International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 6, Issue 4 [April 2017] PP: 53-63

Performance Characteristics of Solar Chimney integrated with Evaporative Cooling Technique for Building Natural Ventilation

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ABSTRACT:-In the present study,the integration betweena solar chimney and evaporative cooling as a type of passive cooling technique for building coolingwereinvestigated experimentally.Thetechniques were usedas an alternativetodecrease the energy consumption ina buildingby using hybrid system of the solar chimney and evaporative cooling. The experimentswere conducted to a tested room of 8m x 5m x 3m and the solar chimney of 3m x 1m x0.3m air gab.Six spray nozzlesusing aquifer pumped water were located at the inlet tower.The performance of the solar chimney at different summer times with aquifer spray water as an evaporative cooling was the main point of interest. The effect of the solar chimneyinclination angle,day and year months on the room temperature and ventilatedair change per hourduring solar radiation hours was studied.The experimental runs were carried out at inclination angles ranged from 15^o to 45^o during solar radiation hoursranged from 9AM to 5PMaccording to Atlas Egypt. The results indicated that the using of solar chimney and evaporative cooling is very effective way in natural ventilation method of technique. An accepted room temperatureof 25.5^{o}Cand 4 times per hour air change were obtained in September withinclination angle of 45^{o}withoutinternal equipment load.

Key words:*Solar chimney; Evaporating cooling;Aquiferwater.*

NOMENCLATURE

A area, m^2
ACH air changes per hour
Cp specific heat, kJ/kg.^{o}C
C_d discharge coefficient
D chimney gap, m
D_h hydraulic diameter ($\frac{4A}{wp}$), m
g gravity acceleration (9.81), m/s^2
I solar radiation intensity, W/m^2
i specific enthalpy, kJ/kg
i_{fg} vaporization latent heat, kJ/kg
k thermal conductivity,W/m.^{o}C
L length of the chimney, m
$\dot{m}$ mass flow rate, kg/s
$\dot{V}$ ventilation rate, m^3/s
R.H relative humidity, %
t temperature,^{o}C
T temperature,K
T_m mean temperature ($\frac{T_s + T_f}{2}$),K
v velocity, m/s
V volume, m^3
w wide of the chimney, m
wp wetted perimeter, m

Greek symbols
α absorptivity
Δ difference
ε emissivity
η efficiency, %
θ chimney inclination angle, Radians
μ dynamic viscosity, kg/m.s
ρ density of air, kg/m^3
τ transmissivity of glass
ω humidity ratio, (kg/kg. dry air)

Subscripts
a air
chim. chimney
f film
i inlet/inside
o outlet/outside
r ratio
s surface
v vapor

I.INTRODUCTION

The theoryof direct evaporativecoolingdepending on the fact of water must have a large amount of energy to change from liquid phaseto vapor. While the heatenergy required raisingthewater temperature by1°C equals4.18kJ/kg,thespecificlatentheatof vaporizationis 2257 kJ/kg[1].In the case ofanevaporative cooling system, thisenergy issupplied primarily by theintakeair,which heatcontentandcapacitytoholdvapor are indicated byitsdrybulb temperature andrelativehumidity.Numerical simulation of cooling performance of wind tower (Baud-Geer) in hot and arid region was studied by Kalantar [2] the results indicate that the evaporative cooling is very effective in a hot and dry region. The temperature decreases considerably, if the wind towers are equipped with the water vaporization system. This causes the air becomes heavier and a natural motion of air through downside of wind tower to be produced. Chunglooetal.[3] investigated experimentally the performance of a solar chimney and water spraying system placed on the roof. They reported that the system performed well in high ambient temperature.The performance of integrated evaporative cooling system driven by solar energy was studied by Miyazakia et al. [4] The results showed that the system was capable of coping with the radiative cooling load as much as 40–50 W/m^2 without a severe increase of the ceiling temperature.Chen [5] investigated the thermal analysis of a wet porous evaporative plate for building cooling. A mathematical model was developed to analyze the influences of ambient conditions and the porous plate thickness on the cooling performance of the porous evaporative plate. the results presented that with decreasing in ambient relative humidity and an increasing in ambient temperature, more cooling of the porous evaporative plate can be supplied for the inside of room. Abdallah et al. [6]developed an integration of direct evaporative cooling tower with a solar chimney in multi-zone thermal ventilation model. The simulation was done using commercial couple multi-zone airflow under COMIS-TRNSYS software to assess natural ventilation and indoor thermal comfort. The results show that the system generates 130.5m^3/h under the effect of solar radiation only and minimum 2 ACH without pressure coefficient which is considered the minimum requirement of ACH.

A parametric investigation of using the solar chimney with new cooling tower in a single room for new Assiut city, Egypt climate was studied by Abdallah et al. [7] the parametric study of the integrated system in phase two were studied to achieve high performance with new compact small design especially for the hottest days in the summer season. The result showed that the system achieved nearly 80 % acceptable comfort range with optimum ventilation rate 414m^3/h for the hottest day.A study of vaulted roof assisted evaporative cooling channel for natural cooling of one floor buildings was studied by Haghighi et al. [8] The results indicated that the air inside the building will be ventilated efficiently at wind velocity is higher than 0.4m/s, As the wind velocity or the ambient air temperature increases, thermal comfort was achieved at lower values of relative humidity. The maximum allowable values for relative humidity of the ambient air to meet thermal comfort conditions are calculated based on the adaptive thermal comfort standards.

Benhammouet al. [9] analyzed the performance of an earth to air heat exchanger assisted by a wind tower for passive cooling of buildings in arid and hot climate. The results showed that the wind tower dimensions (height, cross section) have not an important impact compared to the pipe dimensions (length, diameter). The results also found that a tower with a total height of 5.1m and a cross section area of 0.57m^2 can generate an air flow rate of 592.61m^3/h. Furthermore, it has been also observed that the daily cooling potential reached a maximum of 30.7kW/h corresponding to a pipe length of 70m. Alemu et al. [10] developed an integrated model incorporating passive airflowcomponents into coupled multizone ventilation and building thermal model. This model allows an assessment of a combination of passive features such as solar chimney and windinduced earthair tunnel for bothnatural and hybrid ventilation systems at the design stage.As the author knowledge, a few of papers had been shown the cooling potential ofhybrid the solar chimney and aquifer water in passive cooling and natural ventilating. So the present study aims to investigate experimentally the integration between solarchimney and evaporative cooling using aquifer water for building natural ventilation.Theeffected parameters were chimney inclination angles, solar radiation intensity during daylight hours and at different year times. The study carried out in hot arid climate condition of Cairo–Egyptas a case study.

II.EXPERIMENTAL APPARATUS

Figure (1) shows a schematic diagram of the experimental setupof the passive cooling techniques.The experimental set up consists ofthe tested room,aquiferwater circuit, inlet tower and solar chimney. The room internal dimensions were8m x 5mx3mlong,width and height respectively. All walls were brick with a thickness of 0.2mand both base and roof were a concrete with a thickness of 0.2m. The room is oriented to basic geographicorientation (east, west, north and south directions).This system was developed from the reference system of inclined solar chimney attached to a room[11]. An aquifer water circuit is the source of water (Aquifer River) at 22m depth, a circulating pump, a ball valve, a rotameter and nozzles. That provide to the inlet tower to applying the evaporative cooling technique. The open-loop circuit which consists of a long pipe that immersed in undergroundaquifer water was pumped to the inlet air tower by using 1HPcentrifugal pump and the flow rate was controlledby a ball valve and measured using the rotameter (0 to 18 Liter/minute) with accuracy of ±0.5%. An inlet tower with internal dimensions of 0.6m length, 0.3m width and 1m height with a thickness of 0.02m wasconnected to the room through the roof opening with stainless steel duct with dimensions of 0.3m x 0.6m. The purpose of the inlet tower is to pre-processing of the air at the room inlet. Six nozzles were installed at the inlet openingto sprayaquifer water at 18^{o}C ±0.5^{o}C at the air inlet direction.

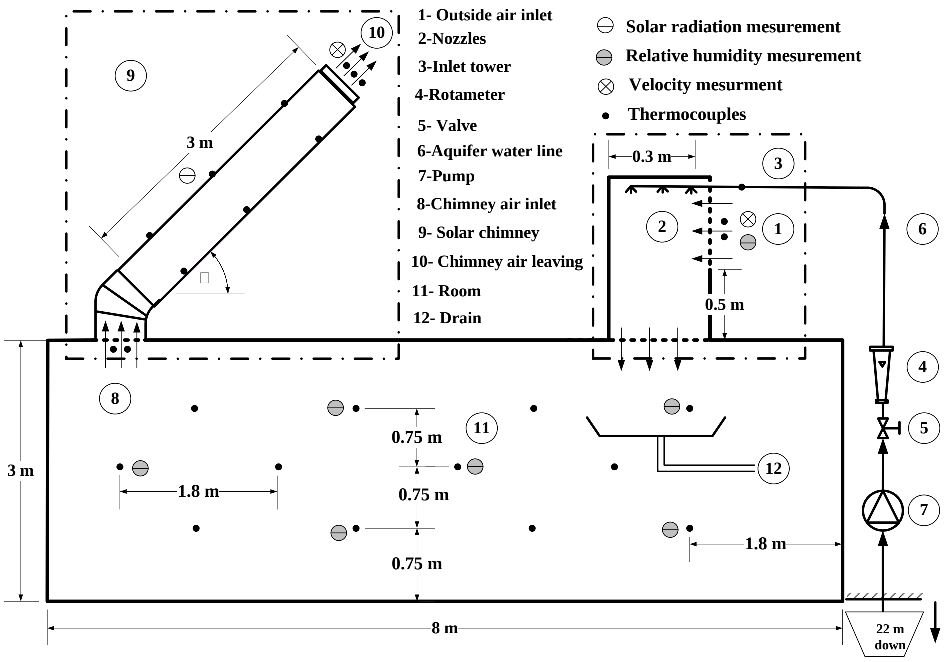


Fig. (1) Schematic diagram for the experimental set up.

A roof solar chimney of3m long, 1m width and 0.3m air gab was connect to the room through a roof opening by stainless steel duct with dimensions of 0.3m x 0.8m. The chimney was positioned to geographic south direction at inclination angle of θ. The purpose of the chimney is to pull air from the room depending on buoyancy effect. The solar chimney upper face is a clear glass (0.004m thickness) of transmissivity (τ=0.78) and absorptivity (α=0.15) at zero incident radiation angle. The bottom face of the solar chimney is a mild steel of (0.0012m thickness) as absorber wall;the absorber wall bottom was thermally insulated by a glass wool thermal insulation of 0.025m thick. Details of the physical parameters and the range of experimental conditionswere given in table (1) and table (2) respectively. A sample of the average outside air conditions ofdry-bulb temperature and relative humidity for experiments run from 5 to 25 of July was given inTable (3).The temperatures of the inlet air tower, aquifer water, solar chimney air inlet and outlet openings, glass surface and absorber surface were measured by pre-calibrated K-type thermocouples. Also, twelve thermocouples were fixed at different positions to measure the average room air temperatures as shown in figure (1). All thermocouples that used in this study were 0.8mm diameter. The thermocouple wires were connected to the digital device with accuracy of ±0.1%. An anemometer was installed at the exit of the solar chimney with an accuracy of ±0.25% and 0.1m/s minimum reading to measure the air velocity. The solar radiation intensity was measured by a solar power meter device installed on the solar chimney to measure the global solar radiation in W/m^2 with accuracy of ±0.1% and 1W/m^2 minimum reading. Digital hygrometer with accuracy of ±0.1% was used to measure the relative humidity at the following positions;

1. At inlet air to the tower
2. At six positions inside the tested room as shown in the figure (1) and hence the average was taken. The measuring parameters were air temperature, air velocity, solar radiation, and relative humidity.
   The experiment location is presented in Cairo, Egypt with latitude of (30.13^o), longitude (31.4^o), and time zone GMT+2. Also the solar radiation intensity and air temperatures are measured according to ASHRAE recommendation.

Table (1) Experimental setup physical dimensions

Parameter	Dimension	Unit
Room L x W x H	8 x 5 x 3	m^3

Room air inlet openingArea	0.18	m^2
Room air outlet openingArea	0.24	m^2
Length of chimney	3	m
Width of chimney	1	m
Air gab of chimney	0.3	m
Glass coverL x W x H	3 x 1 x 0.004	m^3
Absorber plate (Mild steel) L x W x H	3 x 1 x 0.0012	m^3
Chimney air inlet	0.8 x 0.3	m^2
Chimney air outlet opening	1 x 0.3	m^2
Inlet tower dimension L x W x H	0.6 x 0.3 x 1	m^3
Spry nozzle outlet diameter	0.001	m

Table (2) Experimental conditions for the present work.

Variables	**Range**	**Number of runs**
Chimney inclination angles	15^o- 22.5^o- 30^o- 37.5^o- 45^o	5
water mass flow rate, Kg/s	0.017	1
Day hours	9 Am-5 Pm	9
Days	6^{th} of June to 15^{th} of October	50

Table (3) Average inlet air conditions from5 to 25 of July.

Day hours	**Dry-bulb temperature (^{o}C)**	**Relative humidity (%)**
9:00 AM	30.5	52.32
10:00 AM	32.7	47.72
11:00 AM	33.6	40.18
12:00 PM	35.9	34.44
1:00 PM	39	32.28
2:00 PM	39.8	32.94
3:00 PM	38.3	29.7
4:00 PM	38.4	29.16
5:00 PM	36.9	31.82

III.UNCERTAINTY ANALYSIS

The experimental error analysis indicates the implication of error of the measured parameters on the uncertainty of the results. The uncertainty analysis of the various calculated parameters are estimated according to Holman [12], Given W_1, W_2, W_3,…, W_n uncertainties in the independent variables (X_1, X_2, X_3,…X_n) and W_R is the uncertainty in the result at the same odds, then the uncertainty in the result can be given as;
The uncertainties of the experimental parameters are given in Table (4).

$$W_R = \left[\left(\frac{\partial R}{\partial X_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial X_2} W_2 \right)^2 + \left(\frac{\partial R}{\partial X_3} W_3 \right)^2 + \ldots\ldots + \left(\frac{\partial R}{\partial X_n} W_n \right)^2 \right]^{\frac{1}{2}} \quad (1)$$

Table (4) Accuracy and Uncertainty of measuring devices.

Instruments	**Unit**	**Accuracy (%)**	**Uncertainty (%)**
Rotameter	kg/s	±0.5	±0.5
Thermocouple K-type	^{o}C	±0.1	±0.11
Anemometer	m/s	±0.25	±6.28

Solar power meter	W/m^2	±1	±0.11
Digital Hygrometer	%	±0.1	±0.12
ACH	-	-	±6.29
Chimney efficiency	%	-	±6.7
Heat dissipationrate	W	-	±6.68

IV.DATA REDUCTION

The solar chimney efficiency can be determinedas [13]:

$$\eta_{Chim.} = \overset{g}{m}_f \, C_p \left(t_{Chim.,o} - t_{Chim.,i} \right) / \, I \, A \qquad (2)$$

Air mass flow rate in chimney due to stack height can be as[14]:

$$\dot{m} = C_d \, \rho_{Chim.,o} \, A_o \sqrt{\frac{2gL \sin\theta \, (T_f - T_{Chim.,i})}{(1 + A_r^2) \, T_{Chim.,i}}} \qquad (3)$$

Where A_r is the ratio between the chimney air outlet cross section areaA_o and its inlet cross section area A_i.
In natural ventilation the mean air temperatures in solar chimney can be calculated as[13]*:*

$$T_f = 0.75 T_{Chim.,o} + 0.25 T_{Chim.,i} \quad (4)$$

The coefficient of discharge C_d was taken as 0.57 as suggested byAnderson[15].The velocity of air in the chimney can be calculated as:

$$v_o = \frac{\dot{m}}{\rho_{Chim.,o} A_o} \quad (5)$$

The room air change per hour can be calculated as:

$$ACH = \frac{\dot{V} \ x \, 3600}{V_{room}} \quad (6)$$

The energy balance equation for the heat dissipation from the air to evaporated water in the inlet tower is expressed as[1]:

$$\dot{m}_{a,o} \, i_{a,o} = \dot{m}_{a,i} \, i_{a,i} + \dot{m}_v \, i_{fg} \quad (7)$$

Where *i*is the specific enthalpy which can be calculated as [1]:

$$i = 1.005T + \omega \, (2501.1 + 1.86 \, T) \quad (8)$$

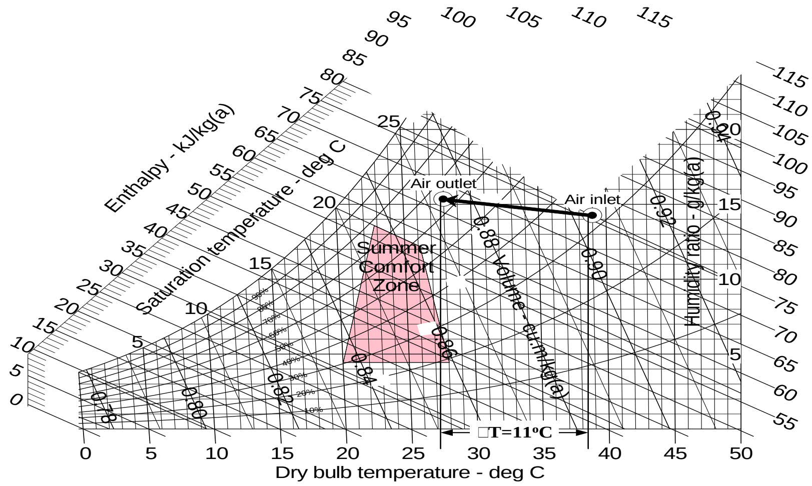


Fig. (2) Evaporative cooling process on psychometric chart.

V.RESULTS AND DISCUSSION

The performance characteristics of the solar chimney with evaporative cooling were investigated as the effect of chimney inclination angleand the effect of year times on the system performance;

5.1. Effect of Chimney Inclination Angle

Figure (3) illustrates the effect of the chimney inclination angle on the chimney air temperature difference. It shows the relation between the chimney air temperature differences versus day time at different solar chimney inclination angles ranged from 15^o to 45^o at July. It can be seen that there are significant effects of the solar chimney inclination angle on the air temperature difference during day time. Also the chimney air temperature difference increases with increasing in chimney inclination angle from 15^o to 45^o by approximately (32%) at 1PM. The temperature difference increases according to the buoyancy-driven flow effect which induced due to the incident solar radiation upon the cavity of solar chimney.The relation between the room air changes per hour and day time at different chimney inclination angles ranged from 15^o to 45^o at July were presented in Fig. (4). It is noted that the room air changes per hour increases with the increase in day time hours and reached a maximum value of 3.23 at 1PM. Due to change the inclination angle from 15^o to 45^o the room air changes per hour increases by approximately (73.4%) at 1PM. According to equation (3) as the temperature difference increases, the buoyancy-driven flow effect increases which led to increase in the air velocity output from the solar chimney and consequently the ACH.As the solar chimney inclination angle increases, the stack height ($L \sin \theta$) increases and henceincreases the air mass flow rate, velocity and consequently the ACH.Figure (5) presented theeffect of chimney inclination angle ($15^o$to 45^o) on solar chimney efficiency at July. It can be shown that the chimney efficiency increases with increasing in day time hours till 1PM then reduced after noon time. At certain time of 1PM and chimney inclination angle of 45^o the chimney efficiency reached to maximum value of approximately 52%. This can be attributed toincreasing in air temperature differences through the chimneythat resultsinincreasing in the heat transfer rate relatively to incident solar radiation upon the cavity of solar chimneytill middle day then decreases.

The effect of the evaporative cooling on the room air temperature during day time can be illustrated inFig. (6).It can be noticed the reduction in room air comparing to outside air temperature atdifferent chimney inclination angles(15^o to 45^o) during day time at July. At a certain time of 1PM the room temperature decreases than outside air temperature by approximately (49%) when chimney inclination angle was 45^o. This can be attributedto decreasing the thermal content of outside air due to direct contact with Aquifer water through inlet tower which applying evaporative cooling and decreasing the air temperature.Figure (7) demonstrate the variation of air temperature differences through the inlet tower during day time hours at different chimney inclination angle (15^o to 45^o) at July. It can be noticed that the air temperature difference through the inlet air tower increases during day time hours and reach to maximum value of 9.7^{o}C at 1PM at chimney inclination angles of 45^{o}C then slightly deceases after noon time. This can be attributed to reduction in heat content of air due to occurring evaporative cooling through inlet air tower. Figure (8) describes the variation of air relative humidity at both outside and inside positions during day time hours due to using evaporating cooling at July. It can be noticed that there is a significant effect of using evaporative cooling on increasing room relativehumidity at all chimney inclination angles. When aquifer water evaporated due to evaporativecooling occurring, the partner air carried the water vapor to the tested room which results in increasing the vapor content in air andhence increasing the relative humidity. At a certain time (1PM) the relative humidity of room at inclination angle of 45^o is higher than the outside air relative humidity by approximately (98.8%).

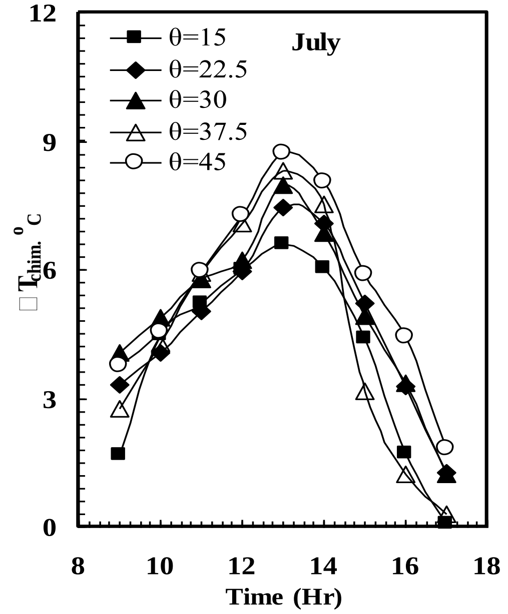


Fig. (3) Chimney air temperature difference versus day time at different inclination angles.

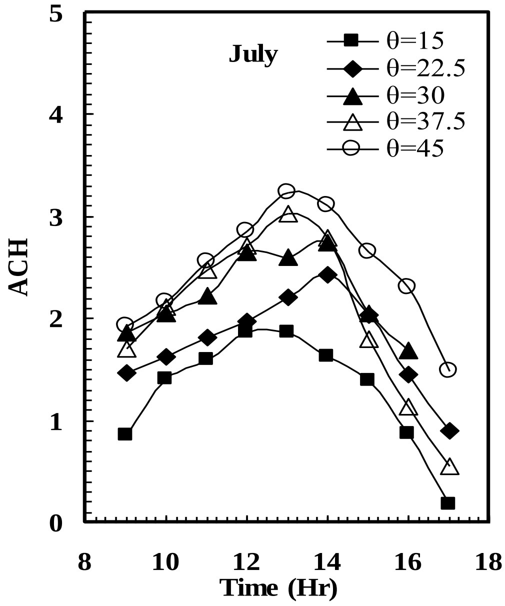


Fig. (4) Air change per hour versus day time at different inclination angles.

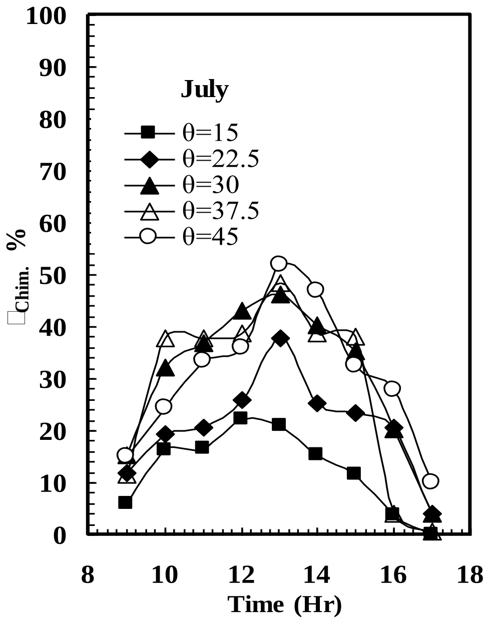


Fig. (5) Chimney efficiency versus day time at different inclination angles.

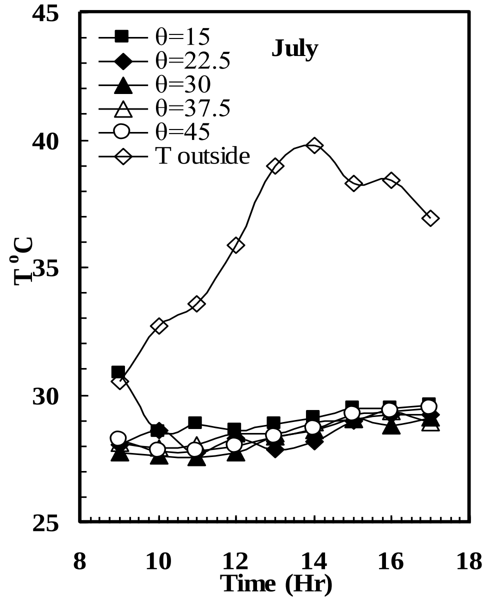
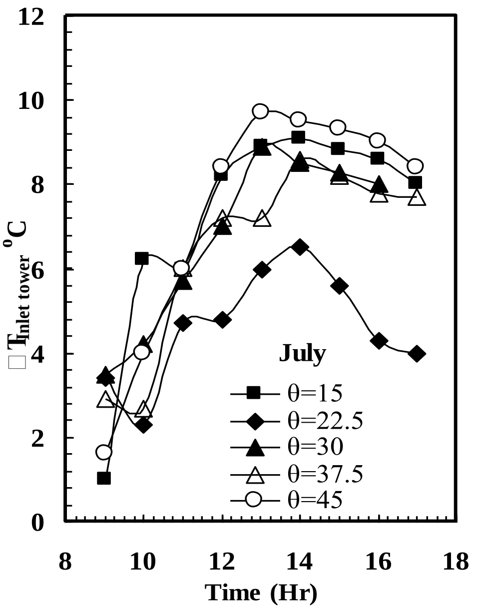


Fig. (6)Air outside and inside temperature versus day time at different inclination angles.

Figure (9) shows the relation between the heat dissipation rates through inlet tower during day time hours at different solar chimney inclination angle (15^o to 45^o) at July. It can be shown that the heat dissipationrate of the entering air to inlet tower increases with increasing in day hours and reached to maximum value of 1180W at solar chimney inclination angle of 45^o at 1PM in 25th of July then decrease after noon time. Due to



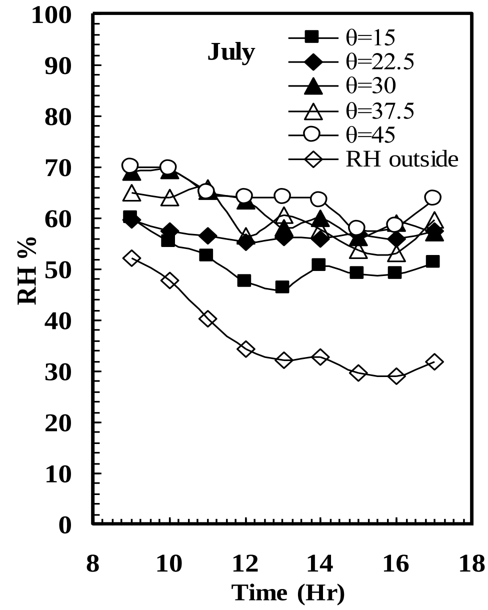
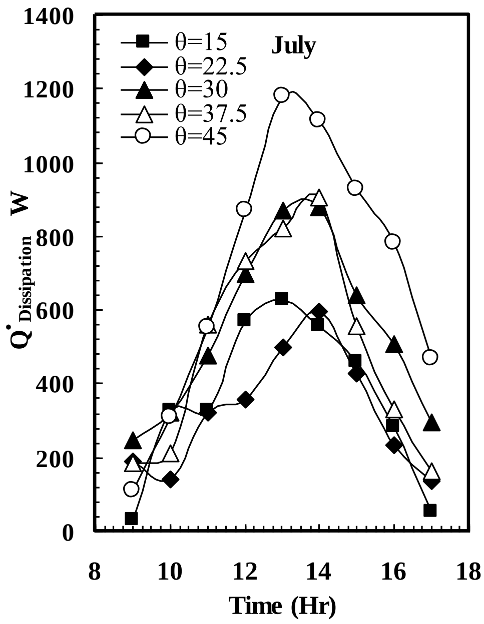


Fig. (7) Inlet tower air temperature diff. versus day time at different angles.

Fig. (8) Average relative humidity versus daytime at different inclination angles.



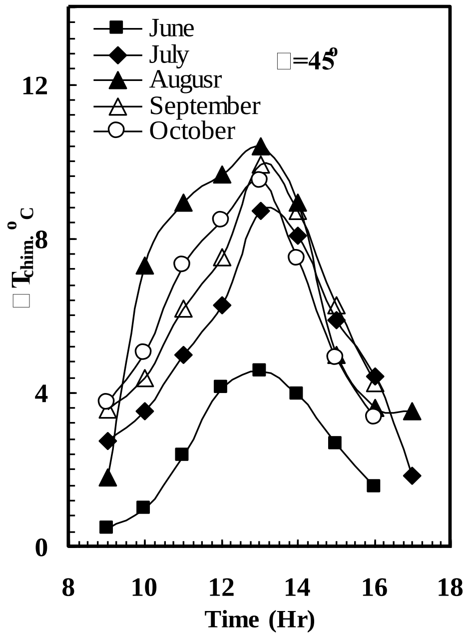


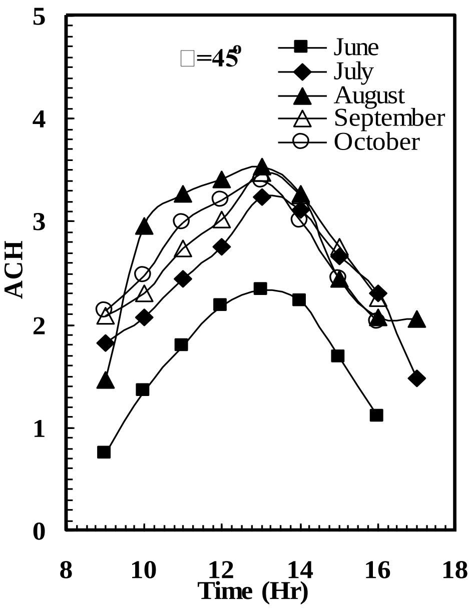
Fig. (9) Inlet tower heat dissipation rate versus day time at different inclination angles.

Fig. (10) Chimney air temperaturedifference versusday time at different year times.

increasing in temperature differences between outside air temperature and aquifer water the evaporative coolingrate increases through inlet tower and hence increasing air temperature difference and consequently the heatdissipation rate.The effect of change the year times on chimney performance is point of interest in this work. Figure (10) shows the effect year months which reflect to sun angle with summer season on chimney air temperaturedifference at inclination angle of 45o. It can be noted that there are significant effects of the year times on chimney air temperature difference during day time in which the maximum values is observed at 1PM and then tended to reduce slightly. The maximum value of air temperature difference occurs at 1PM in August month. This value is approximately (152%) higher than the value at June month. this can be attributed to change in solar radiation intensity due to solar angle change from June to August months intensity and produce the increase in both ΔT_{chim}.

5.2. Effect of Year Times on the system performance

Figure (11) describe the variation of the room air changes per hour during day time at different year times and at chimney inclination angle of 45°. It is noticed that the room air changes per hour increases with the increasing in day time hours and reached to maximum value at 1PM at the maximum solar radiation intensity, also the air changes per hour increasesduring change in year times from June to October. At a certain time (1PM) the air changes per hour during August month is higher than that of June month by approximately (51.5%). This can be attributed to increasing in solar radiation intensity due to change in year times from June month to August month that results in increasing the air temperature difference and hence produce the increase the buoyancy driven force and consequently increase chimney air outlet velocity and ACH. A variation of chimney efficiency is presented in Fig. (12) during different year times andat chimney inclination angle of 45°, the figure exposed that the chimney efficiency increaseswith increase in solar radiation during day time hours; it means that chimney efficiency is afunction of solar radiation and highest chimney efficiency occurred at peak summermonths(August month) at 1PM of the day. At a certain time (1PM) the chimney efficiency atAugust month is higher than that of June month by approximately (153.1%).



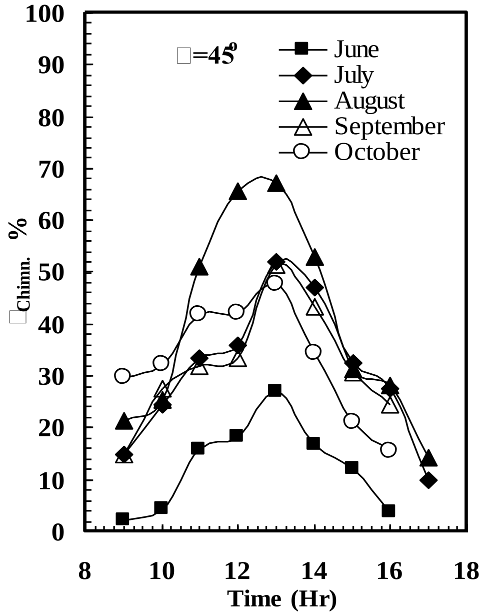
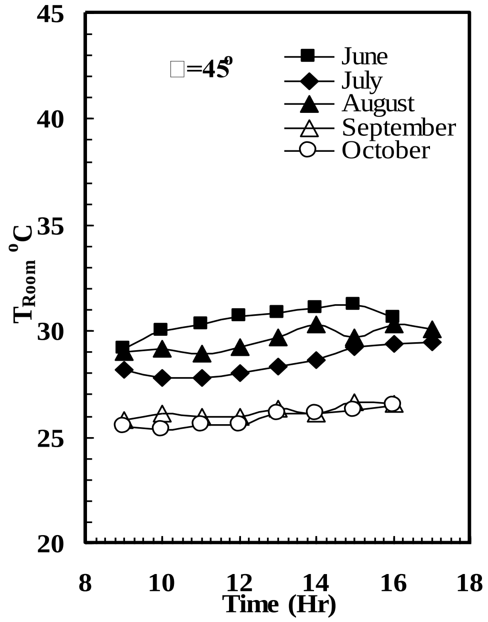


Fig. (11)Air change per hour versus day Fig. (12)Chimney efficiency versus day time at differentyear times.time at different year times.

The effect of the evaporative cooling on the room air temperature during day time hours was illustrates in figure (13). It can notice that there is a significant effect of different year times from June to October and at chimney inclination angle of 45o on room air temperature. At a certain time (1PM) the room air temperature in October month decreases than that in June month by approximately (15.4%).Figure (14) shows the relation between air temperature differences through the inlet tower during day time hour at different year times and at solar chimney inclination angle of 45o. It can be clearly notice that the inlet tower temperature difference increase during day time hours and reach to maximum value of 9.4oC in 25th of July at 1PM then deceases slightly after noon time. Also it can be seen the increasing in inlet tower temperature differences during year months due to change in outside climate condition.

Figure (15) shows the variation in room air relative humidity due to using evaporating cooling with solar chimney during day time hours at chimney inclination angle of 45°. It can be notice that there is a significant effect of using evaporative cooling with solar chimney on increasing room relative humidity. It can be attributed to increasing water evaporation rate that results in increasing in air humidity ratio and hence increase air relative humidity. It can also notice the increasing in room relative humidity due to change in year times from June to October months. At a certain time (1PM) the relative humidity of room at October month is higher than that at June month by approximately (48.3%). This can attribute to change in outside climate condition during year times that effects on evaporative cooling occurring. Figure (16) shows the relation between the heat dissipation rates through inlet tower during day time hours at different year months and at 45° inclination angle. It can be shown that the heat dissipation rate increases during day time hours and reached to maximum value of 1180W at1PM in 25th of July then decrease after noon time, also there are significant effect of year months on



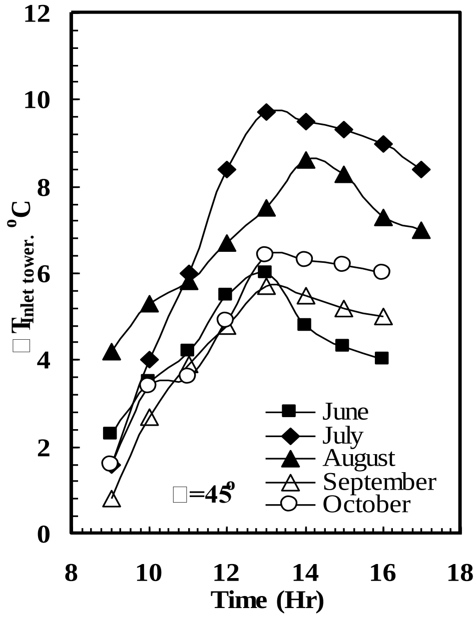
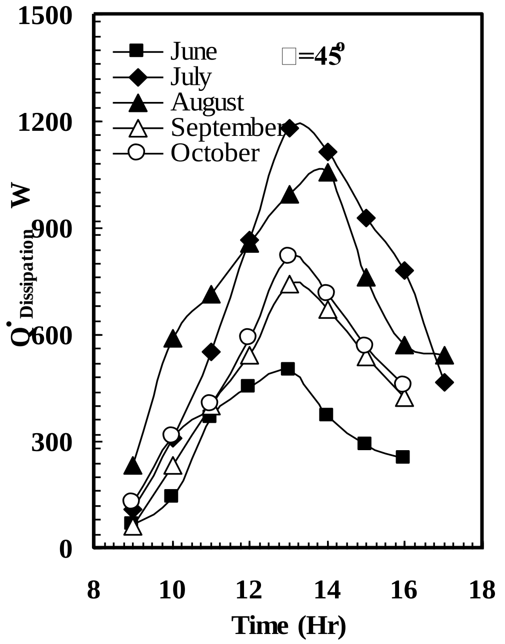


Fig. (13)RoomairtemperatureversusdayFig.(14)Inlettowerairtemperature difference timeatdifferentyear time. versus day time at different year time.



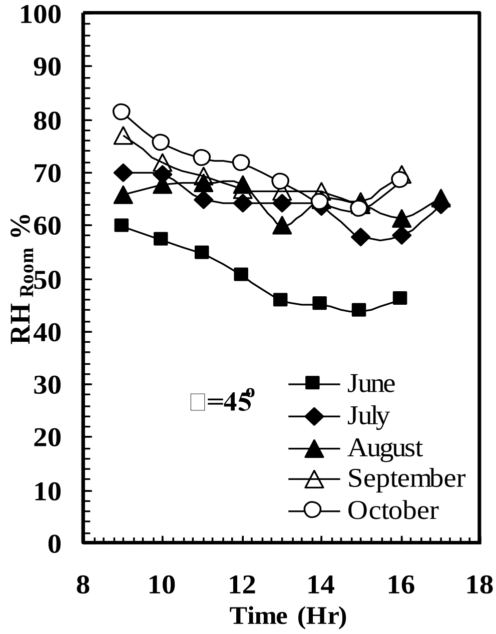


Fig. (15)Room relative humidity versusFig. (16)Inlet tower heat dissipation rate day time differentyear times.versus day time different year times.

heat dissipation rate of air through inlet tower. At a certain time (1PM) the rate of heat dissipation from the entering air through inlet tower July is higher than that June by approximately (198.2%).

VI. CONCLUSION

A new passive cooling system of hybrid between solar chimney and evaporative coolingwith aquifer water was experimentally investigated. The system presented as one of apractical alternatives to the conventional air conditioning systems to decrease energy consumption in building. The study was carried out at chimney inclination angles varied from 15^o to 45^o during different year times of June to October. The room air change per hour and room temperature difference were examined during daylight hours; the main conclusions are summarized as follow:

- The solar chimney inclination angles have a significant effect on the buoyancy-driven flow induced from inlet tower which achieved of air charge per hour = 3.5.
- There is an acceptable room air temperature (in average $\Delta T = 8^oC$) due to the use evaporative cooling with solar chimney hybrid system.
- The maximum temperature difference through inlet air tower of 9.4 ^oC was obtained at 1PM at 25th of July which was due to the effect of evaporative cooling.
- For all cases the best solar chimney efficiencywas achieved at inclination angle of 45^o.
- At a certain time of 1PM the air changes per hour at inclination angle of $45^o$was higher than that at 15^o by approximately 73.4% in July month.
- At a certain time of 1PMthe rate of heat dissipation due to evaporative cooling through inlet tower in July is higher than that June by approximately (198.2%).
- The solar chimney and evaporative cooling system is more effective for reducing the room air temperature with less energy consumption in buildings however the increase in room relative humidity is expected.

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