A NATURALLY CIRCULATED HUMIDIFYING DE- HUMIDIFYING SOLAR STILL WITH BUILT-IN PASSIVE CONDENSER

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ABSTRACT

A numerical study has been carried out to investigate the transient thermal performance of a naturally circulation humidification - dehumidification solar still of Fath et al. [1], Comparison of with forced circulation performance and the influence of different environmental, design, and operational parameters on the still productivity have been investigated. Natural circulated still shows almost very similar results to the forced circulation which is of significant technical and economical importance. Different attempts have been considered to investigate the effect of both partial basin energy storage and partial recovery of condensation energy. The results show insignificant changes on the still performance. Economical assessment of water production cost has also been highlighted and shows that solar stills can challenge other technologies for special applications.

Key Words: Desalination, Solar Still, Humidification, Dehumidification

NOMENCLATURE

A	Area (m^2)	B	Still Width (m)
C	Specific Heat (J/kg C)	Gr	Grashoff Number
h	Specific enthalpy (J/kg)		
H_{fg}	Latent Heat of Evaporation (J/kg)		
H	Film Coefficient of Heat Transfer (W/m^2 C)		
I	Solar Intensity (W/m^2)	K	Thermal conductivity (W/m.C)
L	Characteristic Length (m)	M	Mass (kg)
m	Mass Rate (kg/s)	P	Pressure (Pa)
Pr	Prandtl Number	Q	Heat Transfer Rate (W)
t	Time (s)	T	Temperature (C)
Th	Thickness (m)		
U	Overall Coefficient of Heat Transfer (W/m^2 C)		
v	Velocity (m/s)	V	Volume (m^3)
w	Specific Humidity (kg_{water} / kg_{air})		

Greek Letters

α	Absorbtivity	Δ	Difference	ε	Emissivity
η	Efficiency	q	Tilt Angle	ρo	Density
ρ	Reflectivity	σ	Radiation Constant	Σ	Summation
τ	Transmistivity				

Subscripts

a	Air	am	Ambient	av	Average
ab	absorber	b	basin	C	Convection
CD	Condensation	co	Condenser	D	Drive
Dh	de-humidification	E	Evaporation	erth	earth
g	Glass	h	Humidification	hyd	Hydraulic
i	Insulation	in	input	K	Conduction
out	output	p	Projected	pw	Product Water
Re	Resisting	R	radiation	pw	Product Water
sid	Side	sk	Sky	su	Sun
sw	Saline Water	w	Wind	1	inlet
2	Outlet				

1. INTRODUCTION

Fresh water is the essence of human life. It is the most important constituents of environment and a basic human requirement for domestic, industrial and agriculture purposes. The international rapid developments, industrial growth and population explosion all over the world have resulted in a large escalation of demand for fresh water. On the other hand, the surface water (rivers and lakes) pollution caused by industrial and agricultural wastes and the large amount of sewage, limits the suitability of fresh water availability resources. By the beginning of this century, fresh water shortages and quality became an international problem confronting human groups and countries. The problem is more apparent in the Arabian and Middle Eastern / North African (MENA) countries due to its limited natural resources.

Desalination has been presented for decades as a suitable alternative solution to the world fresh water crises. Although it seems more expensive in area of surface or ground water availability, it is not so in areas 300 – 500 km far from surface fresh water availability or of deep ground fresh water. For large water production, conventional desalination technologies as MSF, MED, RO, VC … etc. are technically and economically suitable. However, for small communities, and for areas far from the sources of water and energy (fuel & electricity), and of small technical capabilities, direct solar distillation is more applicable. Direct solar distillation in many respects, might be an ideal solution to small communities in many MENA countries, due to the following facts:

i- Many of these countries enjoy an abundant solar intensity (Annual daily average is between 200 – 300 W/m^2) and large annual sun hours (3000 – 5000 hrs/year), and therefore incident energy of about (5 – 6 kWhr/day),

ii- The diurnal and seasonal fluctuation in solar distillation productivity are intrinsically linked to the fluctuating water demand,
iii- Direct solar stills involve simple technology that needs less design, manufacturing, operation and maintenance capabilities,
iv- Solar energy is almost available in every location and, in addition, is an environment friendly energy resource (with no CO_2 emission).

Many researchers have investigated and developed solar stills of different configurations in order to increase the still efficiency & yield, see for example Fath [1 & 2] and Nafey et al. [3 & 4]. The efficiency of solar stills can be increased by increasing the input energy. This could be partially achieved by; (i) having the liquid surface oriented at an optimal inclination to receive maximum solar radiation and (ii) placing the transparent glass cover of the still parallel to the water surface to minimize reflection losses. Several methods have been tried including the inclined stepped still, Radwan [5], tilted tray, and multiple ledge multi wick, see Malik et al. [6]. Humidification Dehumidification techniques have also been introduced more effective solar distillation systems. Different systems have been proposed in literature; (i) with/without air heating, (ii) with/without water heating, (iii) forced/ natural air circulation see for example Dater [7], Fath & Ghazy [8], Nafey et al. [9 & 10].

There are two main draw back of most of the single effect solar stills. The first is the loss of condensation energy. The combined evaporation, convection and radiation energy received by the condenser, represents about 40 - 50 % of the energy lost to the atmosphere. One may consider the partial recovery of this heat for; i) feed preheating, as in Mink et al. [11 & 12], and Kunze [13], or (ii) in an energy storage system for after sun-set recovery. Note that full recovery is almost impossible, since the glass (as a condensing surface and the door of the inlet solar energy) can not be covered during the day and additional condenser might be needed, see Fath et al. [14 & 15]. The capital & running cost of the energy recovery system as well as the additional technical complexities should be justified with the additional yield production. The second drawback is the sinusoidal trend of water productivity i.e. the water production is not available after sunset and during cloudy periods where the atmospheric temperature is minimum and heat sink is mostly available. The reason is the limited heat capacity of these distillation systems. This drawback can, however, be overcome by adding a thermal storage capability to the system, in order to store part of the sun energy and re-utilize it after sunset and cloudy periods. The comparison between such energy storage with the simple water storage (and only daily production) is to be investigated.

For both energy storage or condensation energy recovery, two thermal storage systems could be used; either sensible or latent heat system. Latent Heat Thermal Energy Storage System (LHTESS) has many advantages over sensible heat storage including; (i) larger energy storage capacity per unit volume, (ii) almost constant temperature for energy charging and discharging, see Fath [16]. Paraffin wax and Glauber's Salt are typical Phase Change Material (PCM) generally used in solar energy storage systems. Table (1) shows the main properties of the energy storage materials; (i) paraffin wax (to be used for basin energy storage), and (ii) Glaubert's salt (to be used for condensation energy storage & recovery).

Table (1) Thermo-physical Properties of Some Storage Materials

Material Properties	Sand	Paraffin Wax (Sunoco – P116)	Glaubert's Salt Na_2SO_4-$10H_2O$
Melting Temperature (^oC)		60	30
Latent Heat of Fusion (kJ/kg)		190	251
Solid/Liquid Density (kg/m^3)	1500	930/830	1460/1330
Thermal Conductivity (W/m. ^oC)	0.29	0.21	2.25
Solid/Liquid Sp. Heat (kJ/kg. ^oC)	0.798	2.1	1.72/3.3

Fath et al. [1] proposed a simple and efficient Humidification Dehumidification Distiller (HDD). The main drawback of this still is the forced circulation which requires a fan. For small communities, rotating equipment is a cost effective component technically and economically. On the other hand, the authors indicated that, within the parametric studied values, decreasing circulating air flow rate has insignificant effect on still productivity and efficiency. This result leads to the possible use of natural circulation to drive the air flow rate. Natural air circulation with the small still sizes is more desired since the absence of rotating equipment means a big reduction both capital and running costs in addition to the elimination of the technical complexities. How natural air circulation affects the total productivity and other performance parameters is what the present study addresses.

2- SYSTEM DESCRIPTION & ANALYSIS

2.1 System Description

Figure (1.a) illustrates the proposed HDD configuration and its main components, Fath et al. [1]. The still body is a relatively thin rectangular box constructed of 1.0 mm thickness framed Aluminum sheet with 3.0 mm (window type) glass cover. A central stepped absorber sheet (connected to the two still side walls with two slots at the top and bottom side walls) divides the still into two chambers, upper (glass to absorber) chamber and lower (absorber to condenser) chamber. The dividing stepped sheet carries a series of insulated black coated basins which contains the saline water. Dehumidifying condenser is made of 1.0 mm aluminum sheet. Air is circulated between the upper chamber (where it is heated and humidified) and the lower chamber (where it is cooled and dehumidified for water production). The still has a tilted configuration to enhance solar energy reception. Table (2) summarizes the main physical and thermal properties for the proposed still component's materials

2.2 Heat & Mass Balance

Figure (1.b) illustrates the energy balance of one basin (element) of the proposed still. Incident solar energy (1) is partially reflected from (2) and partially absorbed by (3) the glass cover and is mainly transmitted through the glass cover (4) to the saline water & absorber. Part of the transmitted energy is reflected back from water surface, (5) and the rest is absorbed by both saline water (6) and the absorber surface (7). Part of the absorber energy is transferred to the sea water by convection, another part is conducted to the insulation (8) and the rest heats the absorber. Some of the insulation energy is transferred to the de-humidified by convection (9) and to the condenser by radiation (10).

As soon as the water temperature exceeds the surrounding air temperature, saline water starts transferring heat to the humidified circulating air. The generated vapor carried both convection (11) and evaporation (12) energies. Saline water surfaces also radiate some energy (13) to the glass cover. The generated vapor is entrained by the circulating air. Part of the entrained water vapor is condensed on the glass and leaves its convective (14) and condensation energy (15) while the air carries out the rest of the entrained vapor to the next element. As a limiting criterion, the circulating air humidity can not exceed the saturation condition at its temperature. The heated glass cover losses heat to the ambient by convection (16) and to sky by radiation (17).

Table (2) Thermo-Physical Properties of Still Main Components, [17]

Property (units)	**Glass Cover**	**Basin/ Condenser**	**Insulation**
Material	Window Glass	Aluminum	Fiber Glass
Density (kg/m3)	2700	2707	24
Specific Heat (J/kg. C)	0.754	0.896	0.7
Thermal Conductivity (W/m.C)	0.78	204	0.038
Absorbiltivity	0.1	0.9	0.1
Transmisivity	0.9	0.0	0.0

When the absorber contains PCM for partial energy storage, heat is conducted from the basin to the PCM for energy storage. Heat is first stored (charging process) as sensible heat till PCM reaches its melting temperature. Additional charging heat is, then, stored as a latent heat and the melted PCM (wax) thickness increases. After complete melting, any additional heat will be stored as liquid wax sensible heat. When the absorber cools down (after sunset, say), the liquid wax transfers heat to the absorber (discharging process) and liquid wax temperature decreases till it reaches the solidification temperature, after which any discharged heat will be extracted as a latent heat till all the wax layer is fully solidified. More extracted heat will be a sensible heat to cool the solid wax. Similarly are the charging – discharging processes for the stored energy in the condenser (using Glaubert's Salt)

2.3 Governing Equations

Based on the heat & mass balance discussed above, the governing equations for the still components can all be written in the form:

$$M\,C\,dT / dt = \Sigma\, Q_{in} - \Sigma\, Q_{out} \tag{1}$$

ΣQ_{in} & ΣQ_{out} for each component can be expressed as follows:-

Glass Cover:

$$\Sigma Q_{in} = Q_{su\text{-}g} + Q_{Rsw\text{-}g} + Q_{Ca\text{-}g} + Q_{CDa\text{-}g}$$
$$\Sigma Q_{out} = Q_{Rg\text{-}sk} + Q_{Cg\text{-}am}$$

Absorber:

$$\Sigma Q_{in} = Q_{su\text{-}ab}$$
$$\Sigma Q_{out} = Q_{Cab\text{-}sw} + Q_{Kab\text{-}i}$$

Saline water:

$$\Sigma Q_{in} = Q_{su\text{-}sw} + Q_{Cab\text{-}sw}$$
$$\Sigma Q_{out} = Q_{Csw\text{-}a} + Q_{Esw\text{-}a} + Q_{Rsw\text{-}g}$$

Basin Insulation:

$$\Sigma Q_{in} = Q_{Kab\text{-}i}$$
$$\Sigma Q_{out} = Q_{Ri\text{-}co} + Q_{Ci\text{-}a}$$

Condenser:

$$\Sigma Q_{in} = Q_{Ca\text{-}cu} + Q_{CDa\text{-}cu} + Q_{Ri\text{-}cu}$$
$$\Sigma Q_{out} = Q_{Ccu\text{-}am} + Q_{Rcu\text{-}erth}$$

Humidified Air (Evaporation Chamber):

$$M_a h_{2\,a} = M_a h_{1\,a} + Q_{Csw\text{-}a} + Q_{Esw\text{-}a} - Q_{Ca\text{-}g} - Q_{CDa\text{-}g} \tag{2}$$

Dehumidified Air (Condensation Chamber):

$$M_a h_{2\,a} = M_a h_{1\,a} + Q_{Ci\text{-}a} - Q_{Ca\text{-}cu} - Q_{CDa\text{-}cu} \tag{3}$$

PCM container:

$$M_{eq} C_{eq} dT_{eq} / dt = \Sigma Q_{in} - \Sigma Q_{out} \tag{4}$$

In this equation, the PCM (wax or Glaubert's Salt) and its container (absorber, condenser, and insulation) are combined as one equivalent lumped body (for each element). Based on its temperature, the PCM and its container are combined by the container material equivalent mass (M_{eq}) of heat capacity equivalent to;

(i) the sensible heat for both the container and solid PCM, (For $T < T_m$)
(ii) the sensible heat of the container and the latent heat of fusion, ($T = T_m + \delta$)
(iii) the sensible heat for both the container and liquid PCM ($T > T_m$.)

For example, the equivalent absorber/wax heat capacity ( ) is calculated as follows:

$$M_{eq} C_{ab} = [M_{ab} * C_{ab} + M_{pcm} * C(s)_{pcm}] \qquad \text{For} \quad T_{ab} < T_m$$
$$M_{eq} C_{ab} = [M_{ab} * C_{ab} + M_{pcm} * H_{sL}] \qquad \text{For} \quad T_{ab} = T_m + \delta$$
$$M_{eq} C_{ab} = [M_{ab} * C_{ab} + M_{pcm} * C(l)_{pcm}] \qquad \text{For} \quad T_{ab} > T_m$$

Similar equations are written for condenser/ Glaubert's Salt and other combination. Details of the above terms can be expressed as follows:

$$I = I_o \sin(\pi t / t_{su})$$
$$Q_{su\text{-}g} = \alpha_g \; I \, A_p$$
$$Q_{Rsw\text{-}g} = \sigma \, \varepsilon_{sw} \, A_p \, [(T+273)^4_{sw} - (T+273)^4_g]$$
$$Q_{Ca\text{-}g} = H_{Ca\text{-}g} \, (T_a - T_g) \, (A_p + A_{sid})$$
$$Q_{CDa\text{-}g} = H_{CD} \, (P_a - P_g) \, (A_p + A_{sid})$$
$$Q_{Rg\text{-}sk} = \sigma \, \varepsilon_g \, (A_p + A_{sid}) \, [(T+273)^4_g - (T+273)^4_{sk}]$$
$$Q_{Cg\text{-}am} = H_{Cg\text{-}am} \, (A_p + A_{sid}) \, (T_g - T_{am})$$
$$Q_{Csw\text{-}a} = H_{Csw\text{-}a} \, A_p \, (T_{sw} - T_a)$$
$$Q_{Esw\text{-}a} = H_E \, A_p \, (P_{sw} - P_a)$$
$$Q_{s\text{-}ab} = \alpha_{ab} \, \tau_{sw} \, \tau_g \, I \, A_p$$
$$Q_{Cab\text{-}sw} = H_{Cab\text{-}sw} \, A_b \, (T_{ab} - T_{sw})$$
$$Q_{Kab\text{-}i} = (K_i \,/\, Th_i/2) \, A_p \, (T_{ab} - T_i)$$
$$Q_{su\text{-}sw} = \alpha_{sw} \, \tau_g \, I \, A_p$$
$$Q_{Ri\text{-}cu} = \sigma \, \varepsilon_i \, A_p \, [(T+273)^4_i - (T+273)^4_{cu}]$$
$$Q_{Ci\text{-}a} = H_{Ci\text{-}a} \, A_p \, (T_i - T_a)$$
$$Q_{Ca\text{-}cu} = H_{Ca\text{-}cu} \, (A_p + A_{sid}) \, (T_a - T_{cu})$$
$$Q_{CDa\text{-}cu} = H_{CDa\text{-}cu} \, (P_a - P_{cu}) \, (A_p + A_{sid})$$
$$Q_{Ccu\text{-}am} = H_{Ccu\text{-}am} \, (A_p + A_{sid}) \, (T_{cu} - T_{am})$$
$$Q_{Rcu\text{-}erth} = \sigma \, \varepsilon_{cu} \, (A_p + A_{sid}) \, [(T+273)^4_{cu} - (T+273)^4_{am}]$$

$$M_{E/CD} = Q_{E/CD} / H_{fg}(t)$$
$$T_{am} = T_{am\text{-}min} + T_{am\text{-}o} \sin(\pi t / t_{day})$$
$$T_{sk} = [0.0552 \, (T_{am} + 273)^{1.5}] - 273$$
$$H_{Chot\text{-}cold} = 0.884 \, [(T_{hot} - T_{cold}) + (P_{hot} - P_{cold}) \, (T_{hot} + 273) \,/\, (268900 - P_{hot})]^{0.33}$$
$$H_{CD/E} = 0.016 \, H_{Chot\text{-}cold}$$
$$H_{am} = 5.7 + 3.8 \, V_w$$
$$H_{Cab\text{-}sw} = 0.54 \, (K_{sw} / L_{ab}) \, (Gr\,Pr)^{1/4} \qquad \text{If } Gr\,Pr < 8 * 10^6$$
$$= 0.15 \, (K_{wtr} / L_{ab}) \, (Gr\,Pr)^{1/3} \qquad \text{If } Gr\,Pr > 8 * 10^6$$
$$H_{Ci\text{-}a} = 0.27 \, (K_i / L_i) \, (Gr\,Pr)^{1/4}$$
$$P = 0.14862 \, T - 0.0036526 \, T^2 + 0.0001124 \, T^3$$
$$H_{fg}(t) = [2503.3 - 2.398 \, T(t)] * 10^3$$

Natural Circulation Air Flow Rate

The naturally developed air mass flow depends on the balance between both driving and resisting forces (pressure). The driving force depends on:- (i) the difference of average air density in both humidification and dehumidification channels (which varies with air temperature & humidity) and (ii) the still height. The resisting force varies with circuit resistance coefficient and flow velocity. The air flow rate can be calculated as follows:

$$m_a = (\Delta P_D / \Delta P_R)^{0.5} \tag{5}$$

where, Ghazy [18]:

$\Delta P_D = (\rho o_{dh} - \rho_h)\, g\, L \cos(\theta)$

$\Delta P_R = \Delta P_{R1} + \Delta P_{R2} + \Delta P_{R3}$

$\Delta P_{R1} = 0.018\ L/2\ D_h\ \rho o_h\ A^2_a$

$\Delta P_{R2} = 0.018\ L/2\ D_{dh}\ \rho o_{dh}\ A^2_a$

$\Delta P_{R3} = (0.3 / 2\ A^2_a)\ (1/ \rho o_{dh} + 1/ \rho_h)$

$D_{hyd} = 4\ A_a\ / \text{Perimeter}$

$A_a = L\ (B-Th_i) / 2$

$\text{Perimeter} = 2\ [\ L + (B-Th_i) / 2\ ]$

Productivity & Efficiency

The still productivity, instantaneous and daily average efficiencies are calculated as follows:

$$\text{Productivity} = M_{pw-g} + M_{pw-cu} = \Sigma\ M_E(t)\ \Delta t \tag{6}$$

$$\eta_{inst} = (M_{pw-g} + M_{pw-cu})\ H_{fg(t)}\ / (I\ A_p) = [\ M_E(t)\ H_{fg(t)}\ ] / [\ I(t) A_p] \tag{7}$$

$$\eta_{av} = [\ M_E(t)\ H_{fg}(t)\ ]\ \Delta t / [\ \Sigma\ I(t)\ \Delta t\ A_p] \tag{8}$$

A computer program was developed to simultaneously solve the above equations. The still component's transient temperatures, heat transfer components, still productivity, instantaneous and daily average efficiencies are then calculated.

Table (3) Range of Studied Parameters for 2.0 m^2 Projected Area Still

Parameter	**Min. Value**	**Reference (Base) Value**	**Max. Value**
Environmental			
Solar Intensity at mid-day, Io (W/m2)	600	800	1000
Min/Max ambient temperature (C)	10/20	20/30	30/40
Wind Speed, V_w (m/s)	0	2	5
Design			
Basin Absorbitivity (α_{ab})	0.5	0.9	1.0
Condenser Absorbitivity (α_{co})	0.5	0.9	1.0
Condenser/Projected Area ratio		1	1.5 , 2.0
Evaporation/Projected Area ratio		1	1.5 , 2.0
Basin (glass wool) Insulation Thickness (mm)	10	50	100
Operational			
Basin Water Mass, M_b (kg)	12	15	20
Initial Water Temperature (C)		20	30
Still Tilting Angle	10	30	60

3- RESULTS & DISCUSSION

Table (3) summarizes the parameters environmental, design, and operational and their studied values used for both the reference (basic) case study and the range used for the parametric study.

Circulating Air Flow Rate

As indicated above, circulating air flow rate depends on the balance between the driving and resisting forces (pressures). Both forces depend on air conditions along the still chambers and still channels configuration. The prediction of circulating air flow rate requires an iterative approach for the solution of equation (5) simultaneously with equations (1) to (4). Figure (2) show the changes of air flow rate with time for the reference case. Air flow rate increases sharply in the first three hours, then remains almost uniform for the next seven hours (of about 0.0138 kg/s), then drops sharply during the rest of the day. Comparing with Fath et. al. [1], the results indicate that natural air circulation gives a very close value of air flow rate to that of the forced circulation most of the effective hours of the day. Forced air flow rate of 0.01 kg/s is almost the average value of the natural circulation rate.

Energy Balance

Figure (3) illustrates the still overall energy balance for the reference case at midday. The figure shows that for incident solar intensity of 800 W, 80 W is absorbed in the glass cover, 72 W reflected from the sea water basin, 56.5 W reflected from the absorber surface. The rest is mainly absorbed in the absorber (518.4 W) and the sea water (72 W). Very little of the absorbed energy in the sea water is radiated the glass cover (16.3 W) and the large amount forms the evaporation heat (525.2 W), in addition to the convection heat of (33.5 W) transferred from the sea water to the circulating air in the humidifying channel. The circulating air carries the added energy to its large recirculating enthalpy of 3995.74 W (Note here that the values of the enthalpy is not drawn is not to scale but just descriptive).

The total air enthalpy is mainly recirculated (4181.26 W) to the de-humidifying channel where it is partially transferred to the condenser as convection (30.6 W) and condensation (309.95 W) heat. Condensation heat produces the condenser water (after dividing by the latent heat of condensation). The total heat transferred to the condenser is dumped to the environment by convection to atmosphere (238.8 W) and radiation to earth (109.5 W).

The recirculated air enthalpy to the humidifying channel (4181.26 W) is partially transferred to the glass cover by convection (18.64 W) and (condensation (200.38 W) and the rest (3995.74 W) is recirculated to repeat the cycle. Condensation heat on glass produces the glass cover water production (after dividing by the latent heat of condensation). Heat transferred to and absorbed by the glass is dumped to the environment by convection to atmosphere (289.8 W) and radiation to the sky (23.5 W). Note that at midday a very small amount of energy is stored in the glass cover (1.95 W), sea water (5.03 W), insulation material (0.21 W) and condenser (0.75 W).

Figure (4) shows a comparison between forced & natural air circulation for the overall still performance main parameters. The figure shows very close results between naturally circulated and forced circulated cases. With natural circulation, the still daily average efficiency (η_{av}) is about 56 % and still productivity is 5.1 kg/day.m^2. In both cases, water production ends almost one to two hour after sunset due to the limited system heat capacity. Water production at glass cover is about 2.15 kg/day.m^2 (42 % of the total), while the condenser produces 2.95 kg/day.m^2 (58 % of the total).

Figure (5) shows that the still temperature profile at middle nodes follows the sinusoidal trend following the input solar intensity. Figure (5) shows also the gradual changes in still components temperature along its length after 7 hours of operation. As was expected, the absorber has the highest still temperature followed by (with a very small difference) the saline water, and then the flowing air (Humid & Dehumid), and glass, condenser temperatures, respectively. The saline water temperature in the basins reaches its maximum value of about 69 °C at the highest (top) nodes and almost half an hour after midday. Difference in temperatures between the first and the last nodes is in the range of 3 °C to 5 °C. Humidified & dehumidified air temperature difference is in the range of 0.5 °C to 2.0 °C.

Air Conditions

Similar to forced case of Fath et. al. [1], air condition lies always on the saturation line of psychometric chart, Figure (6). During the day hours, air is heated and humidified till midday and its temperature reaches about 57 °C at the humidifier exit and 53 °C at the dehumidifier exit. After midday, air starts to cool till sunset and its temperature reaches almost the ambient condition.

Parametric Study

The effect of environmental, design, and operation parameters, Table (3), on the still productivity has been studied. Similar results to forced circulation are shown. These results agree with the published results of [1 & 8]. The results indicated that increasing the solar intensity, ambient temperature, basin absorbitivity, and initial saline water temperature increases the system productivity. On the other hand, increasing wind velocity, basin insulation thickness, evaporation and condensation surface areas, condenser emissivity, and saline water mass have small effect on the productivity.

The natural circulation operating parameter that influences the system circulating airflow rate is the still tilting angle. Figure (7) show that increasing still tilt angle increases the air flow rate (higher driving force). However, within these values increasing air flow rate does nor increase the still yield. Increasing airflow rate has two effects; the first is to increase the capability of flowing air to entrain and carry more vapor, and the second is to reduce the heat content of the hot water (and therefore the evaporation rate). The two effects seem to balance out.

Energy Storage & Condensation Energy Recovery

Different cases have been considered to investigate the effect of both basin energy storage and for the partial recovery of condensation energy at the condenser. These cases cover; (i) only partial storage of basin energy for after sunset reuse, (ii) only partial recovery of condensation energy at the condenser, and (iii) Combination of basin energy storage & partial recovery of condensation energy.

(i) Partial Basin Energy Storage

Figure (8) shows the case of only partial basin energy storage for overnight reuse. The first attempt assumes 2.0 cm of paraffin wax (melting temperature of 60 C) are to be contained within the high temperature absorber. The figure shows a comparison of the overall still performance with and without energy storage. With paraffin wax (solid lines), the components temperatures are more flattened during both wax melting / solidification period (hr 5 to hr 12), after which they drop gradually till the hour 24. The temperature is maintained almost constant at 60 ^{o}C due to wax melting (energy charging period continues till almost midday) and solidification (energy discharges from midday to about sunset). By sunset hour, the absorber/wax temperature starts to drop and heat is discharged from the absorber/wax as sensible heat. Similarly, the air temperature and glass temperature follow approximately the same trend. For the still without wax (dotted lines), these parameters follow the sinusoidal trend of the solar energy (i.e. no energy is available after sunset). The figure shows also small reduction in both still daily average efficiency and yield. The still productivity is about 9.6 kg/day.2m^2 as compared to 10.2 kg/day.2m^2 without wax.

The second attempt assumes replacing the insulation material with the 2.0 cm paraffin wax (wax acts as both basin insulator and energy storage medium). The results show similar trend as the case presented above with even more reduction in productivity and daily average efficiency. A reversed air circulation flow took place after hour 20 as will be explained in other cases below.

These two attempts indicated clearly that storing water produced during the day is more effective and economical than storing the energy for overnight reuse. Storing energy is technically more complicated by adding wax (or other PCM) within the still, than storing water in the product tank.

(ii) Partial Condensation Energy Recovery

Figures (9) & (10) show the second case of only partial recovery of condensation energy (no basin energy storage). 2.0 cm of Glaubert's Salt (melting temperature of 30 C) are assumed to be contained within the low temperature condenser. The figure shows a comparison of the overall still performance with and without the Glaubert's Salt. With Glaubert's Salt (solid lines), there is no significant changes in the effective heat gained, Q_{eff}, average daily efficiency and total still productivity. The water productivity increased on the condenser on the expenses of glass cover productivity. The circulating air flow rate shows a reversed circulation after sunset since condenser temperature rises above the glass temperature, and consequently the air in the lower dehumidification channel becomes hotter and lighter than air in the humidification channel. This is more apparent in the temperature distribution where the dehumidified air temperature is lower than the humidified air till hour 12 after which the case is reversed. Figure (10) shows also that the condenser temperature increases till hour 3 where its temperature reaches the melting temperature of the built in Glaubert's Salt of 30 C. Condenser temperature is maintains constant till all the Glaubert's Salt is melted, at about hour 8, after which the condenser temperature increases. By about hour 10, the condenser temperature reaches its maximum and starts to drop again till the solidification temperature of 30 °C, where it maintains constant (during solidification process) till hour 21 where it is fully solidified and the temperature drops again. It is clear that at about hour 11, the condenser temperature starts to be higher than the glass temperature, and so is the de-humidified air above the humidified are which causes air circulation to reverse. The reversed circulated air does not cause any significant vapor to condense on the glass cover since air condition departs from the saturation conditions after hour 13, as shown in the psychometric charts of Figure (11).

(iii) Combined Energy Storage & Recovery

Figures (12) & (13) show the third case of combining the partial storage of basin energy for overnight reuse and the partial recovery of condensation energy at the condenser. 2.0 cm of paraffin wax (melting temperature of 60 °C) are assumed to be contained within the high temperature absorber. In addition, another 2.0 cm of Glaubert's Salt (melting temperature of 30 °C) are also assumed to be contained within the low temperature condenser. The figures show a comparison of the overall still performance with and without these modifications. With these modifications (solid lines), the figure shows a very small improvement in both still daily average efficiency and productivity. Similar to Figure (10), the condenser water productivity increased on the expenses of glass cover productivity. Also, the circulating air flow rate shows a reversed circulation after sunset between hours 13 to 21. However, there is a shift for the starting reversed air flow than that in Figure (10) due to basin partial energy storage. Due to the same reason, after hour 21, the humidifying channel starts to get hotter than the dehumidifying channel which causes the air to re-circulate in the normal direction again as shown in Figure (13). The figure also shows that between hours 5 to 10 the temperature difference between the humidifying channel and the dehumidifying channel is constant (melting process of both paraffin wax at 60 °C and Glaubert's Salt at 30 °C). This causes a constant air circulation flow rate during this period. The almost reversed constant flow rate is due to the same reason but in reversed condition. Figure (14) shows that air condition is maintained saturation with water vapor up to hour 14, after which air condition is far from saturation conditions.

One last attempt of combining the partial recovery of condensation energy and reuse the energy for basin heating is shown in Figure (15). In this case, 2.0 cm of Glaubert's Salt (melting temperature of 30 °C) are assumed to be attached to the condenser in form of side by side strips. When the basin is cold down and its temperature reaches below 30 °C, the 2.0 cm of Glaubert's Salt strips are moved from condenser side and placed under the basins to heat it with the recovered stored energy. The figure shows a comparison of the overall still performance with and without this modification. With modifications (solid lines), the figure shows also a very small improvement in both still daily average efficiency and productivity. Also, the circulating air flow rate shows a reversed circulation after sunset and continues till hour 24. Air condition is maintained saturation till hour 12 after which it shifts from saturation condition.

Economical Assessment

The water production unit cost is the sum of both initial and running costs. The initial cost covers all expenses starting from the project being concept until its commissioning. The running costs cover all the O & M expenses (staff salaries, energy & its conversion, chemicals, overheads, … etc.), Fath [19].

The proposed solar still configuration was manufactured for testing, Figure (16). The still costs 500 Egyptian pound (about 75 $). The expected life time is 10 years and its yield is about 4 Liter/m^2.day. For 1.0 m^3/day unit (1000 Liter/day), 250 units are required. 10 % of the stills are added to guarantee the continuous production of water with the failure or malfunction of some stills. Table (4) summarizes the cost calculations of 1.0 m^3 water production by the still farm. The table shows that 1.0 m^3 of water costs 45 E.P. (8 $). However if the still cost is reduced to 100 E.P., the 1.0 m^3 will cost only 25 E.P. (3.0 $). In general, solar still can not challenge the lower cost of large units (M.S.F., R.O. … etc.). However for special applications of; (i) very small communities, (ii) the unavailability of drinking fresh water, (iii) the un availability of energy (fuel or electricity) and (iii) the un availability technical support within the communities, solar still seems to be the only (technically & economically) competing alternative.

Typical Case Study for 1.0 m3/day Solar Distillation Unit
(1.0 $ = 5 E.P.)

Parameter	**Normal case**	**Cheaper -1-**	**Remarks**
Still Dimension (m2)	1		
Still Productivity (L/m2.day)	4		
Unit No of Stills	275	275	Assumed 10 % extra stills
Unit Area (m^2)	250		
1- Annual Production (m^3)	**350**	**300***	* assumed less efficient still
Still Cost (E.P.)	500	100	
Unit Cost (E.P.)	137,500	27,500	
Annual O & M	2,000	2,000	One operator for 10 units. 500 E.P./month + 800 E.P. spare parts
Capital Installment (E.P.)	13,750*	5,500**	* 10 years, 0 % interest ** 5 years, 0 % interest
2- Total Annual Cost (E.P.)	**15,750**	**7,500**	
Cost of 1.0 m^3 (E.P.) 2/1	**45 (9 $)**	**25 (3 $)**	

CONCLUSION

1- The thermal performance of a naturally circulated HDD solar still is investigated. The still has a simple design of tilted configuration. The results show a still productivity and efficiency of about 5.1 kg/m2.day, similar to that in forced circulation of Fath et al. [1]. In addition to its simplicity, natural circulation is more economical and of less complexity than forced circulation still.

2- The influence of different environmental, design, and operational parameters show that increasing solar intensity (high input energy) and ambient temperature (less energy losses) improves still productivity. This is an advantage of solar desalination as water production increases in summer conditions which are in consistence with the water demand during this season. Similarly for the higher ambient temperature which reduces the still losses and increases the productivity. Wind velocity has, however, an insignificant effect on still productivity.

3- Different attempts to partially store basin energy and or recover condensation energy. These cover the cases of; (i) only partial storage of basin energy for overnight reuse, (ii) only partial recovery of condensation energy at the condenser, and (iii) Combination of energy storage & partial recovery. The results show insignificant improvement in the still productivity. It is more economical, therefore, to store water rater than store energy.

4- Economical assessment of water production cost show that 1.0 m^3 of product water costs 45 E.P. (8 $). However if the still cost is reduced to 100 E.P., the 1.0 m^3 will cost only 25 E.P. (3.0 $). In general, solar still can not challenge the lower cost of large units (M.S.F., R.O.,…etc.). However, for special applications of; (i) very small communities, (ii) the unavailability of drinking fresh water, (iii) the un availability of energy (fuel or electricity) and (iii) the un availability technical support within the communities, solar still seems to be the only (technically & economically) competing alternative.

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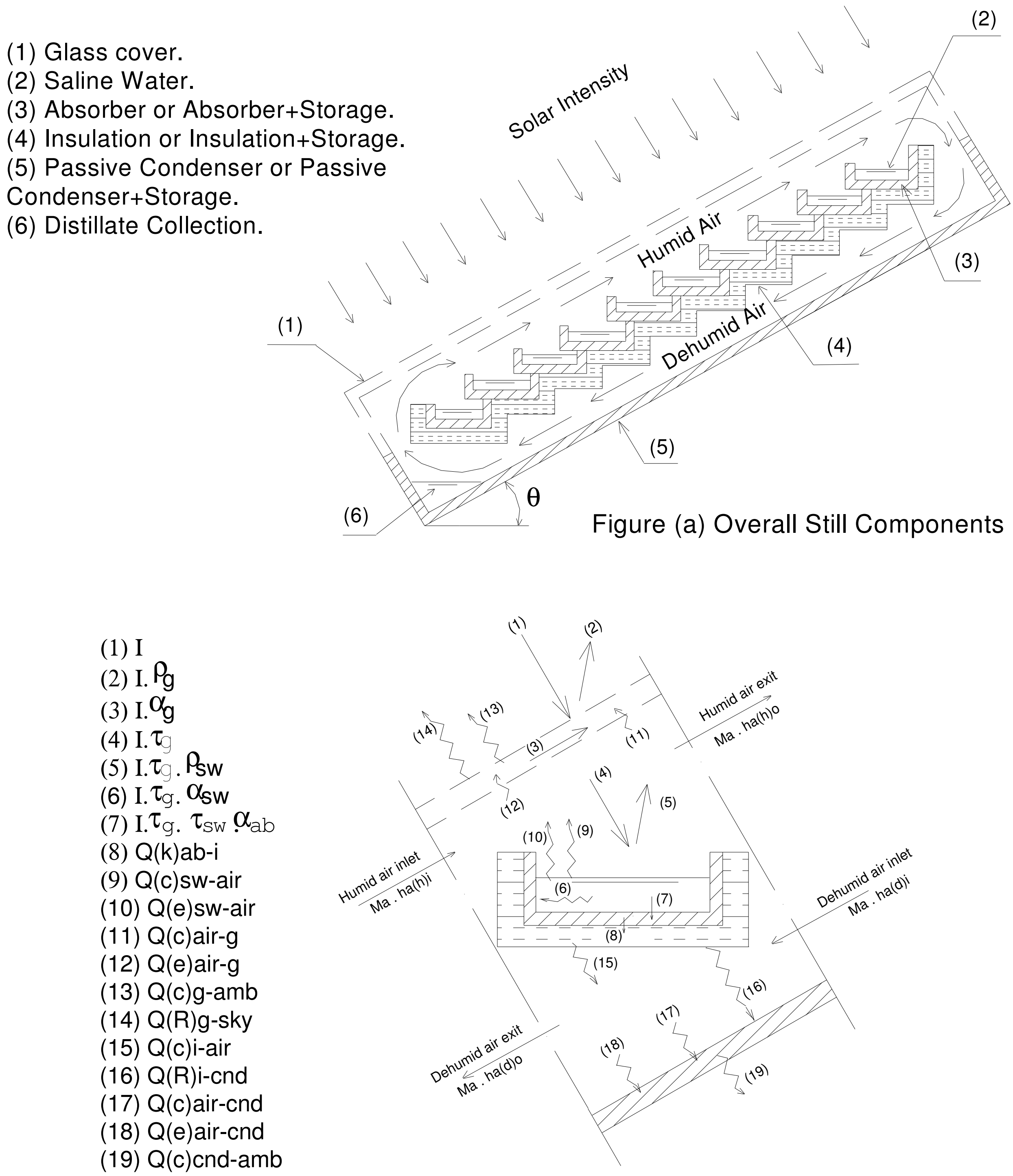


Figure (a) Overall Still Components

(b) Still Component's Energy Balance

Fig. 1. Proposed humidifier-dehumidifier Solar Still

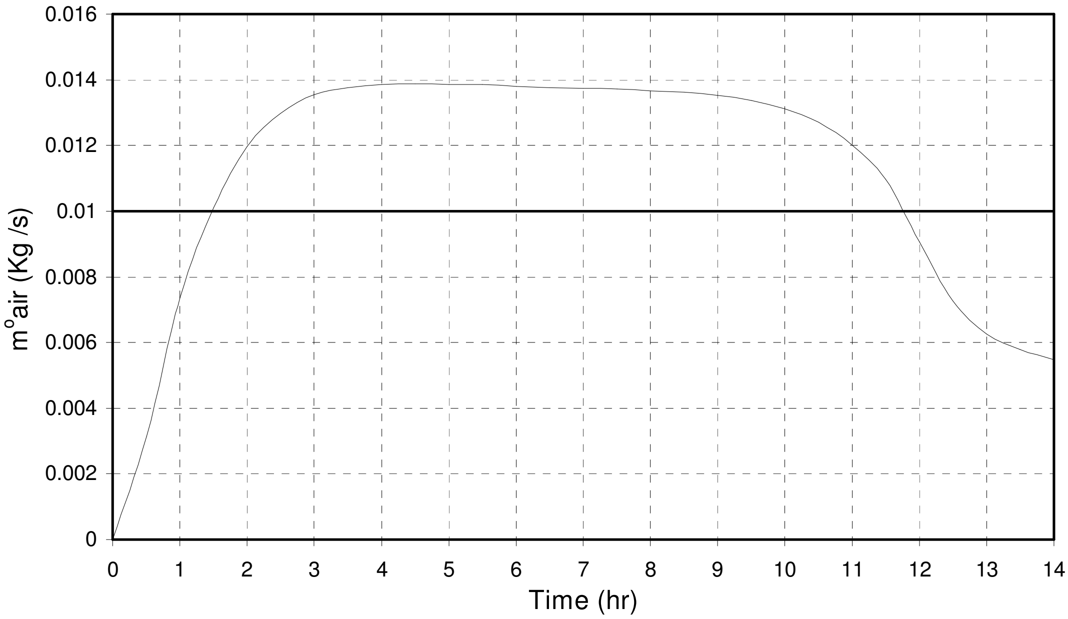


Fig. 2. The Naturally Circulating Airflow Rate

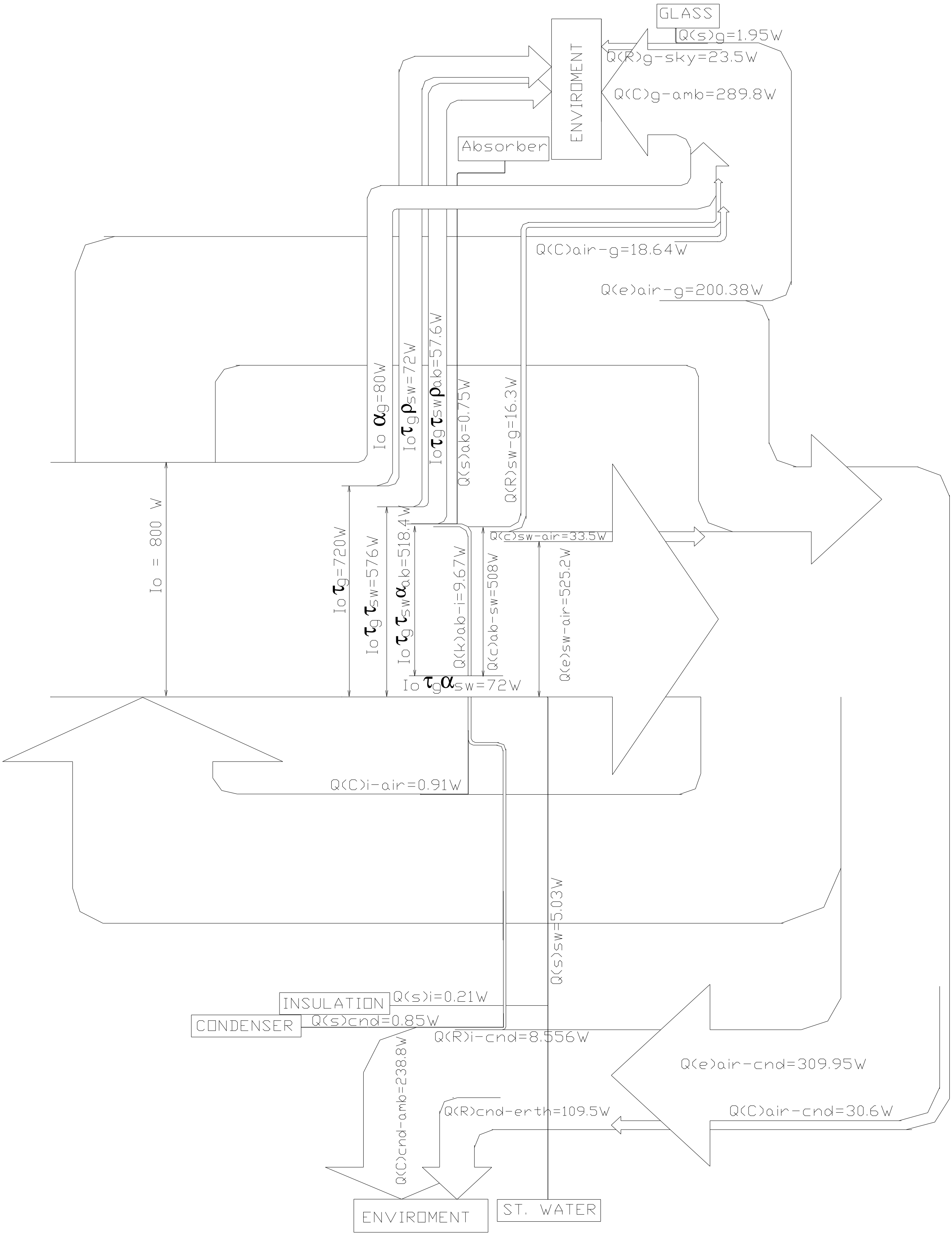
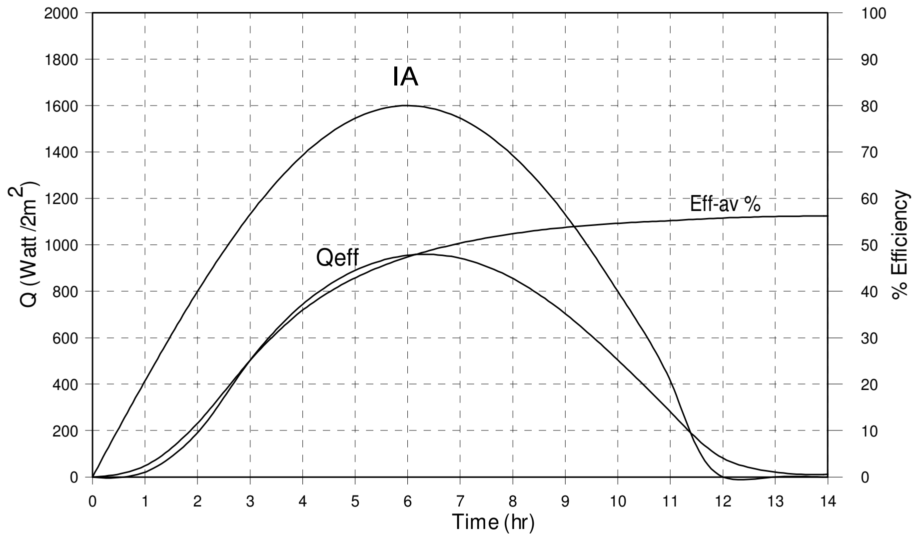


Fig. 3. H.D. Energy Diagram



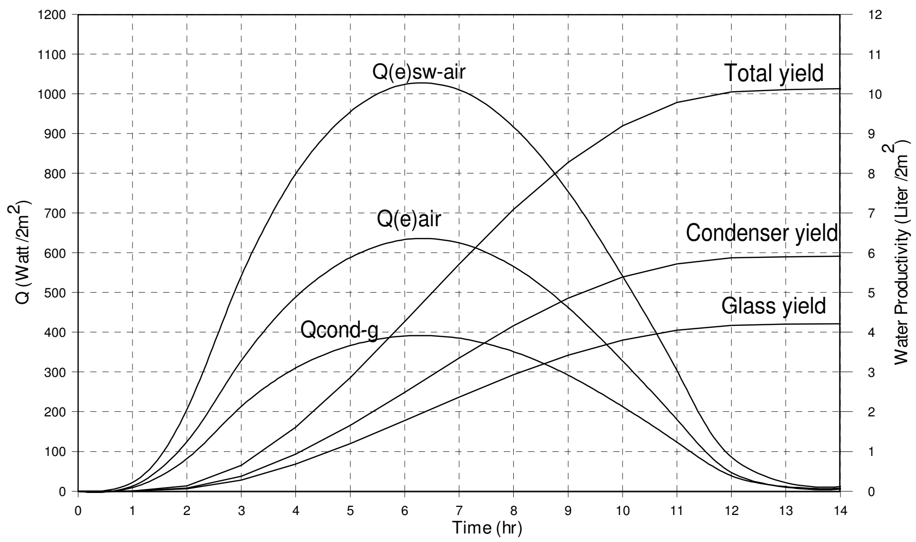


Fig. 4. The Still Performance

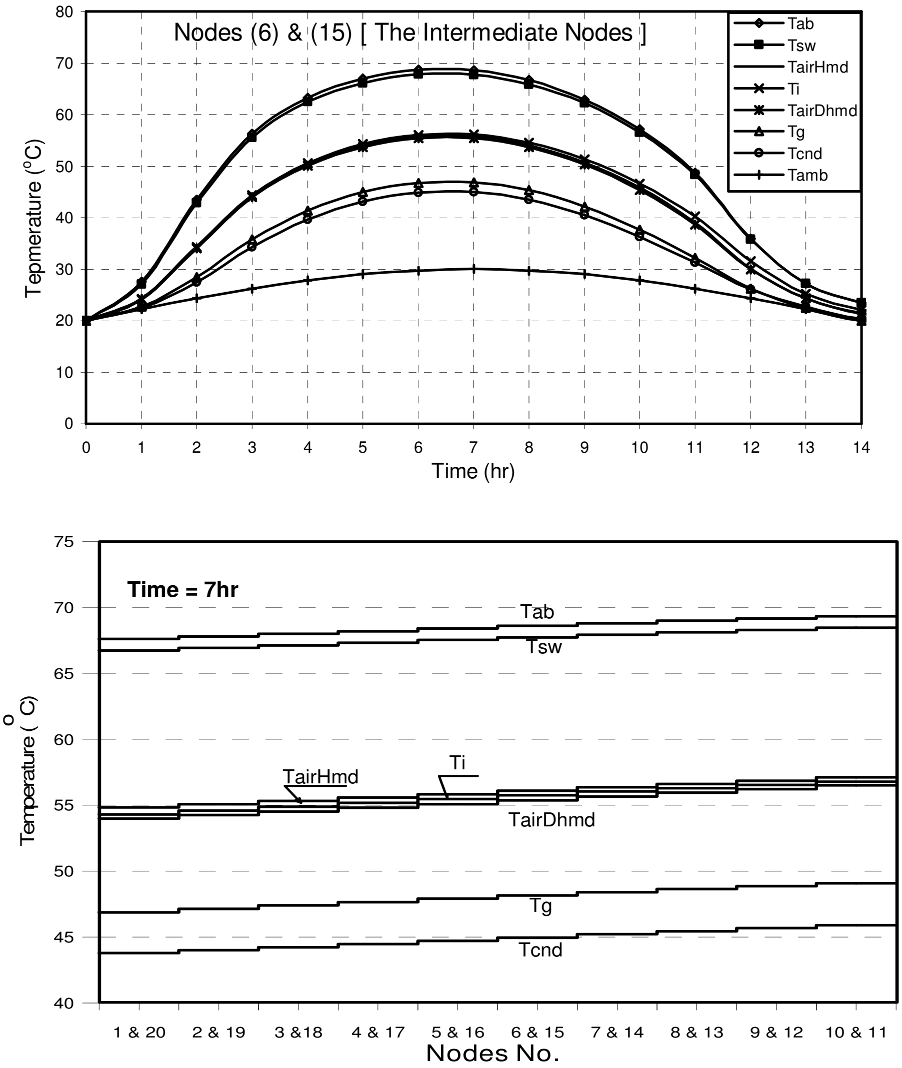


Fig. 5. Still Component's Temperature Distribution

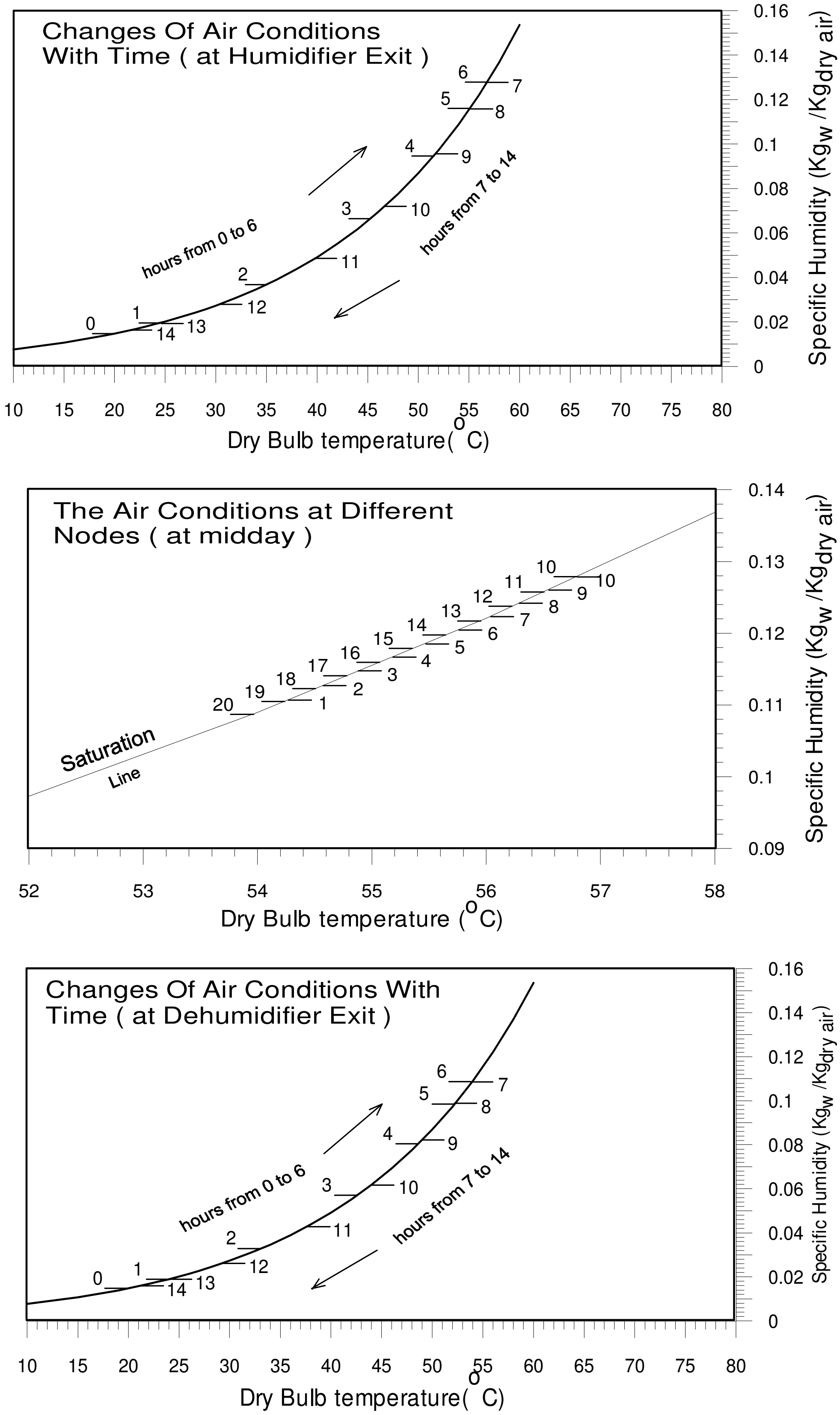


Fig. 6. Naturally Circulated Air Conditions

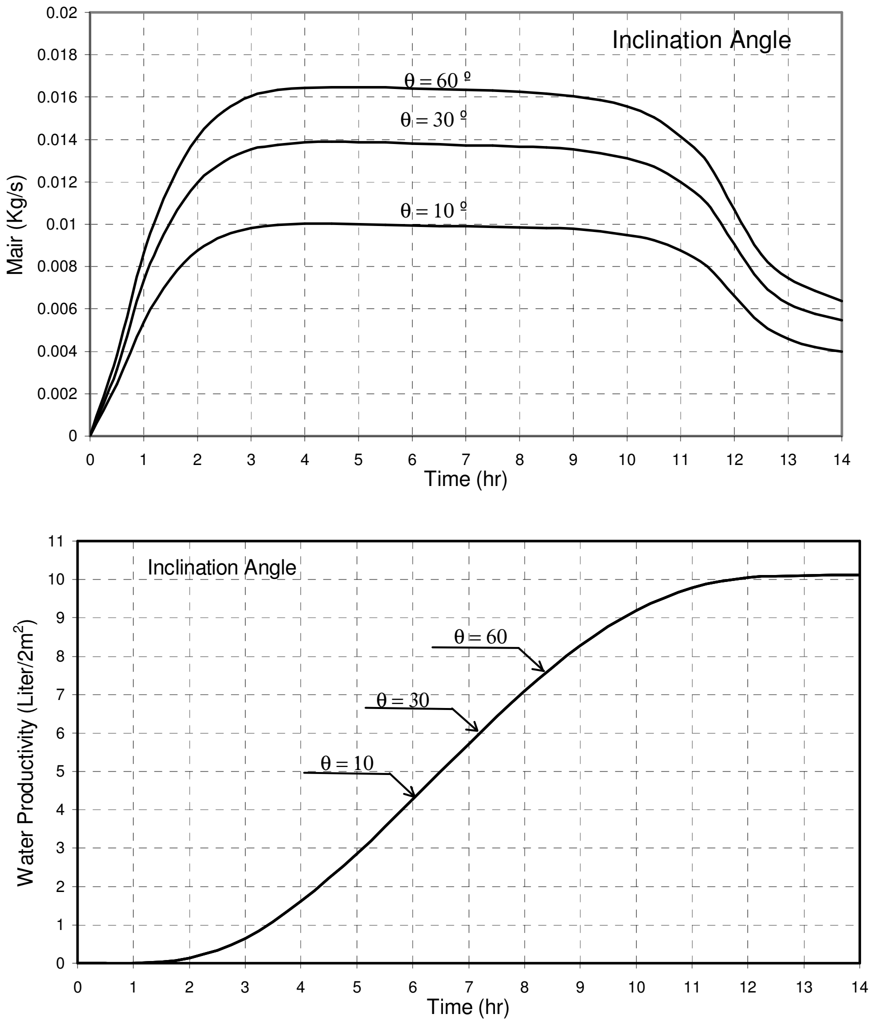


Fig. 7. The Influence of the Still Tilting Angle on Still Performance

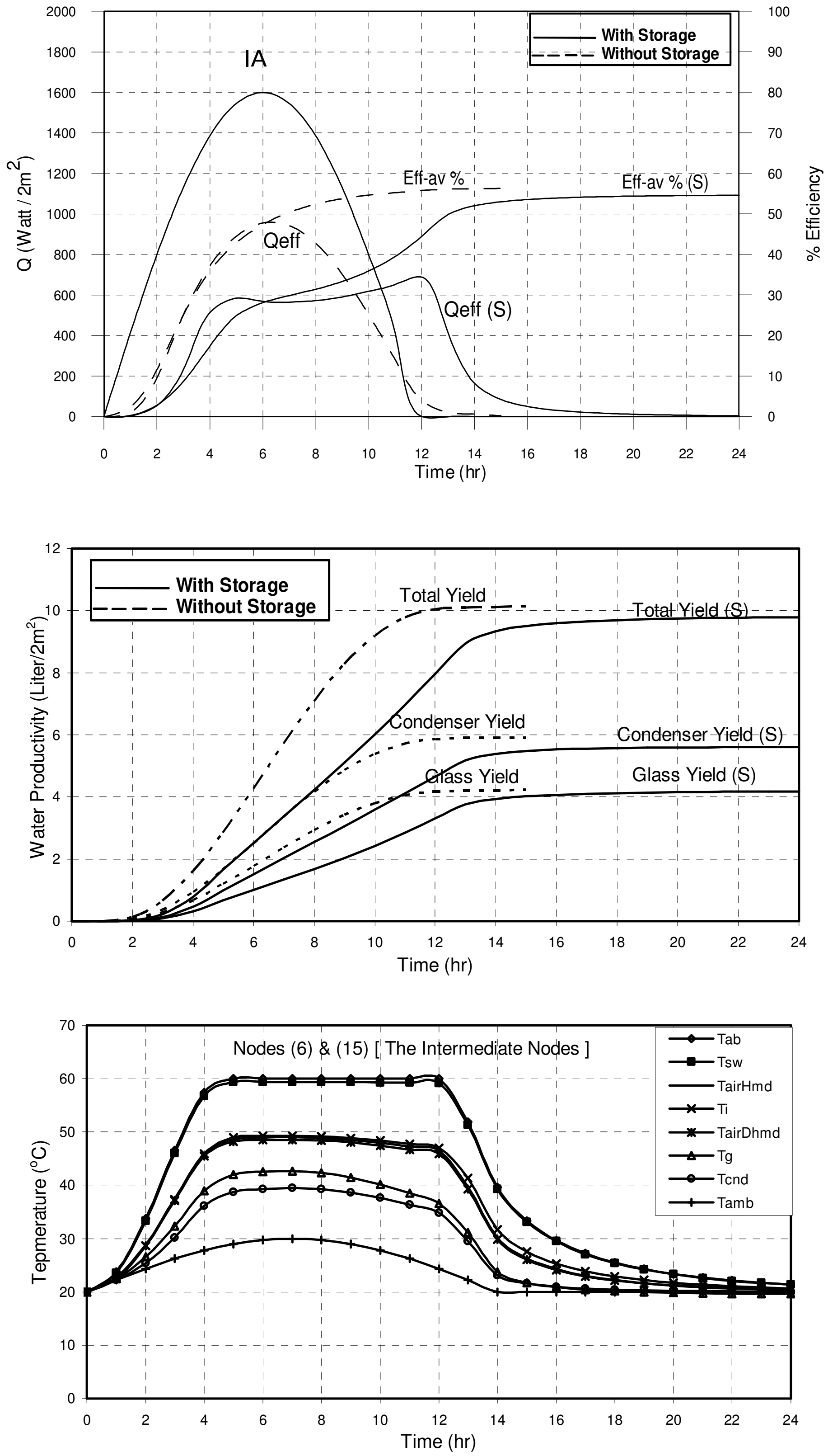


Fig. 8. Effect of Partial Storage of the Basin Energy on Still Performance

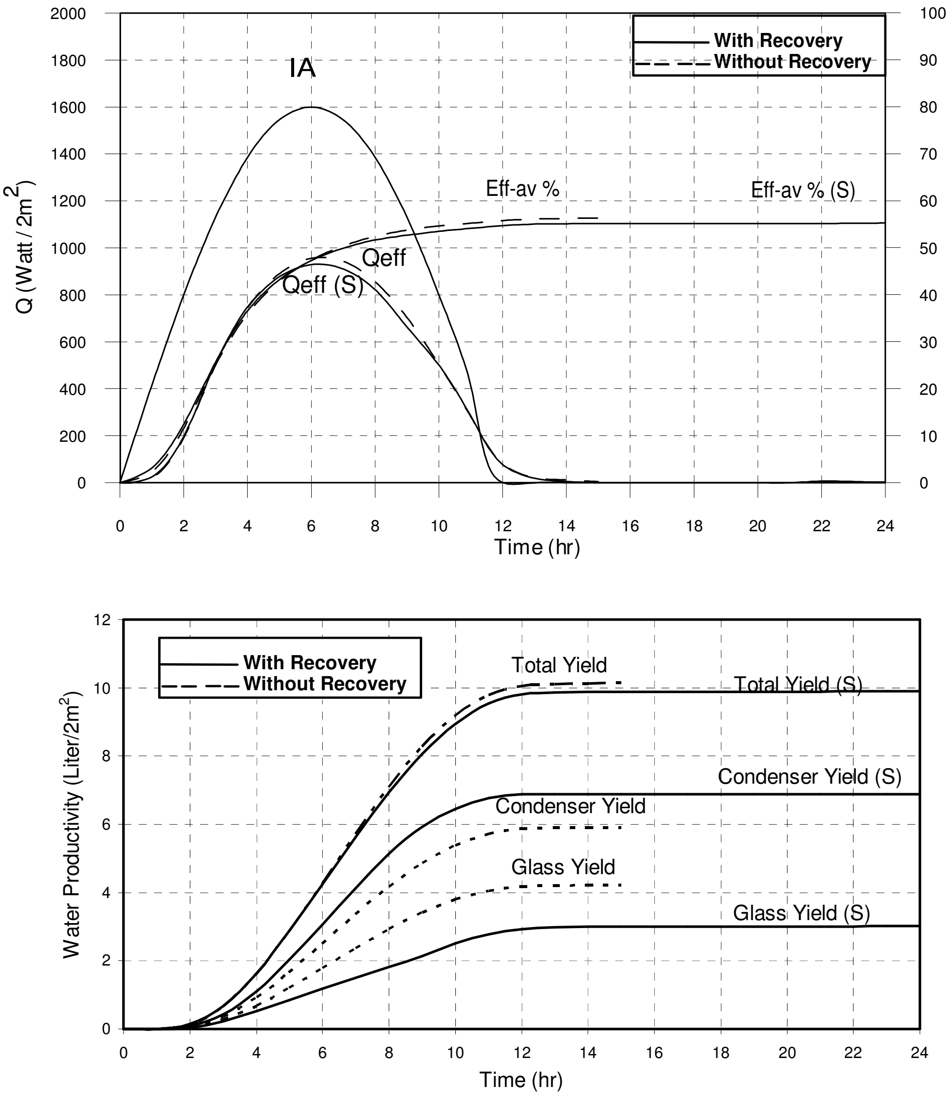


Fig. 9. Effect of Partial Recovery of Condensation Energy on Still Performance

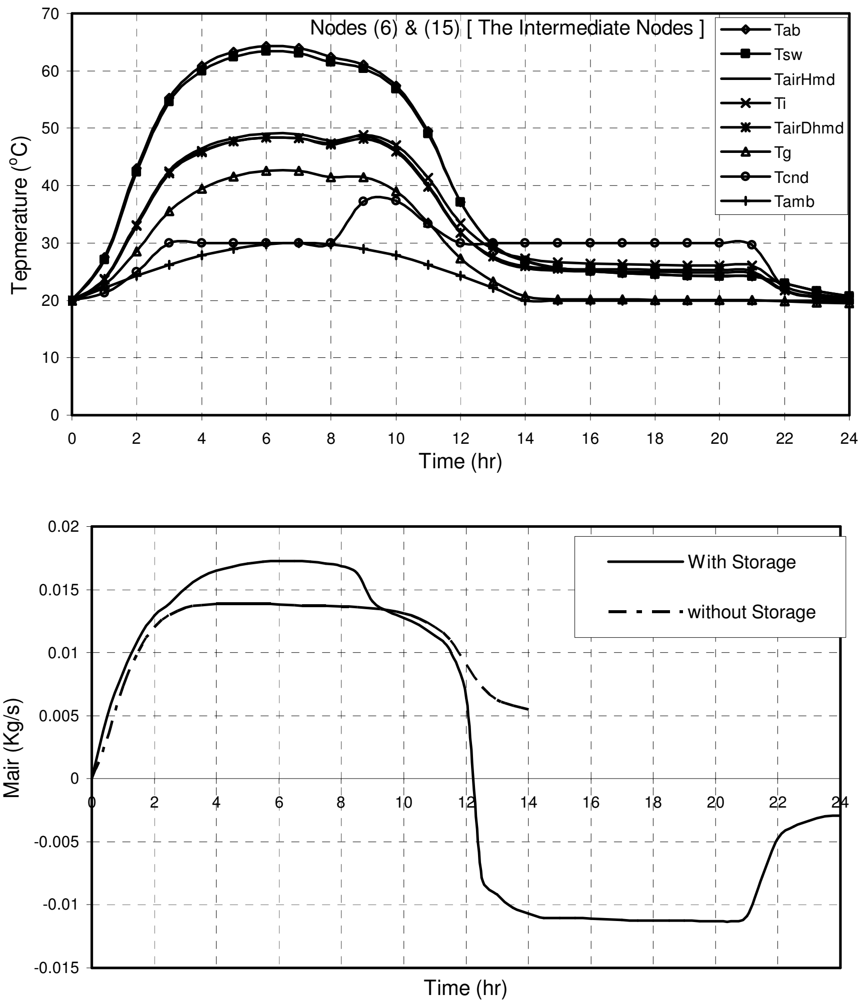


Fig. 10. Effect of Partial Recovery of Condensation Energy on Still Temperature & Air Flow Rate

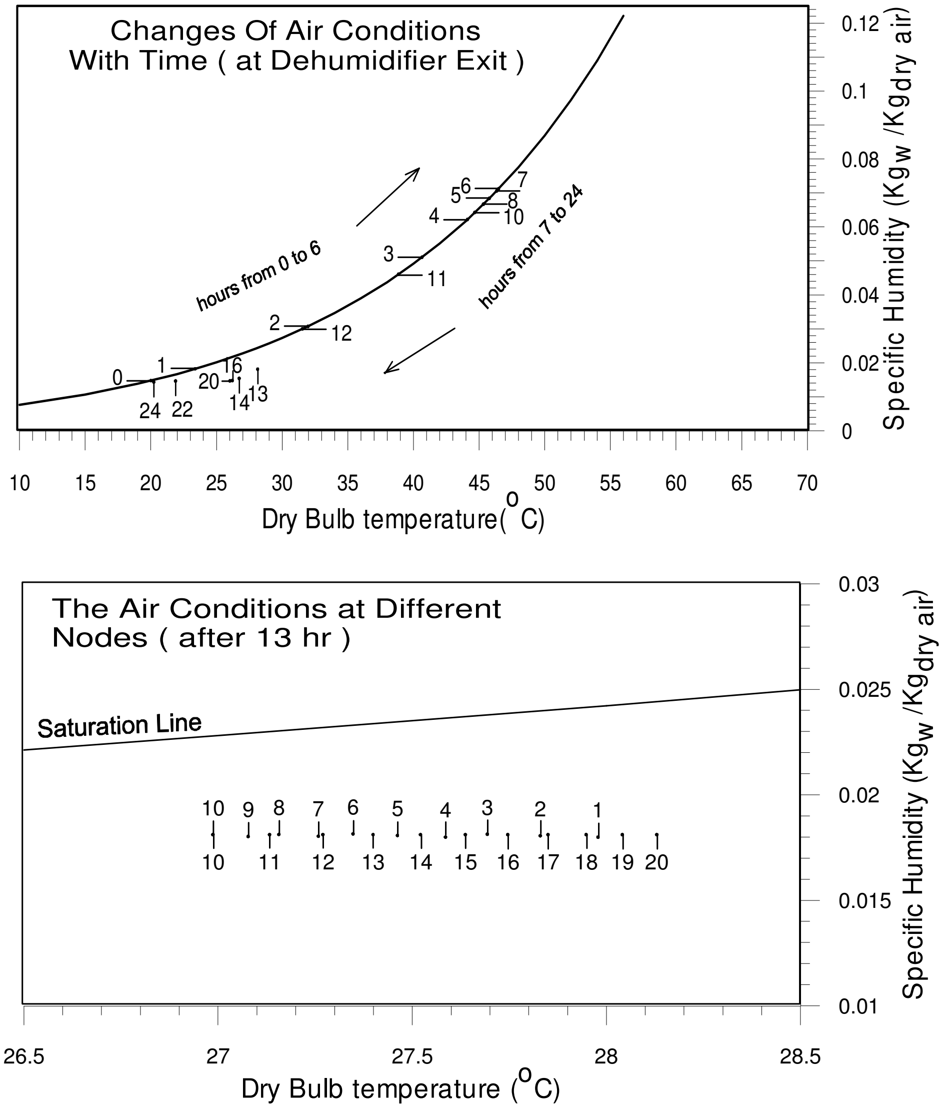


Fig. 11. Air Conditions with Partial Recovery of Condensation Energy

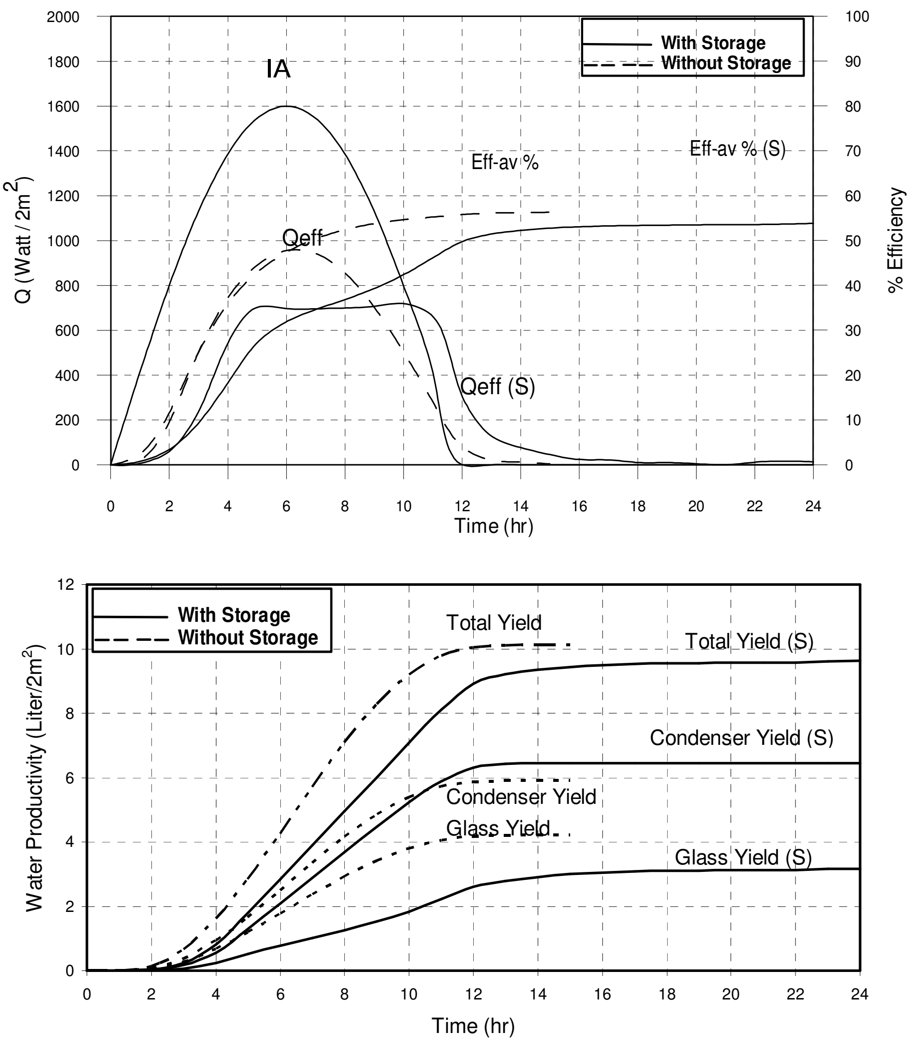


Fig. 12. Effect of Combining Absorber Energy Storage & Condensation Energy Recovery on Still Performance

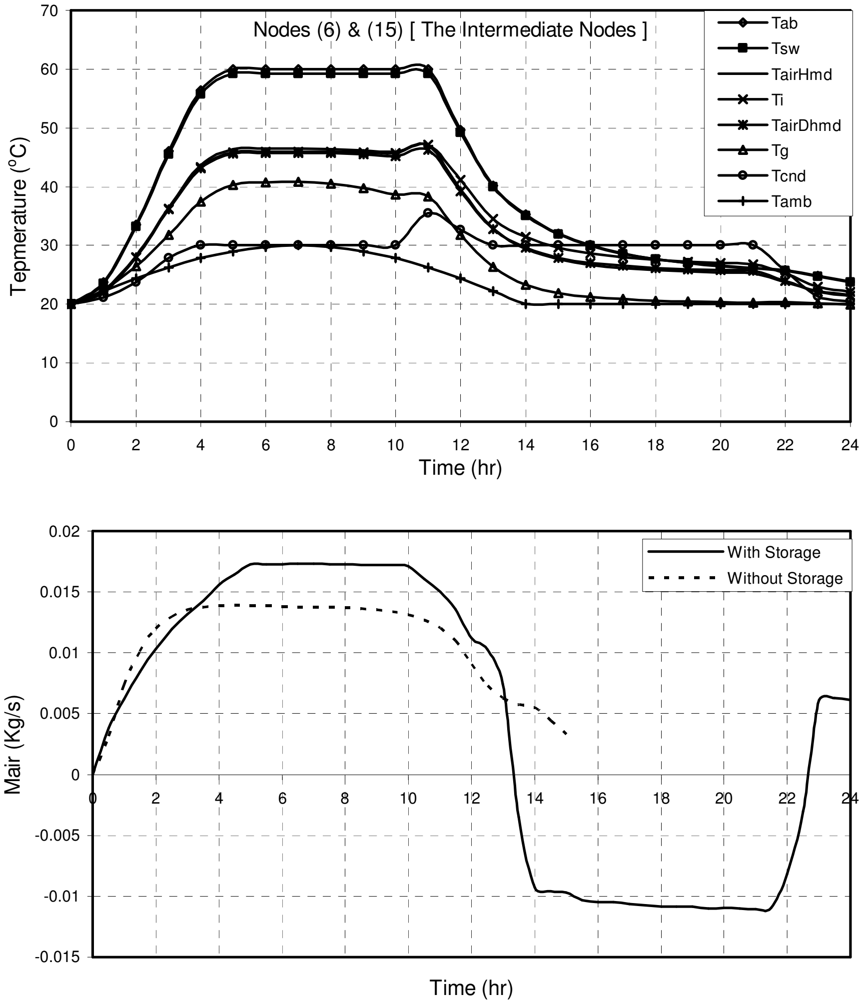
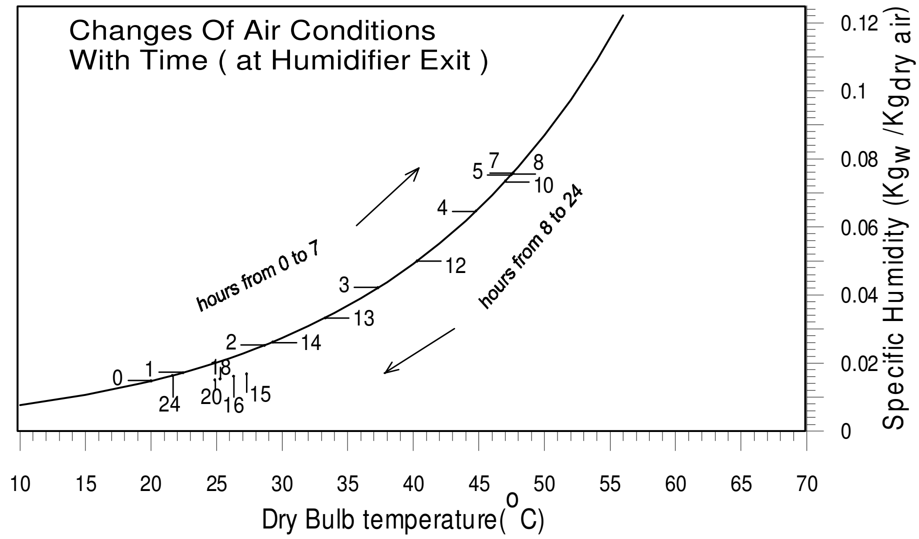


Fig. 13. Effect of Combining Absorber Energy Storage & Condensation Energy Recovery on Still Temperature & Circulating Air



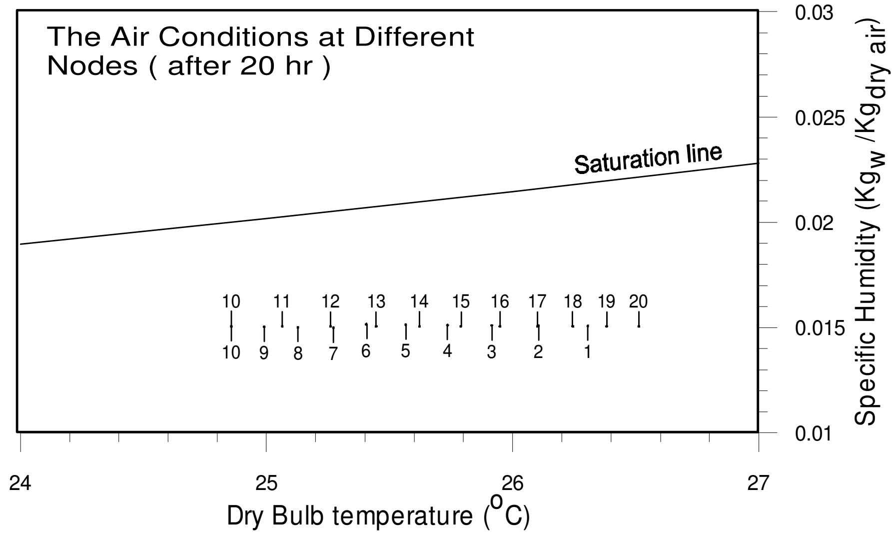


Fig. 14. Effect of Combining Absorber Energy Storage & Condensation Energy Recovery on Air Conditions

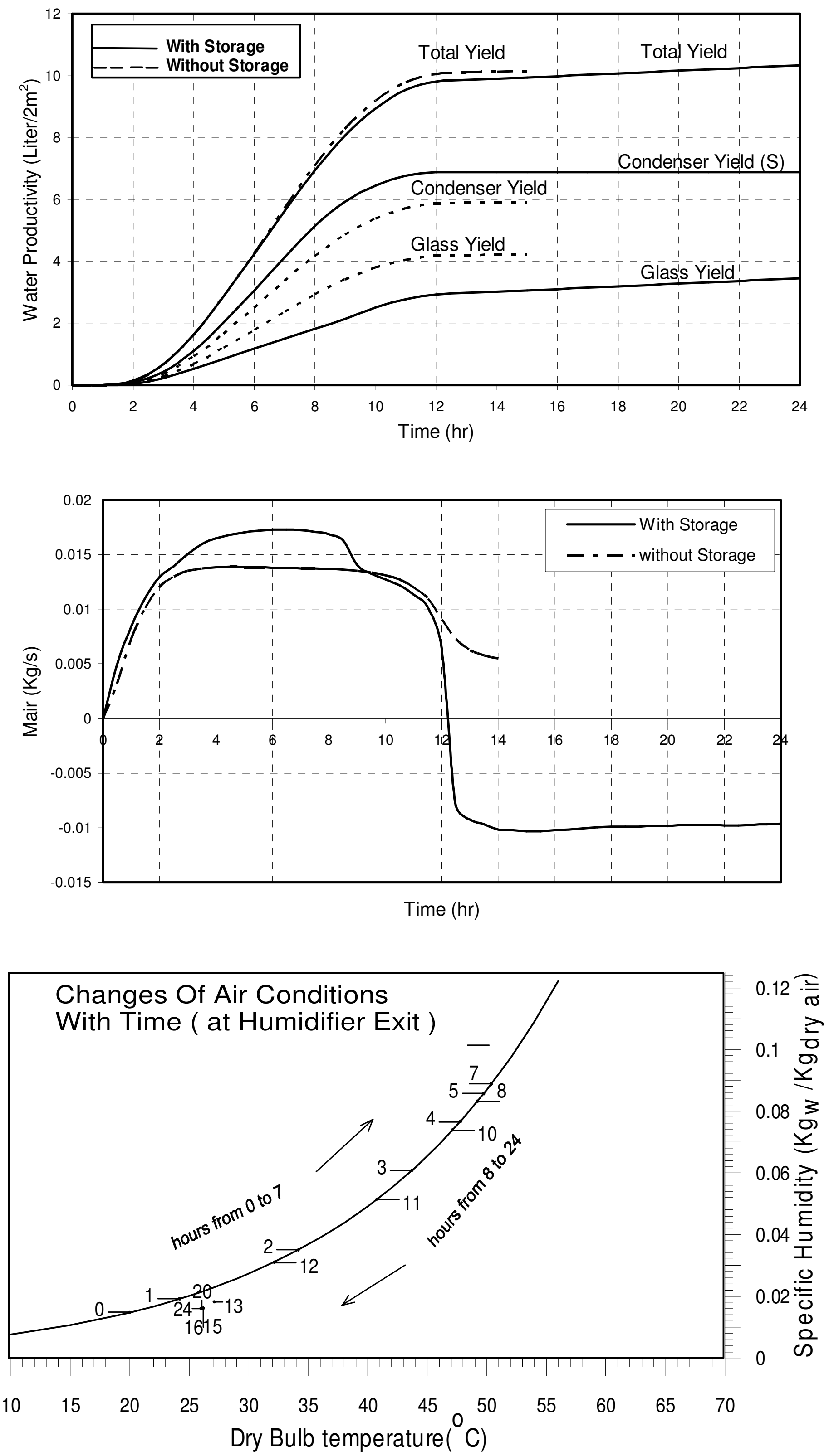


Fig. 15. Condensation Energy Recovery Placed Under the Basin

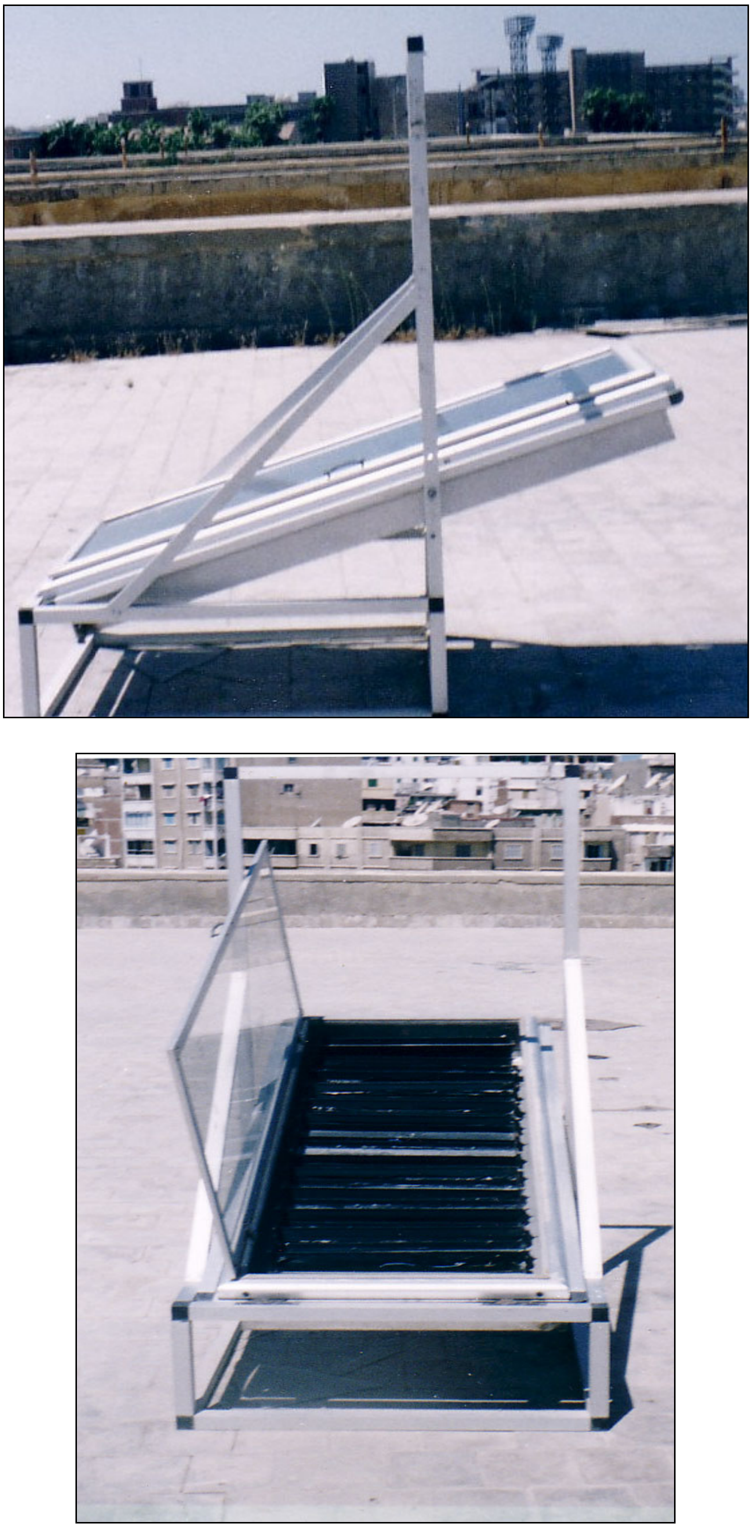


Fig. 16. Manufactured HDD Solar Still