Some construction parameters of unglazed perforated solar dryers for medicinal plants

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Abstract: Erecting solar dryers for medicinal plants require the best design option to suit such plants. Investigations were carried out on some design parameters of the unglazed perforated solar dryers under the prevailing weather conditions of Ismailia, Egypt. Effects of different parameters on the heat exchange effectiveness were investigated. Parameters considered in this study including hole (perforation) diameters, dimensions apart, material being used and its thickness all were investigated to reveal the effects of suitable suction velocity, prevailing wind speed and its direction under the simulated incident solar radiation of the investigation site. Based on the obtained results for heat exchange effectiveness under controllable conditions, solar drier was built and investigated outdoors under the prevailing weather conditions of the investigation site. Holes diameter of 3 mm for all the investigated plates and under the different conditions resulted the highest obtained heat exchange effectiveness. Diamond shape for Holes distribution with dimensions of 29 mm×29 mm apart gave higher heat exchange effectiveness above the commonly used distribution (square shape). Temperature increase above ambient per unit of incident radiation was found as (0.0162±0.0007) ℃ m^2/W, when the best designed performance was investigated in the open environment. Using that perforated surface as an absorber in constructed dryer to dry Rosemary (*Rosmarinus officinalis L.*), reduced the moisture content from 65% (wet basis) to 38.1% on eight hours on the first drying day of the 18th April, 2010 while the reduction in moisture content of the sample dried in the shade area was from 65% (wet basis) to 42.2% under the same prevailing weather conditions at the same time.

Keywords: solar dryers, construction, air-heating, perforation, unglazed material, medicinal plants, Egypt

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1 Introduction

Unglazed perforated (transpired) solar air heaters play a significant role in low solar air-heating. These concepts can be used for solar drying of the medicinal plants, as a way to reduce the energy requirements and to improve the quality of the dried substances. The improvement in the dried medicinal plants is resulted from: systems protecting the dried plants from direct exposure to the sun-rays which harm and degrade their vitamins, oil and other chemical components. The moderate temperatures obtained from such systems avoid affecting the volatile oils of medicinal plants.

Hole-diameter and its distributions on the unglazed perforated surfaces, needs further research to find the matching suction velocity for different construction materials of the unglazed perforated dryers. Carrying out such research requires repeatable investigations, as it cannot be achieved in the open environmental conditions under the direct sunrays or under wind/no-wind conditions. It is carried out inside controllable lab under solar simulator techniques.

Unglazed perforated solar dryers are effective devices

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where the outside air is to be heated directly for drying purposes. As the outside, air in question is drawn straight from ambient, uniformly through the whole surface of a perforated black-colored plate (the absorber plate). The glazing traditionally used for reducing radiant and convective head losses can be dispensed within this situation. The convective boundary layer is continually sucked off, thus virtually eliminating the convective loss, and the intimate heat transfer between the dryer surface and the sucked air keeps the surface temperature low, minimizing the radiant loss[1].

Simulation of the solar radiation depends upon the kind of the investigation that will be carried out under that simulator. For solar thermal experiments, spectrum in the range of the solar heat rays region must be simulated. Within these experiments performance of the tested system is affected by the thermal radiation of the indoor environment in which it operates, walls and air temperatures are approximately equal[2].

The most commonly used light sources for the purpose of simulating the artificially sunlight are the xenon lamps, the Compact Iodide Daylight (CID), Tungsten-Halogen Lamps (THL). Spectral matching for sunlight simulation can be achieved by the THL, although these lack output in the ultraviolet portion of the spectrum and have a larger proportion of infrared light[3].

Previous investigations were carried out by the author[4] on the thermal performance of unglazed perforated solar dryer loaded by Rosemary, Margoram, and Henna. The study did not give the suitable construction of the perforated dryer, which suits the investigation site. In another investigation in that area, Hassanain[5] indicated that the heat exchange effectiveness was found increasing with the wind speed increase for the same wind-blowing angle. Apart of the wind speed of 1.51 m/s, no trend was noticed for the effect of the blowing wind angle with the perforated surface. A directly relationship was found between the heat exchange effectiveness and the wind speed in m/s for the same blowing angle. The investigations were carried out indoors only so there is no verification of these experiments outdoors under the prevailing weather conditions.

The study undertaken, which is contentious to previous work, aims to investigate the effect of some design parameters of the unglazed perforated solar dryers on the heat exchange effectiveness under the Mediterranean and sub Mediterranean conditions (Egypt) where there is demand to assemble such systems for drying medicinal and ornamental plants. Parameters considered in the study are; hole (perforation) diameters, dimensions apart, material being used and its thickness, all were investigated indoors (solar simulator) under the effect of suitable suction velocity, average simulating wind speed and its direction under the simulated incident solar radiation of the investigation site. The best performed design was investigated outdoors under the prevailing weather conditions of the investigation site where this design was investigated to be applied to dry medicinal plants for the future generation of such dries.

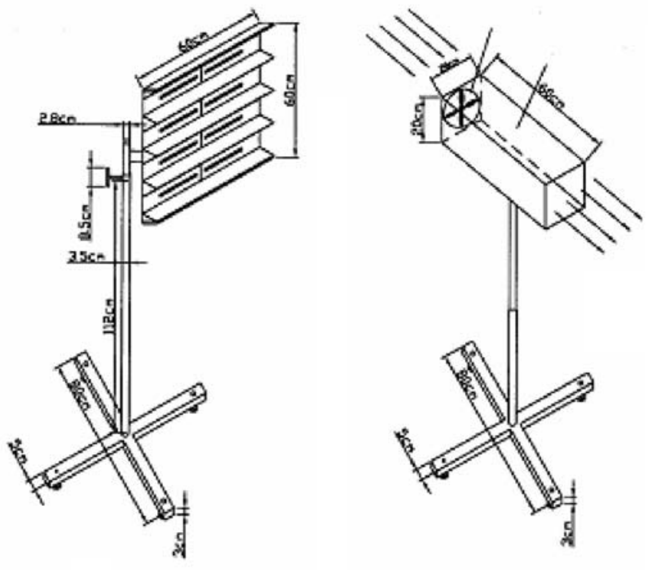
2 Materials and methods

2.1 Investigation under simulation environment

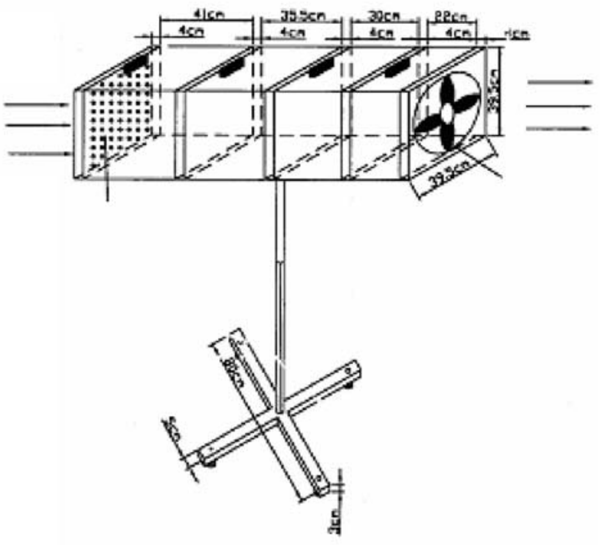
The utilized experimental rig in this study is shown in Figure 1. It composed three main components; the plenum wooden box with the perforated plates under investigations, solar simulator and wind apparatus, these components are explained as follows:

Wooden plenum box shown in Figure 1 was completely sealed and insulated. Gates were used to add or subtract the using instrumentation. Air was sucked with different suction velocities of 0.58, 0.67, 0.69, 0.91 and 1.3 m/s by a fan. An electric switch was used to vary the fan velocity as a result of the input current to obtain different suction flow rates of air.

Different metals plates, which call isothermal good thermal conductors, were examined. Thickness of 0.5, 0.9, 1.2 and 1.4 mm, for each of the three metals Steel, Galvanized steel and Aluminum plates were investigated. Holes with the investigated diameters were punctured without leaving stains as results of the perforation process. Holes of 2, 3, 4, 5, and 6 mm diameters were investigated for all the investigated plates metals and thickness. The punctured holes were distributed in squares and diamonds shapes of 80 mm×80 mm, 40 mm×40 mm, 20 mm×20 mm and 10 mm×10 mm square shapes and 57 mm×57 mm, 29 mm×29 mm and 14 mm×14 mm diamond shapes. A black paint of 0.95 absorpitivity and emissivity[6] were applied on the front surface that faced the solar simulator lamps, to increase the absorbed radiation by the surface. The investigated plates were fitted precisely on the front aperture of the plenum to face the simulator lamps. Table 1 gives the thermal conductivity (k), density (ρ) and the specific heats (c_p) which were used to determined the thermal diffusivity (θ) which was found to be 2.28×10^{-5}, 1.2×10^{-5} and 9.71×10^{-5} m^2/s, respectively for steel, galvanized steel and aluminum.



a. Solar-rays simulator b. Wind apparatus simulator



c. Plenum box with perforated plates

Figure 1 Rig setup for the laboratory investigation on the perforated drying-surface

Table 1 Thermal conductivity, density (ρ) and specific heats (c_p) for the three investigated metals which were used as a material for the unglazed perforated solar dryers[7]

Plate metal	Thermal conductivity (k) /$W \cdot mK^{-1}$	Density (ρ) /$kg \cdot m^{-3}$	Specific heat (c_p) /$J \cdot kgK^{-1}$
Steel	80.2	7870	447
Galvanized steel	45.3	7833	480
Aluminum	237	2702	903

Solar simulator was constructed which has advantages such as getting a stable incident radiation flux to test different solar techniques, the ambient air temperature and the environmental conditions can be controlled where the indoor experiments are carrying out. Tungsten-Halogen (phoenix Electric) Lamps (THL), 220-240V, 1,000 W each, were selected to simulate the solar radiation. Details of the solar simulator room were given previously by the author in Hassanain[5]. Investigations were carried out under THL with four different artificial illumination resources from 2 kW to 8 kW to simulate the solar energy intensity flux on Ismailia region. Solar simulator enable simulates any month all year around with adjusting the distance between the techniques being investigated and the simulator to match the monthly average incident solar radiation in W/m^2 according to Mostafa[8].

Due to the relationship between wind speed and the convective heat loss coefficient, wind was required indoors to investigate the effect of the crosswind on the obtained heat exchange effectiveness of the investigated plates. A small open circuit wind simulating apparatus was assembled from centrifugal fan and a 200 mm by 200 mm-square shape cross section with a length of 500 mm and 1 mm aluminum wall with a screen mesh that was mounted on the outlet square shape orifice. Fan of 150 mm diameter, 220–240 V (50 Hz), 0.13 A was used for the wind apparatus simulator. The fan air velocity was calibrated, determined and averaged using tachometer (speedometer). An electric switch was used to vary the fan velocity as a result of the input current to obtain different flow rates of air corresponding the average monthly wind speed (m/s) for the investigation site (Ismailia, Egypt) according to Smith[9].

2.2 Investigation in the open environment

Investigation in the open air under the prevailing weather conditions of Ismailia, Egypt (Agricultural Engineering Department of the Suez Canal University, latitude angle of 30.5° and longitude angle of 32.41° and 17 m above sea level) was carried out on the perforated plate which gave the highest heat exchange effectiveness and higher temperature increase above the ambient. Set-up for the investigations rig is shown in plates in Figure 2. Investigation rig composed a prototype solar drying system. The front side, which composes the perforated plate, was vertically with the ground base and it was oriented toward south direction. Wooden box of 50 cm long, 40 cm wide and 40 cm high was sealed from cracks and stainless-steel shelf was put horizontally in the middle of the dryer height.

Figure 2 Rig-setup for the field investigation

2.3 Methods and measurements

Heat exchange effectiveness: This factor was determined to measure the effectiveness of the air to sweep and gain surface temperature, it is taken as indicator to quantify the temperature gained from the surface. It is a ratio of the air temperature increase above ambient to the surface temperature increase above ambient. It is given as Dymond and Kutcher[10] and Gawlik[11] as:

$$h\varepsilon_x = \frac{T_o - T_a}{T_s - T_a} \tag{1}$$

This factor is affected due to the design of the unglazed perforated solar drying system. For solar applications, high effectiveness values are mostly of the interest.

The heat exchange effectiveness was determined as an average of 45 replicates. Each replicate was carried out at two minutes interval for both conditions of exposing the unglazed perforated plates to the solar simulator for one hour period (30 replicates) and half an hour after switching the light off (i.e. 15 replicates); this was done in order to imitate sunny and cloudy conditions. The suction air was performed within the investigation, while, wind and no-wind was performed depended upon the investigation type.

Inlet, outlet, ambient air and surface temperatures were measured with accuracy of (0.1±0.25)℃ using Ama-Digit Ad 15th, electronic thermometer type, which had been calibrated before against previously calibrated mercury, -10:100℃-scale thermometer.

Mono-crystalline solar cell connected to Multi-meter was used to determine the incident radiation according to Mujahid and Alamoud[12], Duffie and Beckman[13]. Calibration series was carried out on the solar cell against an Aply Pyranometer, before, during and after using the cell. The resulted formula was used to determine the incident solar radiation.

Wind speed and suction air velocity was measured using a TESTO 405-V1 Hot Wire Anemometer with accuracy of 1cm/s while wind direction (wind blowing angle) was measured using vane direction in the open environment.

3 Results and discussion

3.1 Thickness selection of dryer surface

Figure 3 shows values of heat exchange effectiveness for different galvanized steel with thickness of 0.5, 0.9, 1.2, and 1.4 mm as an instance for the other investigated materials, involved in this study. Among of these thicknesses, it was found that the highest obtained $h\varepsilon_x$ value was from the galvanized steel of 0.9 mm thick graphically. These investigations were carried out on 2 mm hole-diameters, which perforated at 40 mm apart with square shape.

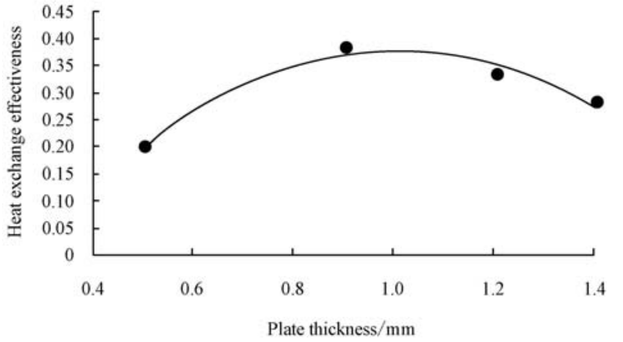


Figure 3 Heat exchange effectiveness as affected by different thickness of the galvanized steel under no wind conditions and average incident radiation of 515 W/m^2

3.2 Materials used to assemble the unglazed perforated dryers

The good thermal-conductor-metals (isothermal materials) with the given thermal properties in Table 1 were compared to find out the suitable material to build up the unglazed perforated solar dryer. A comparison between the galvanized steel plates with the same thickness of steel for all the investigated thickness found that, the steel plates gave 13% higher heat exchange effectiveness over the galvanized steel. In addition, the aluminum plates gave higher heat exchange effectiveness compared with the same thickness of the galvanized steel. For instance, the heat exchange effectiveness for plates of thickness 1.4 mm punctured with 2 mm hole diameter at the no-wind conditions was investigated under average incident radiation of 398 W/m^2, were (0.314±0.484) and (0.279 ±0.0195) for the Aluminum and Galvanized steel respectively. The aluminum plates showed an increase in 14.2% heat exchange effectiveness in compare with the galvanized steel of the same thickness. Comparison between different materials and its thickness are shown in Figure 4.

From the obtained data, it was found that the three investigated materials might be used to design and build the unglazed perforated solar dryer and can be arranged in descending order based on values of heat exchange effectiveness from the obtained results as aluminum, steel and galvanized steel plates. But, the cost of the materials to be used in the dryer must be considered.

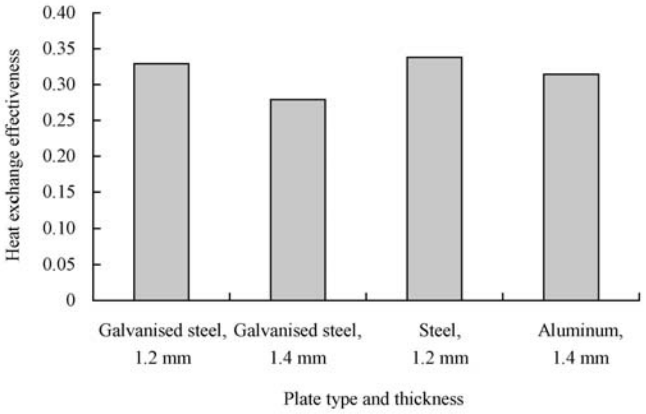


Figure 4 Effect of different materials and its thickness on the heat exchange effectiveness for no blowing wind conditions under average incident radiation of 398 W/m^2

3.3 Suitable perforation diameter

Table 2 represents the changes of the heat exchange effectiveness as a result of changing the hole diameter for the same investigation conditions of suction air velocity of 0.58 m/s, the same surface material and thickness (Galvanized steel of 0.5 mm thick), perforation apart of 40 mm square shape and average incident radiation of 398 W/m^2. Under the previously mentioned circumstances, Temperature increased above ambient ($T_o - T_a$), P/D (pitch/hole diameter) and the surface porosity (hole area/non-perforated surface area) are presented.

Table 2 Average heat exchange effectiveness for different hole diameters for 0.5 mm thick galvanized steel with 40 mm×40 mm distance apart, suction air of 0.58 m/s and no-wind speed, and incident radiation of 398 W/m^2

Hole diameter/mm	$h\varepsilon_x$	$T_o - T_a$/°C	P/D	δ
2	0.220±0.01	7.0±0.20	20	0.19
3	0.462±0.04	8.5±1.34	13.3	0.44
4	0.313±0.02	8.1±1.25	10	0.79
5	0.354±0.03	9.2±1.06	8	1.23
6	0.382±0.03	9.4±0.79	6.7	1.77

3.4 Suitable perforation a part

A range of the ratio P/D (peak between the perforating centers /hole diameter) were investigated and the results were addressed. The followed puncture distribution was squares and diamonds shapes. Distribution apart of different square shapes 80 mm×80 mm, 40 mm×40 mm, 20 mm×20 mm and 10 mm×10 mm and different diamond shapes 57 mm×57 mm, 29 mm×29 mm and 14 mm×14 mm were addressed in this study. The heat exchange effectiveness resulted from the investigation are presented in Table 3. These investigations were carried out on the best perforating hole diameters resulted from the previous step on 3 mm hole diameters, suitable suction air velocity of 0.91 m/s for 1.2 mm steel thickness under average insulation of 475 W/m^2. Heat exchange effectiveness from the Table 2 was found inversely proportional with the P/D for all the squares and diamond distribution. Meanwhile, when (T_o-T_a) were addressed in the comparison for the 29 mm×29 mm diamond shape gave the highest average value of 5.1℃ temperature increase above ambient. As the aim for the unglazed perforated solar dryers is to obtain higher temperature above the conventional solar dryers, this design will be considered as the best design option. Taking into the consideration that, hole diameter of 2 mm hole distributed on square shape of 40 mm×40 mm apart is the commonly used by[1,4,10,14-15]. Also, it is noticed in Table 3 that heat exchange effect has a directly relationship with the number of holes on the same area; but the temperature increase above ambient was increased till a cretin dimensions and design. This design was a diamond shape with 29 mm×29 mm so it will be the selected design option compared with other designs, which are given in the table.

Table 3 Suitable distribution for the perforating apart for the recommended hole diameter of 3 mm, suction air velocity of 0.91 m/s, under no-wind speed and 1.2 mm steel thick (Average simulated radiation of 475 W/m^2)

Shape and dimensions	$h\varepsilon_x$	T_o-T_a/℃	P/D
S 0 mm × 80 mm	0.200±0.093	3.70±1.213	26.7
D 57 mm×57 mm	0.204±0.205	4.40±1.057	19
S 40 mm× 40 mm	0.236±0.239	4.80±0.859	13.3
D 29 mm×29 mm	0.288±0.006	5.10±0.157	9.7
S 20 mm×20 mm	0.304±0.010	4.80±0.136	6.7
D 14 mm×14 mm	0.358±0.007	4.70±0.124	4.7
S 10 mm×10 mm	0.425±0.00003	3.50±0.002	3.3

Note: D = Diamond, S = Squares.

3.5 Results obtained from the investigation in the open environment

Figure 5 shows temperatures of the perforated surface and dryer air as affected by the prevailing wind speed for five minutes interval for one sunny day on 18 April, 2010 under the prevailing weather conditions of the investigation site. This illustration was determined under average wind speed of (0.31±0.18) m/s and measured incident solar radiations on the vertical perforated plate of (253±3.3) W/m^2, average wet and dry bulb temperatures of (15.5±1.3) and (25.5±1.7) ℃ respectively. Average for the temperature increase above ambient per unit of incident solar energy (normalized value) on the perforated plate, (T_o-T_a)/G, in ℃m^2/W was found as (0.0162±0.0007) ℃m^2/W.

It is obvious from Figure 5 that the blowing wind velocity in the investigation site affects surface and drying air temperatures. Using of the drier shown in Figure 2 to dry Rosemary (*Rosmarinus officinalis L.*) under previous mentioned weather conditions of 18th April, 2010, reduced the moisture content from 65% (wet basis) to 38.1% in the eight hours of the first drying day. This compared with reduction in the moisture content (wet basis) from 65% to 42.2% in the samples dried in shade area under the same prevailing weather conditions at the same time.

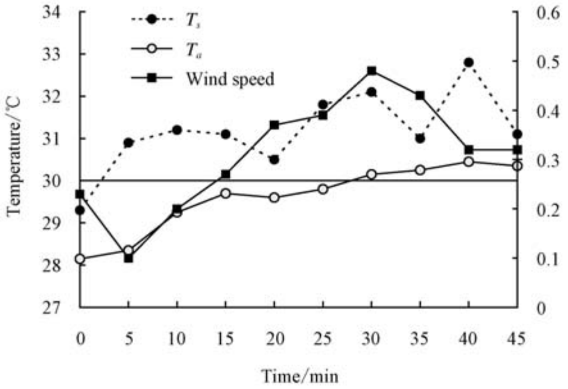


Figure 5 Wind speed and its effect on perforated surface and drying air temperatures at average ambient air temperatures of (25.5±1.7)℃

4 Conclusions

The study has discovered the following conclusions:

The suitable thickness for the unglazed perforated solar dryers was found to be depends upon type of metal in use to construct the dryer. It was found that, the highest obtained $h\varepsilon_x$ value was from the galvanized steel, steel and aluminum plates of 0.9 mm thickness.

Based on the heat exchange effectiveness, the three investigated materials that may be used to construct the unglazed perforated solar dryers can be arranged in descending order as aluminum, steel and galvanized steel plates with taking its cost in considerations.

- The highest obtained heat exchange effectiveness was found for hole diameter of 3 mm for all the investigated plates and under the different conditions.
- Diamond shape distribution of holes with dimensions of 29 mm×29 mm apart gave higher heat exchange effectiveness above the common used shape (square shape).
- Temperature increase above ambient per the unit of incident radiation was found as (0.0162±0.0007)℃m^2/W, when the best performed designed was investigated in the open environment of Ismailia, Egypt.

Nomenclature

P Hole pitch, i.e., distance between center of hole and center of next closest hole, mm

D Hole diameter, mm

δ Plate (surface) porosity (hole area/non-perforated surface area)

$h\varepsilon_x$ Heat exchange effectiveness

T_a Ambient air temperature, ℃

T_s Surface temperature, ℃

T_o Outlet air temperature, ℃, also, drying air temperature, ℃

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