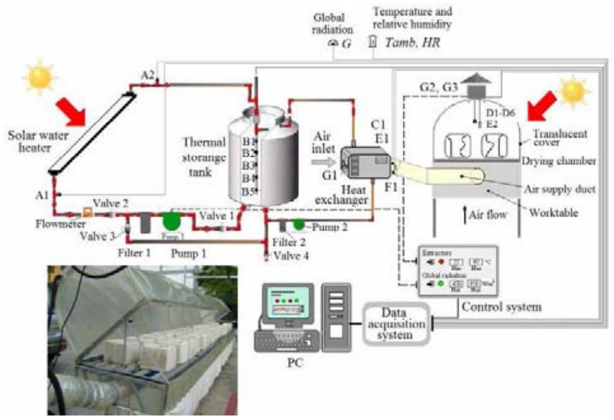


Fig. 2. Experimental setup.

nesses solar energy gains because its transmittance is 78% during daytime on the drying bed (Fig. 2). The drying chamber is 6.0 m long, 0.90 m wide, and 1.1 m high. Its hinges allow the opening angle to reach up to 50° to load and unload the plaster molds. An air supply duct with scattered outlets centered under the drying bed allows homogeneous air distribution over the drying bed. The work table facilitates the following steps: filling, emptying, and removing the ceramic pieces, similar to the traditional work table of the potters. It also eliminates movements when loading and unloading during the drying step until the molds are out of the production line. The heat exchanger couples the drying chamber with the storage solar water heater. The water heater has 7.45 m^2 flat collection area and a 2 m^3 thermal storage tank. Its capability is 43.5 MJ-day under the semi-warm, sub-humid climate of Cuernavaca, Morelos, México. The storage system can supply energy for two days under continuous poor sunny weather. After preheating for 2 days, the average storage temperature can exceed 45°C (>72 MJ).

Temperatures were measured using a LM35 sensor (National Semiconductor) with an uncertainty of ±0.5°C. Relative humidities were measured using Vaisala-HMP50 sensors with an uncertainty of ±3%. Solar radiation was measured using a first-class Eppley-type A pyranometer with an uncertainty of ±1%. Water flow was measured using a GPI turbine flow meter with an uncertainty of ±2%. Air velocities were measured using an Alnor-8525 thermo-anemometer with an uncertainty of ±5%. The ambient temperature and relative humidity were measured using a Vaisala-HMP45A sensor with uncertainties of ±0.2°C and ±2%, respectively. A Vaisala-Maws110 16-bit data acquisition system was used to monitor and record the ambient variables. A NI-PXI 32-bit data acquisition system was used for the rest of the variables.

2.3 Experimental procedure

The drying test starts when the fan (G_1) circulates air inside the drying chamber after recording the weight of wet molds and when the global solar radiation becomes sufficient to heat the inner drying chamber. The direct solar radiation passes through the translucent cover of the chamber and heats its interior. If the solar radiation is insufficient for heating, the solar water heating system then provides complementary energy. The indirect air heater starts at 17:00 h when the solar radiation is frequently less than 450 W/m^2 on average, which occurs when Pump 2 and G_1 heat the air using the thermal storage of the solar heater. G_1 provides air flow at 75 m^3/h to the drying chamber. When the chamber temperature exceeds 50°C, G_2 and G_3 are switched on to remove excess heat from the chamber, thereby avoiding rapid plaster degradation by calcination. On the other hand, when the water temperature of thermal storage is less than 55.0°C and solar radiation is greater than 450 W/m^2, Pump 1 starts to operate. The test is terminated as soon as the change in moisture content is within ±0.25% for 24 h.

During the drying test, the meteorological and drying variables are monitored to calculate the thermal performance of the dryer using Eqs. (1)-(7). The solar radiation G, ambient temperature T_{amb} and relative humidity RH were measured and recorded every hour as meteorological variables. The following drying variables were determined and recorded at 1 min intervals: RH in the inlet chamber (E_1), RH in the inner chamber (E_2), inner temperature of the thermal storage (B_1-B_5), inlet air temperature (T_{amb}), six inner chamber temperatures (D_1-D_6), and air velocity (F_1). The weight of the molds was recorded twice daily at 12:00 and 18:00 h. The moisture content was calculated considering the wet and dry weights of the molds over the process.

The potter drying experience was used as the baseline to assess the progress and evaluate the impact of the proposed dryer. Generally, craft potters can dry from 24% ±1% to 7% ±1% of the molds, which takes 3 to 4 weeks in semi-open areas with different distributions and batch sizes under Cuernavaca weather conditions (average T_{amb} = 21.2°C and RH = 57%) [31].

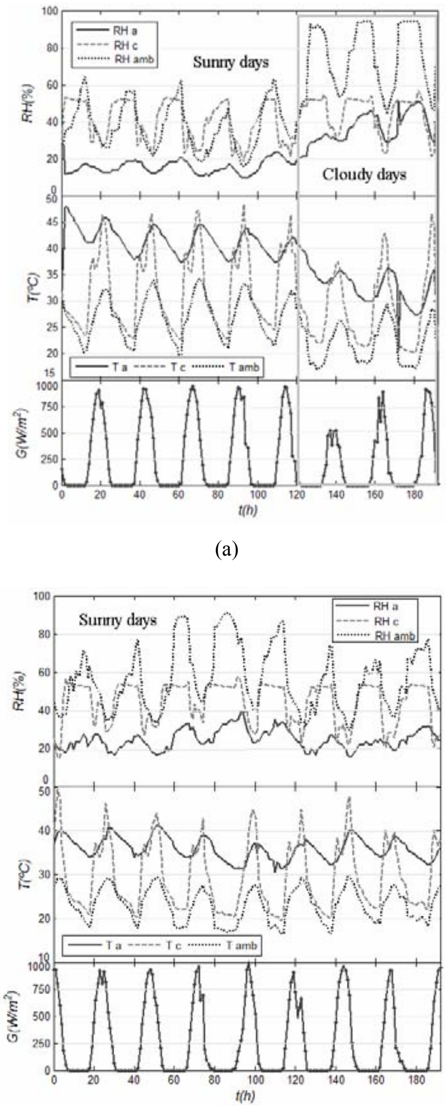
3. Results and discussion

Test 1 (May 31 to June 7, 2008) and Test 2 (June 19 to 27, 2008) were carried out on clear and cloudy days under outdoor conditions. Fig. 3 shows the relative humidities, temperatures, and global solar radiation for both tests (192 h each). Table 1 summarizes the average values. The average solar radiation, ambient temperature, and relative humidity were 21.12 MJ/m^2 per day, 24.1°C, and 55% on average for both tests, respectively.

Fig. 4 shows a psychrometric analysis of the ambient air during the drying process for both tests. Ambient air was first heated (from 1 to 2) and the mold was then dried (from 2 to 3). Fig. 4 shows that during the drying process, air heated on sunny days had twice the drying capacity in terms of the relative humidity compared with air heated on cloudy days. However, drying during cloudy weather took twice the time. Considering both tests, the drying air that flowed through the dryer

Table 1. Average drying conditions during the tests.

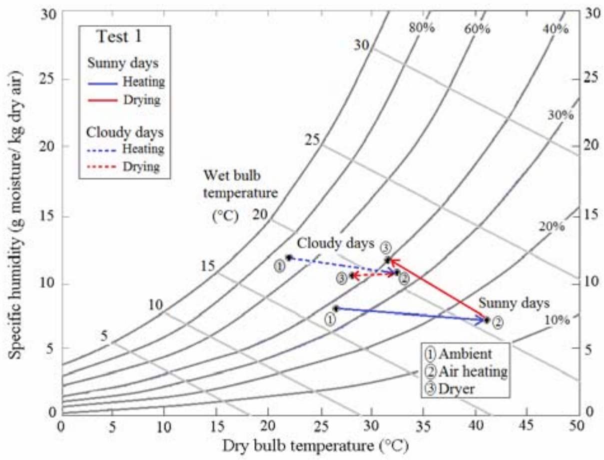
Variables (conditions during tests)	Test 1	Test 1	Test 2	Average
	Sunny	Cloudy	Sunny	
RH_{amb} (%)	37	73	56	55
RH_a (%)	15	36	24	25
RH_C (%)	40	45	44	43
T_{amb} (°C)	27.0	22.1	23.1	24.1
T_a (°C)	41.3	33.0	35.9	36.7
T_C (°C)	32.1	28.3	29.5	30.0
G (MJ/m^{2}day)	23.8	17.1	22.4	21.1
$RH_a - RH_{amb}$ (%) *Heating*	-22	-37	-32	-30
$RH_C - RH_a$ (%) *Drying*	25	9	20	18
$SH_C - SH_a$ (g moisture/kg dry-air)	5	3	1	-------



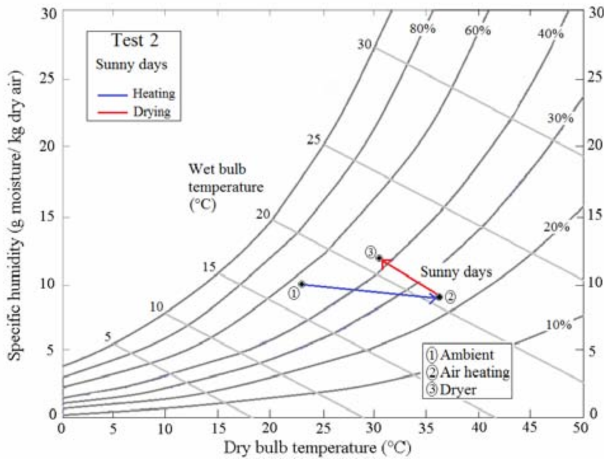
(a)

(b)

Fig. 3. Summary of weather and drying conditions for (a) Test 1; (b) Test 2.



(a)



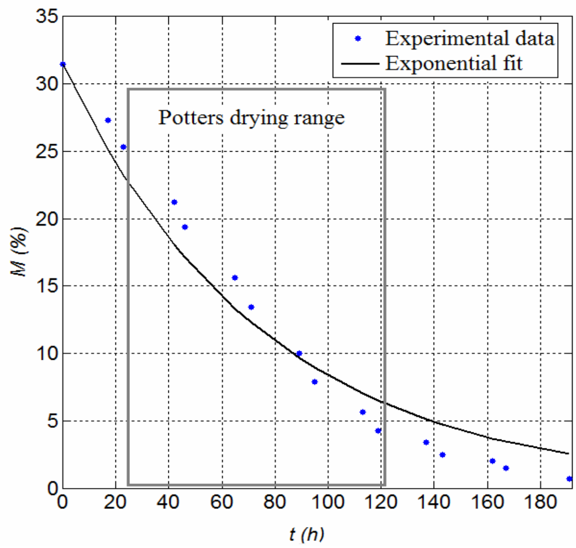
(b)

Fig. 4. Psychrometric analysis of the drying process: (a) Test 1; (b) Test 2.

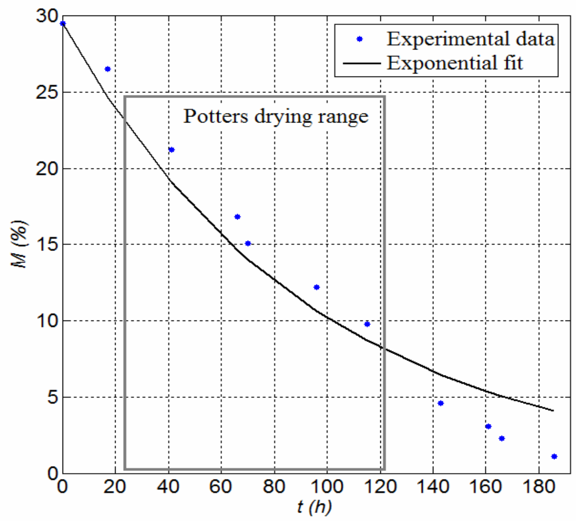
with RH_{amb} values of 37%, 56%, and 73% removed 5, 3, and 1 g-moisture/kg-dry-air, respectively. Thus, the capacity to remove water behaves linearly as a function of the ambient relative humidity within the studied range.

The drying kinetics of both tests is shown in Fig. 5. The total drying time, from 30% ±1% to 1% ±1%, was 192 h on average. By contrast, the potter drying time, from 24% ±1% to 7% ±1%, was 96 h (4 days) on average. This value represents only 20%–29% of the potter drying time based on traditional techniques, which usually takes 2–3 weeks. Fig. 5(a) and (b) show the exponential behavior within the potter drying range, as expressed in Eqs. (9) and (10). The drying constants according to Eq. (2) for Tests 1 and 2 were 0.013 and 0.011, respectively. The results from the drying equation are as follows:

$$M = 31.44 \exp(-0.013t) \qquad \text{Test 1} \tag{9}$$
$$M = 29.53 \exp(-0.011t) \qquad \text{Test 2} \tag{10}$$



(a)



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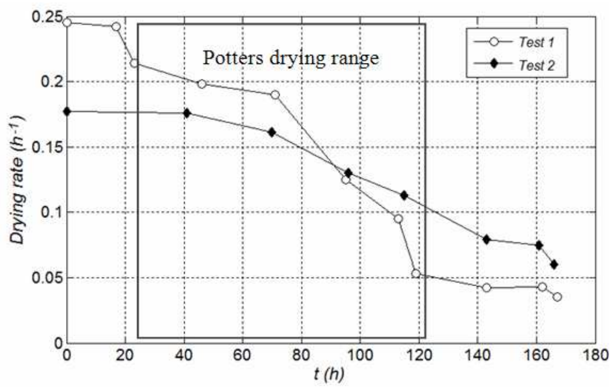

(c)

Fig. 5. Drying kinetics for (a) Test 1; (b) Test 2; (c) Drying rates for Tests 1 and 2.

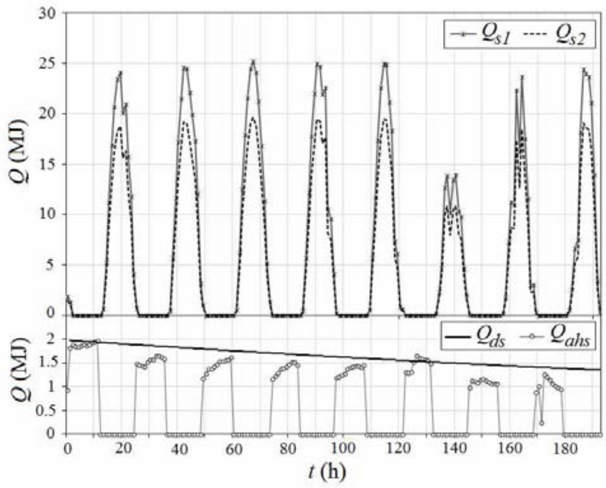

Fig. 6. Energy consumption during the drying process supplied by direct and indirect solar energy for Test 1.

where the average standard error of estimate for both tests were 0.062 and 0.070, respectively. In the same way, the coefficients of determination (R^2) were 0.963 and 0.956, respectively. Water was continuously removed at an average evaporation rate of 0.68 kg/h for total drying and 0.71 kg/h for potter drying. Fig. 5(c) also shows the drying rate, where the potter drying range was mainly within the falling drying rate period.

The energy consumption during the drying process and the energy supplied directly and indirectly for Test 1 are shown in Fig. 6. Fig. 6 also shows that the direct solar energy Q_{s2} was sufficient for drying for 7.9 h per day; thus, the remaining daytime was covered by the indirect solar energy Q_{ahs}. The required energy for drying was 39.4 MJ/day. The direct solar energy supplied was 13.2 MJ/day, and the indirect solar energy complemented the remaining 26.2 MJ/day. The f_{dd} factor was 0.336, which corresponded to 33.6% direct solar energy, indicating lower energy expenses than those of traditional drying techniques. The average energy consumption of this mixed dryer was 2.57 MJ/kg-H_2O evaporated, lower than those of conventional dryer bands (4–6 MJ/kg-H_2O evaporated per product in general [32], and 3.04 MJ/kg-H_2O evaporated for specialized ovens for plaster molds [23]).

The thermal solar water heater efficiency, solar air heater efficiency, and solar dryer efficiency were 0.35 ±0.07, 0.19 ±0.01, and 0.12 ±0.02, respectively. However, if direct solar energy was considered, the solar dryer efficiency was 0.21 ±0.02. In this case, the dryer efficiency was greater than the air heater efficiency because the humidity of ambient air slightly dried the molds.

4. Conclusion

The results showed that the mixed-mode solar plaster dryer achieved continuous drying throughout day and night under clear or cloudy skies for several days. Under the weather conditions in Cuernavaca, Morelos, México, 32 medium-sized plaster molds were dried at an average evaporation rate of 0.7 kg/h, thereby satisfying the requirements of potters.

The novel design considered a work table for three manufacturing stages without moving the molds, and labor was reduced during the manufacturing process. The energy supplied by direct solar energy for continuous drying was 33.6%, which implies lower energy costs than those for traditional techniques, i.e., continuous drying completely by indirect solar energy [6, 12, 15]. The cost of indirect solar energy with respect to direct solar energy for this dryer was about 30 times higher primarily due to the high capital and operating costs. The potter drying time decreased from 2–3 weeks to 4 days on average. This value corresponded to only 20%–29% of the time currently employed for the process, thereby indicating reduced cost. The cost can be further amortized over time due to the decreased operational costs, longer mold life, as well as reduced process time and movements.

Clear and cloudy days changed the drying capacity of air because of the changes in RH_{amb} based on the cloudiness of the day. Drying during cloudy weather took twice the time than during sunny days. The evaporation rate decreased linearly with increased RH_{amb} within the study range. On the other hand, direct solar energy was consumed inefficiently during daytime. This excess direct solar energy led to increased inner drying chamber temperature; thus, a cooling system was required to avoid plaster calcination. Stricter control of the mold surface temperature can improve the dryer performance.

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Nomenclature

A	: Area, m^2
Cp	: Specific heat, J/kg °C
G	: Solar radiation, W/m^2
E	: Standard error of the estimate, dimensionless
f	: Fraction of energy, dimensionless
h_{fg}	: Latent heat of water vaporization, kJ/kg
RH	: Relative humidity, %
k	: Drying constant, /h
$\dot{m}$	: Flow rate, kg/s
m	: Weight, kg
M	: Wet basis moisture content, %
η	: Efficiency, dimensionless
Q	: Energy, MJ
SH	: Specific humidity, g moisture/kg dry-air
T	: Temperature, °C

t : Elapsed time, h
τ : Solar transmittance, dimensionless

Subscripts

a : Outlet of the air heater
ahs : Air heating system
amb : Ambient (inlet air)
ar : Water removal
d : Dryer
db : Dry basis
C : Inside the dryer
ds : Drying system
e : Equilibrium
ex : Heat exchanger
f : Final
o : Initial
rem : Removal
s1 : Solar energy irradiance
s2 : Solar energy irradiance in the dryer
sc : Solar collector
sh : Time with sufficient direct solar radiation
slh : Time without sufficient direct solar radiation
ST : Thermal storage
whs : Solar water heating system

References

[1] O. Bolaji Bukola and P. Olalusi Ayoola, Performance evaluation of a mixed-mode solar dryer, *AU Journal of Technology*, 211 (4) (2008) 225-231.

[2] V. Belessiotis and E. Delyannis, Solar drying, *Solar Energy*, 85 (8) (2011) 1665-1691.

[3] D. Lorriman, *Solar heating and cooling (SHC) programme*, International Energy Agency (IEA) Task29 (2006). Duration: January 1, 2000 to May 31, 2006. Visited on January 20, 2012, 17:00 H. See also: http://www.iea-shc.org/task29/index.html.

[4] S. Shobhana and K. Subodh, Testing method for thermal performance based rating of various solar dryer designs, *Solar Energy*, 86 (2012) 87-98.

[5] A. A. El-Sebaii and S. M. Shalaby, Solar drying of agricultural products: A review, *Renewable and Sustainable Energy Reviews*,16 (2012) 37-43.

[6] V. Belessiotis and E. Delyannis, Solar drying, *Energy*, 85 (2011) 1665-1691.

[7] A. Fudholi, K. Sopian, M. H. Ruslan, M. A. Alghoul and M. Y. Sulaiman, Review of solar dryers for agricultural and marine products, *Renewable and Sustainable Energy Reviews*, 14 (2010) 1-30.

[8] E. K. Akpinar, Energy and exergy analyses of drying of eggplant slices in a cyclone type dryer, *KSME International Journal (Journal of Mechanical Science and Technology)*, 19 (2005) 692-703.

[9] E. K. Akpinar, Mathematical modelling and experimental investigation on sun and solar drying of white mulberry, *Journal of Mechanical Science and Technology*, 22 (8) (2008) 1544-1553.

[10] D. R. Pangavhane, R. L. Sawhney and P. N. Sarsavadia, Design, development and performance testing of a new natural convection solar dryer, *Energy*, 27 (2002) 579-590.

[11] L. Bennamoun and A. Belhamri, Desing and simulation of solar dryer for agriculture products, *Journal of Food Engineering*, 59 (2003) 259-266.

[12] A. Madhlopa and G. Ngwalo, Solar dryer with thermal storage and biomass-backup heater, *Solar Energy*, 81 (2007) 449-462.

[13] G. Çakmak and C. Yıldız, Design of a new solar dryer system with swirling flow for drying seeded grape, *International Communications in Heat and Mass Transfer*, 36 (2009) 984-990.

[14] A. Sreekumar, P. E. Manikantan and K. P. Vijayakumar, Performance of indirect solar cabinet dryer, *Energy Conversion and Management*, 49 (2008) 1388-1395.

[15] A. A. Gatea, Performance evaluation of a mixed-mode solar dryer for evaporating moisture in beans, *Journal of Agricultural Biotechnology and Sustainable Development*, 3 (4) (2011) 65-71. http://www.academicjournals.org/JABSD.

[16] M. Y. Hussain, Islam-ud-Din and M. Anwar, Dehydration of agricultural products by mixed mode solar dehydrator, *International Journal of Agriculture & Biology*, 10 (3) (2008) 333-336.

[17] A. A. Zomorodian and M. Dadashzadeh, Indirect and mixed mode solar drying mathematical models for sultana grape, *Journal of Agricultural Science and Technology*, 11 (2009) 391-400.

[18] B. M. A. Amer, M. A. Hossain and K. Gottschalk, Design and performance evaluation of a new hybrid solar dryer for banana, *Energy Conversion and Management*, 51 (2010) 813-820.

[19] D. S. Roosevelt, S. Sadulla and T. Ramasami, Solar dryer for leather and a comparative study on the characteristics of open-solar- and electrical-dried leather, *Renewable Energy*, 19 (2000) 123-134.

[20] B. Bena and R. J. Fuller, Natural convection solar dryer whit biomass back-up heater, *Solar Energy*, 72 (1) (2002) 75-83.

[21] J. Banout, P. Ehl, J. Havlik, B. Lojka, Z. Polesny and V. Verner, Design and performance evaluation of a Double-pass solar drier for drying of red chilli (Capsicum annum L.), *Solar Energy*, 85 (3) 506-515.

[22] Website: Industrial products division of united states gypsum Co., *Drying Plaster Molds*. Duration: March 01 (2002). Visited on February 10, 2012, 14:00hr. See also: http://www.ceramicindustry.com/articles/drying-plaster-molds.

[23] United States Gypsum Company, *Drying plaster casts*, IG502/rev. 7-00 Printed in U.S.A. Updated 30 March 2005. Visited on March 01, 2012, 18:00hr. See also: http://plaster.com/Howtoguides/DryingProcedures.pdf.

[24] M. V. Ramana Murthy, A review of new technologies, models and experimental investigations of solar driers, *Renewable*

and Sustainable Energy Reviews, 13 (2009) 835-844.
[25] J. J. Flores, *Drying plaster molds for ceramic industry*, FOMIX 2004-C02-040, CENIDET-SEP, Final Project Report, Cuernavaca, Morelos, México, 116 pages.
[26] Website: *Drying plaster mold question*. Updated 22 Feb 01.Visited on March 02, 2012, 01:18 H. See also: http://www.potters.org/subject38176.htm.
[27] Centro Nacional de Metrología, Dirección de Metrología Eléctrica, *Guía BIPM/ISO para la expresión de la incertidumbre en las mediciones*, Reporte técnico CNM-MED-PT-002, Los Cués, Querétaro, México (1994) 134 pages.
[28] M. E. Baltazar-Lopez, J. C. Bahena-Bustos, R. Castillo-Rincon, J. J Flores-Prieto and D. Perez-Salmeron, Modelling, design and construction of a solar space conditioning system, *Proc. of Virtual Concept*, Playa Del Carmen, México (2006) 11 pages.
[29] K. Seyyed, *Engineering design process*, IISME / Solectron/2005, California, USA (2005) 1-24.
[30] K. Wallace and J. Clarkson, *An introduction to the design process*, Cambridge University Press, Cambridge, Department of Engineering (1999) 1-18.
[31] Website: CONAGUA, *Comisión Nacional del Agua*, Servicio Meteorológico Nacional. Updated 12 Jan 2010,10:39hr. Visited on March 02, 2012, 01:13 H. See also: http://smn.cna.gob.mx/observatorios/historica/cuernavaca.pdf.
[32] A. S. Mujumdar, *Handbook of industrial drying*, 3rd Enhanced Edition, Ed. A.S. Mujumdar, Taylor & Francis, NY (2006) 1312 pages.

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