Experimental and Numerical Study of Closed Loop Solar Chimney Assisted with PCM and CFM as Thermal Energy Storage Collector

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ABSTRACT

In this work, a test room was built in Baghdad city, with selective dimensions, while the solar chimneys (SC) where designed with aspect ratio (ar) bigger than 12 and setup to the oriented wall to the south. Collector of SC consist of paraffin wax as a phase change material (PCM) and supported by copper foam matrix (CFM), to enhance the combined of thermal energy storage material box (TESMB). Double transparent acrylic sheets covered the collector from outside. TESB supported by array of evacuated tubular collector with thermosyphon to sincere heat storage in the TESB. Results of experimental work that achieved in 25 January and 26 February refer to effectiveness using TESM in closed loop SC in day time and its effect cover the night time also. The heating system of test room is arrived to the biggest room temperature after sun set, at that moment the difference between indoor and outdoor approximately 15^{o}C, and room temperature value still bigger after five hours from sun- set with a different in temperature by approximately 8 ^{o}C. Numerical solution done by employing CFD with solution the PDE's that present continuity, momentum, energy equations, by using the FVM with algebraic forms of turbulent viscosity and diffusion coefficient and employing turbulent standard $(k-\varepsilon)$model. The comparison between numerical and experimental results indicated that the heat transfer inside test room is dominate by condition, also results shows acceptable convergence in velocity and temperature profile, while the experimental results for air flow inside SC gap appears the turbulent behavior in most duration time.
Keyword: solar chimney (SC), phase change material (PCM), foam matrix(FM).

INTRODUCTION

Conventional heating room or building, by solar was used the direct glazed flat plate collector, or by use the trombe wall. To enhancement the heat control and to keep the room temperature in stable value, beside storage the heat and release it after sun-set, so many mechanisms was used to storage the heat and make self-control temperature. So that don by used (TSM). Burek and Habeb [1] studied experimentally the heat and mass flow in thermosyphoning air heaters, such as solar chimneys and Trombe-Walls. The test rig comprised a vertical open-ended channel with closed sides. Results showed that the mass flow rate through the channel was a function of both heat input and depth of the channel, while the thermal efficiency of the system was represent the function of heat input only. Wei et.al [2] proposed a theoretical model used PCM for energy storage in a lightweight passive solar room. The analytical results showed that the optimal phase change temperature depends on the average

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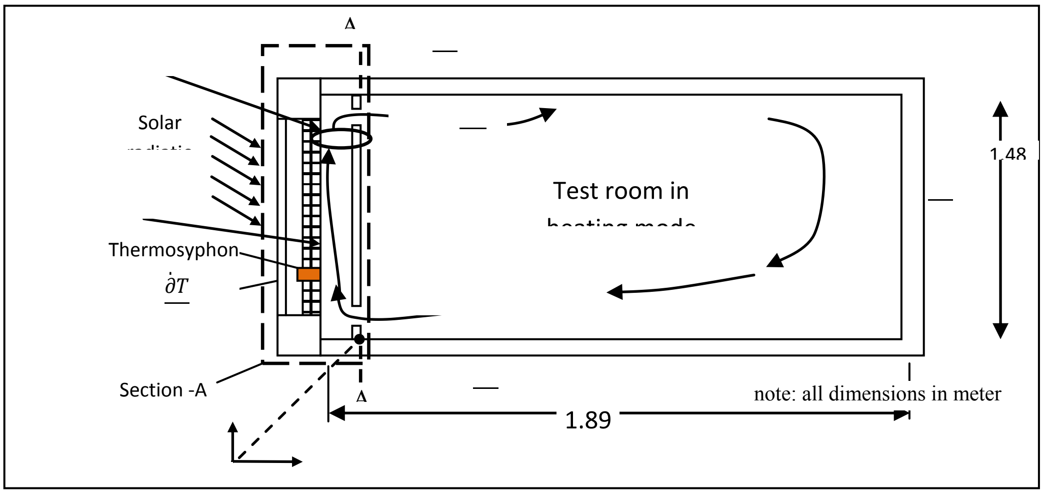
indoor air temperature and the radiation absorbed by the PCM panels; while the interior PCM has little effect on the indoor air temperature; the amplitude of the indoor air temperature fluctuation depends on the product of surface heat transfer coefficient and area of the PCM panels in a passive solar room. Alkilani et.al [3] investigated theoretically the thermal and physical properties of a PCM that consists of paraffin wax with 5% aluminum powder. This composite used as a TES compound for a solar absorber in roof, where cross flow of pumped air, results showed that the air temperature gained due to thermal energy discharge process decreases with increasing of air mass flow rate, and the freezing time for this compound takes long time interval for the lower mass flow rates. Mohammed [4] In this work the test room is equipped with a concrete Trombe wall, and the theoretical investigation of this study is done by solving continuity, momentum and energy equations by employing Finite Volume method (FVM). They found the variation of the temperature with time, had marked the highest temperature with 40 ^{o}C at 01:00pm. The comparison between theoretical and experimental results indicated that the rate of rising in the mean room temperature observed experimentally is higher from than observed theoretically. Haghighi and Maereft [5] Natural ventilation and heating of a room which uses SC as a heating source were studied numerically. Parametric study was carried out to determine the effects of sizes of air gap, openings and environmental ambient condition on ACH and indoor air temperature. The results showed that there is an optimum size of 0.2 m for air gap at which maximum ACH can be achieved. It is also found that there is an optimum inlet and outlet sizes of 0.2 m for SC which leads to maximum ACH. The findings show that the system is capable of providing good indoor air condition at daytime in a room, even with poor solar intensity of 215 W/m2and low ambient temperature of 5◦C. Robinson [6] Previous computer simulations and bench-scale experiments showed that the heat pipe assisted solar wall had the potential for significantly improved performance relative to conventional passive space heating systems. A full-scale prototype of the heat pipe system was designed, built and installed in a classroom. Results showed that during the spring heating season, the maximum hourly average room gain achieved was 163 W/m^2. Amori and Saif [7] In this paper, the effect of integrating the chimney with paraffin wax on thermal behavior has been investigated numerically and experimentally. Results show that integrating solar chimney with PCM extended the ventilation period after sunset.

The objective of the present work is to investigate experimentally and numerically the thermo- fluid air behavior that takes place inside solar chimney-gap, with nontraditional thermal energy storage collector.

Numerical solution

A mathematical model of the fluid flow and heat transfer for natural air that pass in closed loop solar chimney that built in the test room Figure-1 have been adopted. The following assumptions has been done

(1) steady state in interval time (period test time =2hours)along test day.
(2) incompressible 2D flow.
(3) constant temperature along the chimney face that oriented to room.
(4) constant thermo-physical properties of the working fluid.



Figure(1) Physical model of test room

Governing Equations

Following below a set of partial differential equation as a governing equation in Cartesian coordinate [7], [8]:

I- Continuity equation (mass conservation)

—— ——

II- Momentum equation (Navier-Stokes equation)

u-momentum (x-direction)

$$— \quad — \quad — \quad -\left(\mu —\right) \quad -\left(\mu —\right) \qquad \ldots\ldots(2)$$

v-momentum (y-direction)

$$— \quad — \quad — \quad -\left(\mu —\right) \quad -\left(\mu —\right) \qquad 3)$$

III- Energy equation:

$$— \quad — \quad -\left(\Gamma —\right) \quad -\left(\Gamma —\right)$$

Where

μ/σ

σ: the Schmidt , μ: $viscosity$, u, v : mean velocity in x and y direction.

$-\varepsilon$ turbulence model is used for turbulent flow over flat plate (Ra>10^9), so μ and Γ are replaced by the effective value, by adding turbulent term as shown below[9]

Then the effective viscosity coefficient

The effective diffusivity coefficient

$- \; —$ or $—— \; ——$

The turbulent kinetic energy and dissipation rate can be written as follow:

Turbulence energy (k):

$$— \quad — \quad -\left(\Gamma —\right) \quad -\left(\Gamma —\right)$$

$/\sigma$

and /ε

$\mu \left(2\left[\left(—\right) + \left(—\right) + \left(— \quad —\right)\right]\right)$

Dissipation rate of kinetic energy (ε):

$— \quad — \quad —\left(\Gamma_{\varepsilon}—\right) \quad —\left(\Gamma \, —\right) \quad - \quad —$

/σ

The C are empirical constants with standard value [7],[10] Shown in table-1

Table(1), Value of constants in [7],[10]

1.43	1.92	0.09	1.00	1.0	1.3

Initial and boundary condition

No slip boundary conditions are adopted on solid boundaries for solar chimney and test room [7] , [13] as shown in Figure-1.

For room :

For solar chimney:

At walls of SC where (− chimney gap depth n negative direction

At the opening window

The air velocity boundary conditions at inlet of the chimney are

The inlet air temperature to the solar chimney is:

The air velocity boundary conditions at outlet from the chimney are

19)

The outlet boundary conditions are

$—\Big| \quad = —\Big| \quad = 0 \, ; —\Big|$

Left wall of solar chimney gap refer to the hot wall, then

the turbulent kinetic energy and the dissipation rate of kinetic energy at the inlet of the chimney are [10],[11]and[12]:

-

and $\frac{^{3}/_{4} \quad ^{3}/_{2}}{\quad}$

the turbulent kinetic energy and the dissipation rate of kinetic energy at the outlet of chimney:

Obtained from overall mass balance, assuming— = 0, at the outlet in converged solution where the normal gradients equal zero, so the outlet boundary condition can be written as : —

ε, where n is the coordinate direction normal to the outlet.

Numerical Solution

A simulation program will be constructed to solve the mathematical model for steady case By using the finite volume method (FVM), where a fluid flow and heat transfer are presented by the governing equation for continuity, momentum and energy equations beside define the model of flow.

Briefly the procedure stages to solve any problem by CFD by [10]:

- Definition of the geometry of the region of interest the computational domain.
- Grid generation of the domain into a number of smaller control volumes.
- Selection of the physical phenomena that need to be modeled.
- Definition of fluid properties.
- Specification of appropriate boundary conditions at cells.

Then the numerical algorithm consists of the following steps:

- Integration of the governing equations of fluid flow over all the (finite) control volumes of the domain.
- Discretisation-conservation of the resulting integral equations into a system of algebraic equation.
- Solution of the algebraic equations by an iterative method.

Experimental set up

Rig location and direction

In this study the rig is submitted to the Baghdad city location with altitude above sea level approximately equal 34 meter**,** altitude angle equal 33.3°N while longitude 44.24° E. Room face where solar collectors installed is oriented to the south direction of earth.

Rig Set-up

The rig consists of insulated test room. A vertical SC with two types of collectors is instilled at the south oriented wall. High measurement instruments tools are used in different measuring, beside two types of data acquisition data logger DAQ.

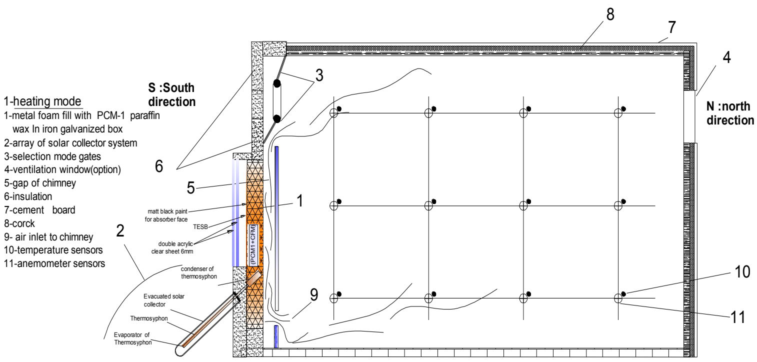
Effective dimensions of the system

The test room with dimensions (2m length, 1.5 m width, 1.5 height), supported by SC's as shown in Figures-1, 2. The length of room is bigger than from width and height, to clarifying the behavior of temperature distribution inside room. Besides clarifying the behavior of velocity inside test room and inside solar chimney gap. Solar chimney is designed with aspect ratio (ar=14.9) to prevent back air flow in chimney pass.

Test room and solar chimney

The structure of test room consists of a wooden frame; walls are insulated by 4 cm of cork with 0.043 W/m. K in thermal conductivity, 2.5 cm thick with 0.05 W/m. K for glass wool. The outside walls are insulated by marmox with U=2.7 $W/m^2.C$, while the roof and floor are insulated by marmox thermo-block with U=1.69 $W/m^2.^oC$. The dimension and description of vertical built-in solar chimney are; one meter in height of galvanized iron box collector installed at the south oriented wall with 0.75 meter in width. The box filled by copper foam matrix (CFM), and fully refined paraffin wax as a phase change material, to form thermal energy storage. Upper half of box is covered by double acrylic clear cover from outside, lower halve part is thermally insulated, and connected to array of evacuated tubular collectors with thermosyphons. The upper side of TESB that exposed to the sun irradiance is painted by a thermally matt black paint. Other side of the storage box (room side) is covered by an acrylic sheet, with 6.7 cm gap space and 14.92 in aspect ratio. Figure-2. Shows steps to manufacture the vertical SC and install it in test room, Figure-3, describes the schematic diagram for the test room.

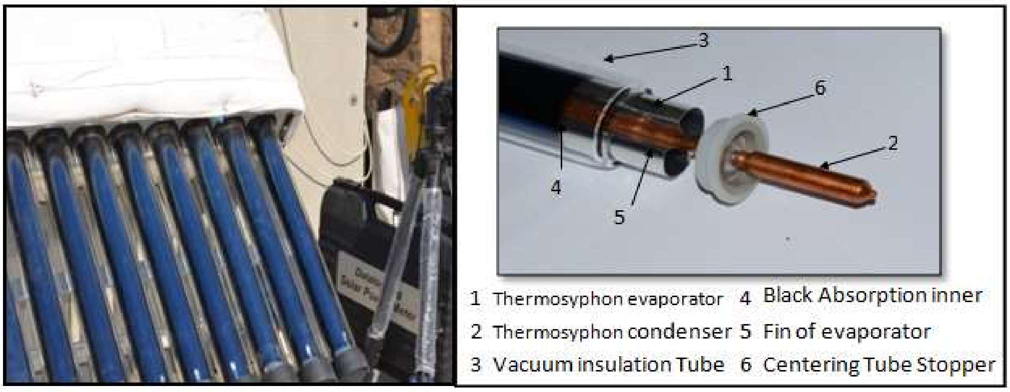
Figure(2), Steps to manufacture the vertical solar chimney and install it in test room



Figure(3), Schematic diagram for the test room

Evacuated tubular collectors with thermosyphon (ETCTS)

Ten pieces of ETC with Thermosyphon (TS) are used to collect heat at an inclination angle of 45^{o}, and transfer heat to the bottom of the vertical SC. ETC 50 cm in length and 5.8 cm in diameter is shown in Figure-2 and Figure-4. TS's condenser instilled inside the TESB, expander tube with expander roll tools are used to make a good contact between TS's condenser and (CFM) in TESB.



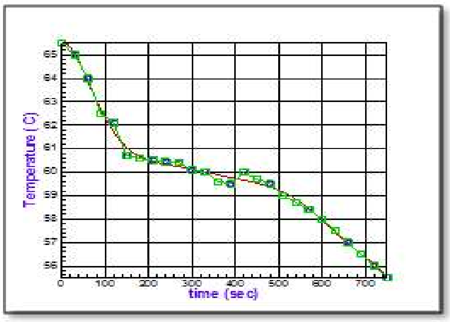
Figure(4), Evacuated Tubular collector with description notes

The absorber

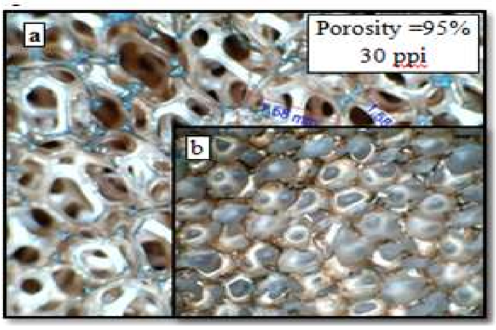
One TESB are used as SC collector in vertical chimney. The emissivity of the painted layer of plate is ε=0.095. And the absorptivity α_p=0.9, while the reflectivity ρ_{plate}=0.1.

Thermal energy storage material

A combined of paraffin wax, as a phase change material, and copper foam matrix are used as a TESM. Where the paraffin wax is used to storage heat, in sensible and latent Heat regions. Figure-5, experimental test show the behavior of full refined paraffin wax in solid, diffusion and liquid state through experimental work.



Figure(5), Experimental result for wax behavior in different Temperature



Figure(6), Copper foam matrix a-with PW, b-without PW

Copper foam matrix (CFM)

The combined of FM-PCM means higher thermal conductivity, with same latent heat of fusion, and same solidification and melting temperature. So, a copper foam matrix CFM is used to enhance the conductivity of the PCM. Figure-6 refers to the CFM with and without PCM.

The transparent cover

Nontraditional double transparent clear acrylic covers with 6 mm are used with SC. The special properties for these materials are; flexibility, light weight, anti-crash, beside other properties that in common with BK-7. All important properties for acrylic and BK-7 except thermal conductivity of BK-7 are calculated for three selective angles, Table-2.

Table(2) Physical properties for Acrylic and commercial window glass(Bk7)

	Angle (degree)	n				ƘL		K (w/m.°C)
Glass BK7	30	1.526	0.799	0.072	0.125	32*L at 4mm	0.92	0.81
	45		0.782	0.0875	0.133			
	60		0.729	0.14	0.141			
Clear Acrylic	30	1.491	0.885	0.0741	0.0414	0.04	0.94	0.7
	45		0.872	0.0868	0.0443			
	60		0.82	0.143	0.0477			
L: cover thickness in mater. n: Average refractive index in solar spectrum of cover materials. Ƙ: extinction coefficient						$\tau+\rho+\alpha=1$ τ= transmitivity, ρ=reflectivity α= absorbtivity, ϵ= emissivity		

The following measurement and instrument devices are used in this paper, beside two types of data logger, data acquisition (DAQ), to measuring the depended and independent variables, especially temperature in the SC gap and space of room Figure-3.

Temperature: Three types of temperature sensors are used in different positions. With 290 meter of type-K thermocouple (TC) are used to cover all the temperature that must be measured in the SC and test room beside the SC's gap. A 3D mesh grid with 36 TC's probe and 36 semiconductors type LM-35dz probe sensors are distributed inside the test room in three horizontal layers (3*4) nodes. The probes are connected to two types of Data Acquisition (DAQ) from labJack U6-PRO and UT-7, also two types of digital thermometers (DM6801A+) model and (DM6803A+) model are used. As well as, array of thermocouple probes are distributed and connected to the SC system, as shown in Figure-3, Figure-10.

Air Velocity: Two types of a thermal digital anemometer with high resolution are used to measure the air velocity in the chimney gap and room. Anemometer type AVM410 model and Testo- 405-V1 model, both of them with 0.01 m/s for resolution and threshold.

Solar radiation intensity: Two types of solar intensity meter are used in the experimental work. TES- 1333 model is fixed on the face SC. Other Type TES-132 with a data logger and interface connection to PC. This type is used to measure the solar intensity before and after the acrylic cover to calculate the transmitivity value. Beside recording solar intensity on surface of ETC. Other average solar intensity recorded by WS.

Weather station system: A modern weather station WS-1000-WiFi model, with 915 MHz in Frequency, outdoor and indoor instrument collection, transmitted the data every 16 second to the analyzer data logger data screen, with built in memory, and external data storage. Data logger records the data transmitted at interval time, that recognized by user to record data each 60 seconds for 24 hour. The following important data can be recorded by the WS-1000-WiFi :Indoor average temperature , Indoor relative humidity, Real and absolute pressure, Outdoor average temperature, Outdoor relative humidity, Solar radiation intensity (horizontally), Wind speed, Gust speed, Wind direction.

Experimental test procedure

The experimental work is achieved in selective day in February, 2015, where data are logging for the dependent variables along approximately 12 hours. All measurement and instruments tools are used as mentioned previously to measure and record the dependent

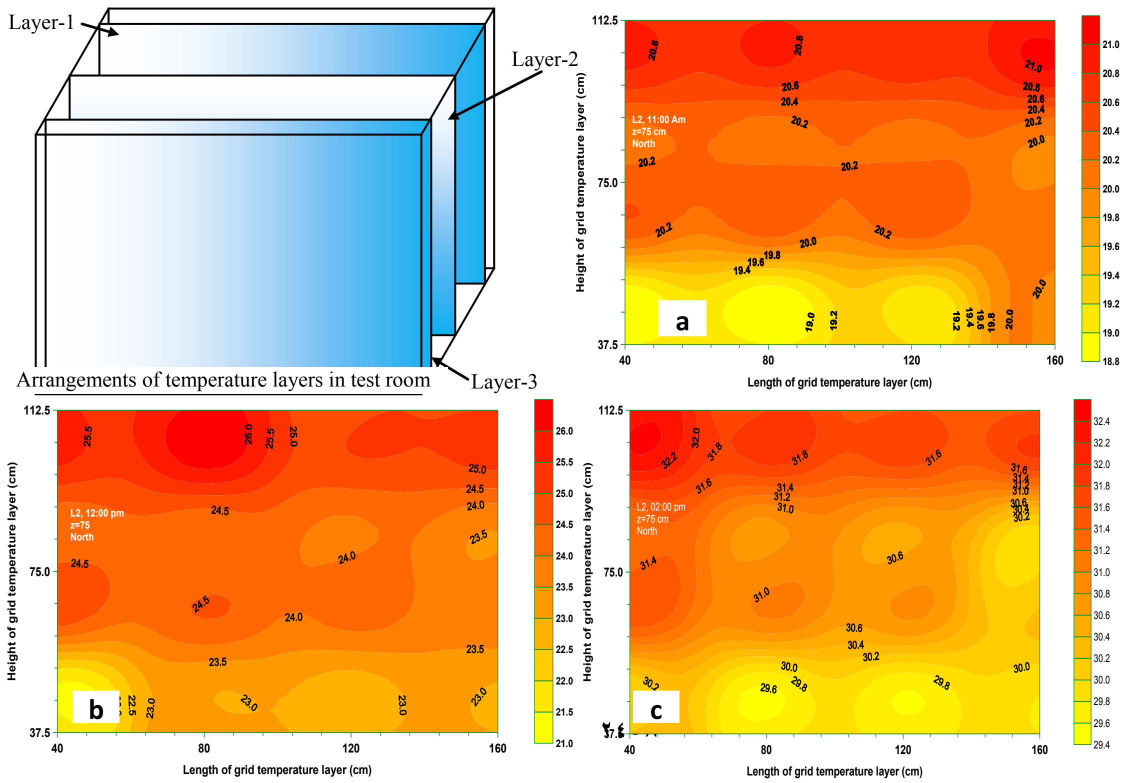
variable, for each 2 hours as test interval, and average value for general variables that measured and recorded by WS data logger along 24 hours, with 20 minutes as test interval time.
The measuring procedure including each of

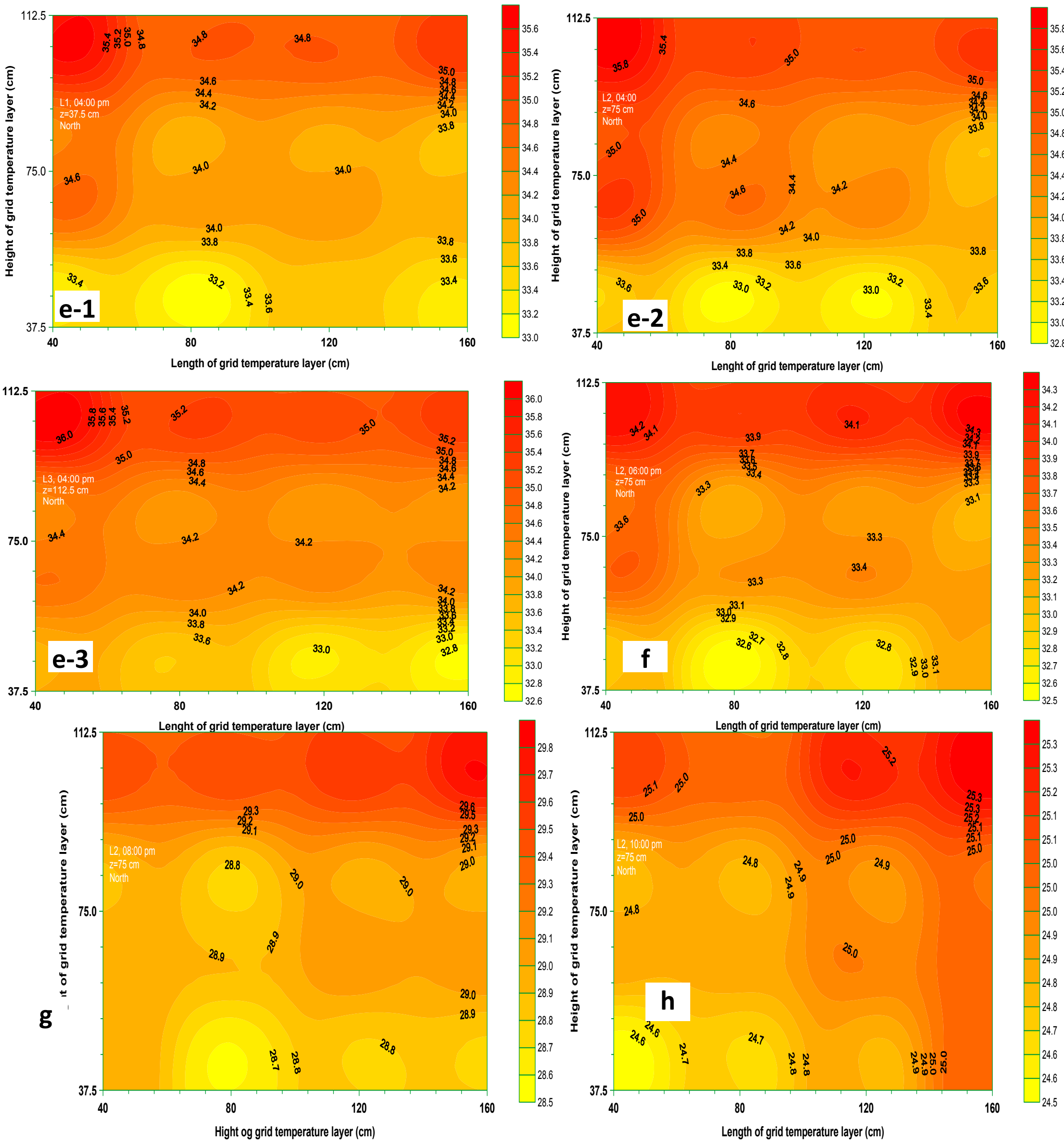
- measuring temperature in; chimneys gap, test room space, TESB, outdoor temperature,
- velocity in chimney gap beside inlet and outlet SC
- solar intensity.

While the general measuring procedure including each variables that measuring by WS.
Many conditions of weather are limited, to select test day such as; clarity (not dusty), acceptable wind speed without gust, the clouds absence or partial cloudy day.

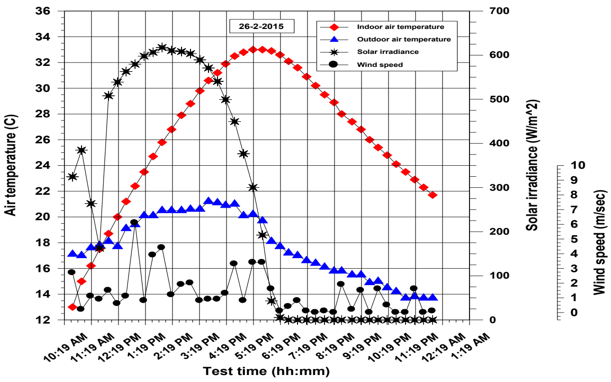
Result and Discussion

Experimental results in Figure-7(a-h), shows the heat effect with temperature distribution in the test room from 11:00am to 10:00 pm, briefly shows 2-dimentional results along test time and 3-D for result in 04:00pm as a sample, figure- (e1, e2 and e3). The effect of solar chimney appears in temperature distribution with a hot area in upper halve of test room, while the worm area in the bottom halve appearing with small difference in temperature between upper and lower, so heat transfer inside room almost in conduction. Figure-8 shows the results of average of temperature inside room, outside room and horizontal irradiance, wind speed and the average of difference in temperature between inside and outside. Results indicated to the maximum temperature difference between inside room and outside occurs after sun- set with 15^{o}C, while the heating effect still after sun-set by five hours with 8^{o}C higher than the environment. Figure-9 shows air temperature inlet and outlet from SC, indoor and outdoor air temperature hourly along test day, results appearing the big effect of SC between 11:00 am to 04:00 pm when the sun effect start to recede. Figure-10 present PCM-CFM temperature in bottom, mid and high of thermal storage collector, the difference in temperature between lower and upper sensors of TESB refer to the difference in air heat transfer coefficient along the height of the air-collector face . Figure-11 (a-f) shows air temperature and average velocity that covered chimney gap length, along test day, where maximum velocity ≈ 0.22 $^{m}/_{s}$ appear near the hot surface at 2:00pm, while the maximum temperature ≈ 44 ^{o}C at 04:00pm

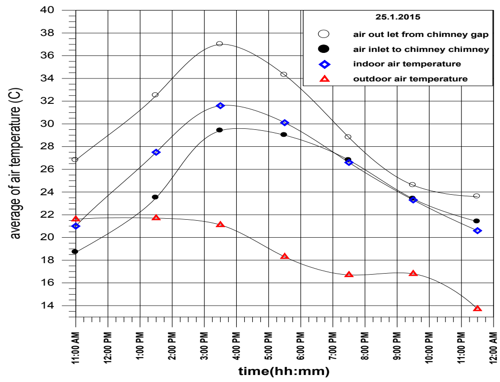




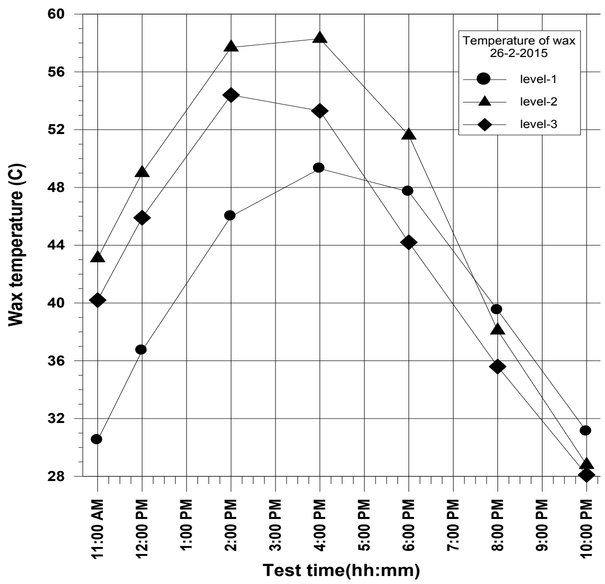
Figure(7)(a-h), 3Dimentional temperature distribution in vertical contour layers for interval test time along test day

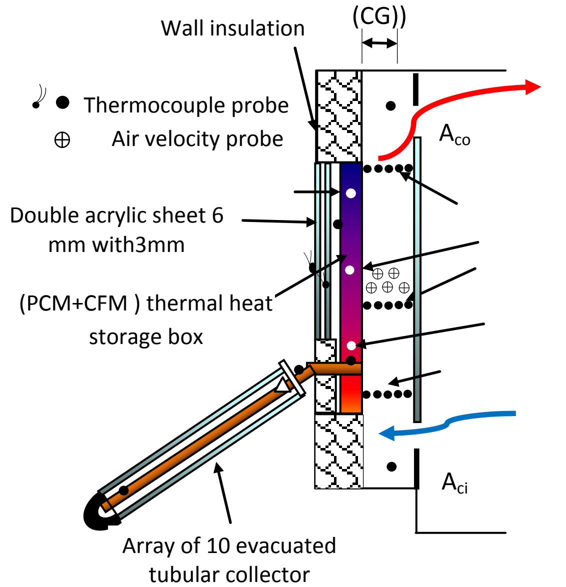


Figure(8), Indoor temperature with outdoor conditions hourly in test day



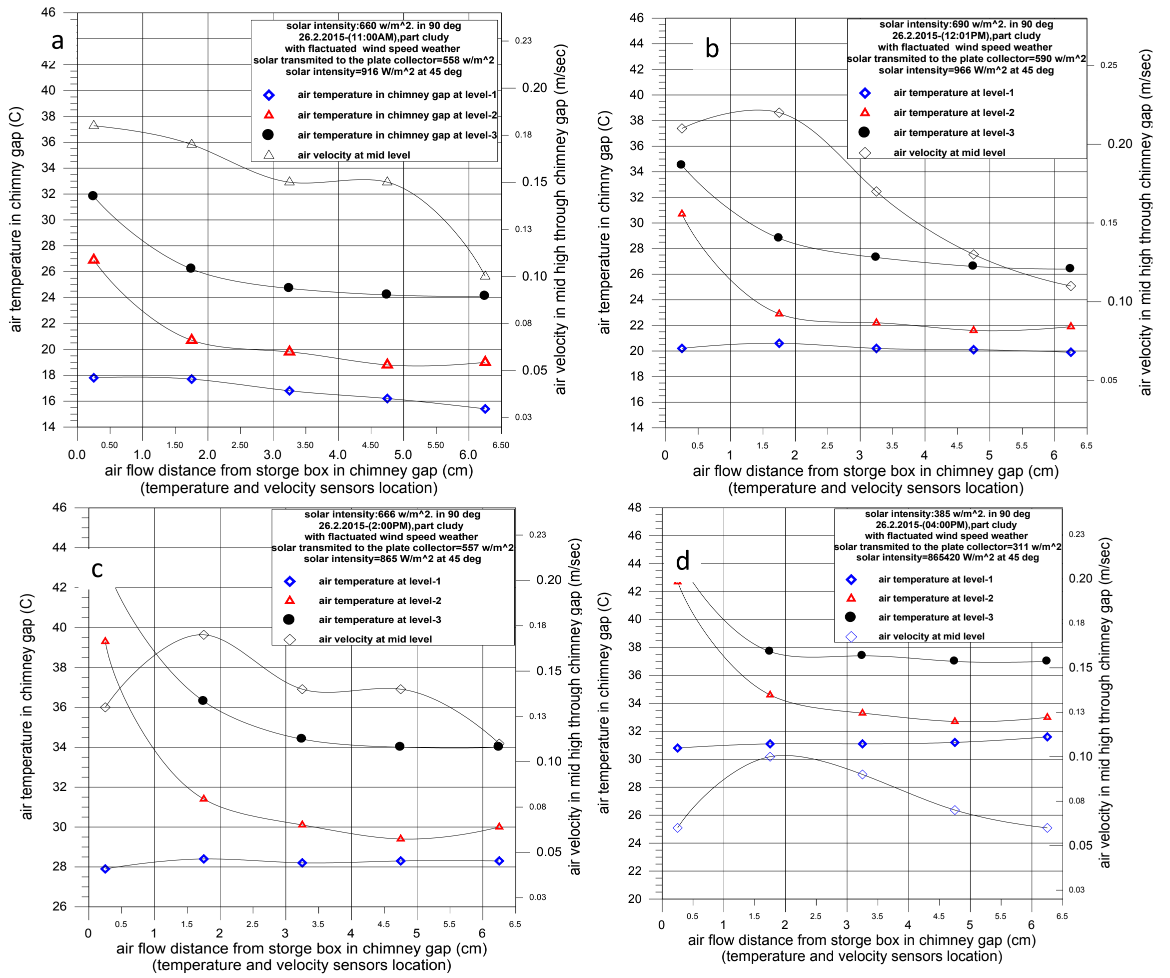
Figure(9), Air temperature inlet and outlet from SC gap simultaneously with indoor and outdoor air temperature

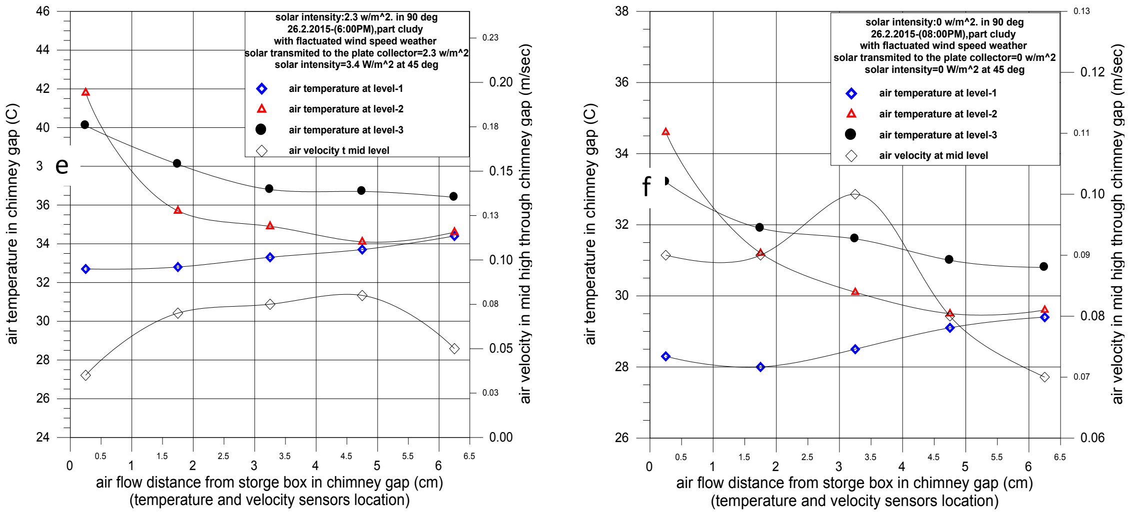




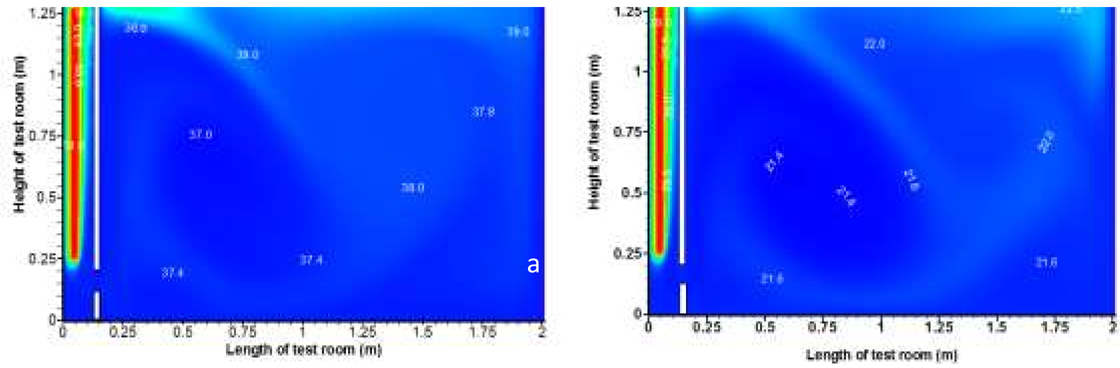
Section side- view of solar chimney

Figure(10), Paraffin wax temperature along the depth of solar chimney gap and in different level

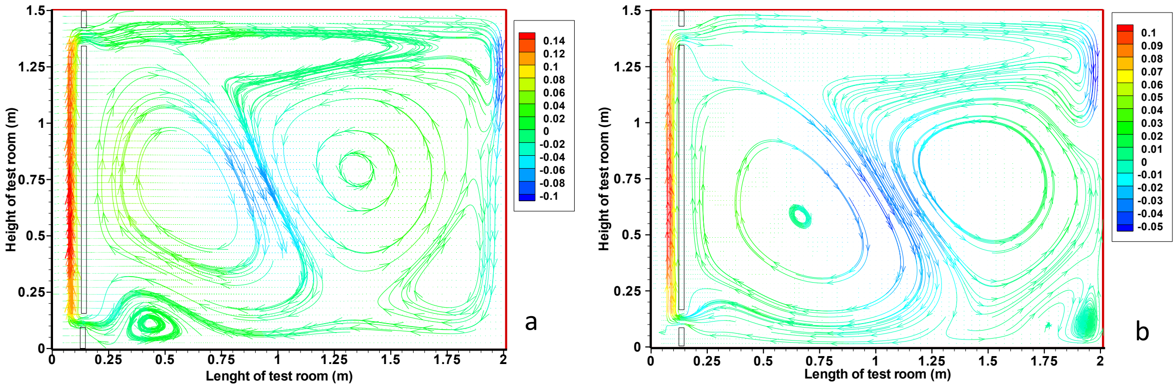




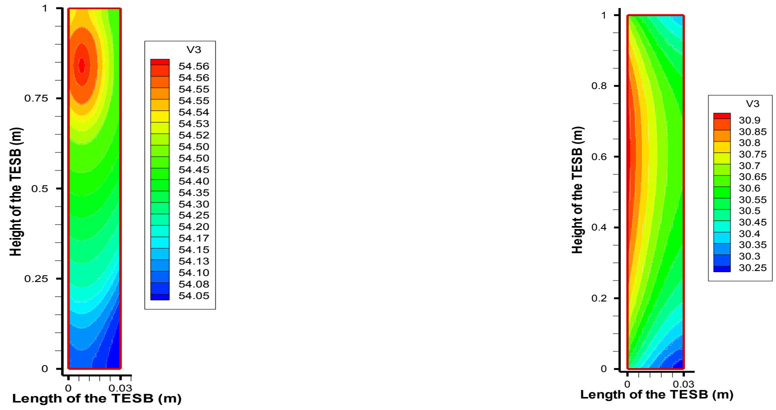
Figure(11) (a-f), Air temperature and average velocity inside chimney gap along test day



Figure(12), Air temperature distribution by simulation results at a-04:00pm, b-10:00 pm



Figure(13), Air velocity streamline by simulation results at a-04:00pm, b-10:00 pm



a b

Figure(14), TESB temperature distribution by simulation results at a-04:00pm, b-10:00 pm

Samples of numerical simulation results depict the behavior of air (for temperature and velocity) inside test room and inside chimney gap Figure-12, Figure-13. Also the temperature distribution of the TESB collector (PCM-CFM) will be exhibited too in Figure-14. The selective time of simulation samples took at a)-4:00 pm and b)-10:00pm respectively, as shown in the figures above. The results of comparison between numerical and experimental results for different functions are tabulated in table-3 as relative error.

Table(3), Relative error between experimental and numerical results.

time	Relative error for average temp. inside	Relative error for average velocity in	Relative error for average temp. in TESB collector (%)
04:00 pm	13.2	28	1.63
10:00 pm	12.5	30	3.9

Nomenclature	Meaning	Units	Abbreviation	Meaning
ar	Aspect ratio=$SC\quad t/ga$	Meter/ meter	ACH	Air change per houre
g	gravitational acceleration	m/s^2	CFD	Computational fluid dynamic
	Solar chimney width gap	meter	CFM	Copper foam matrix
	Level high in chimney gap or in collector box	meter	ETC	Evacuated tubular collector
T , t	Temperature, time	°C, sec	ETCTS	Evacuated tubular collectors with thermosyphon
u,v	Velocity in x, y axis	m/sec		
	Port height of inlet solar chimney	meter	PCM	Phase change material
	Port height of outlet solar chimney	meter	PW	Paraffin wax
Greek letters			PDE	Partial deferential equation
	dynamic viscosity	Kg/m.s	ppi	Porous per inch
	turbulent kinetic energy	m^2/s^2	SC	Solar chimney
	Density	Kg/m^3	TESB,M	Thermal energy storage-box, material

	Dissipation rate of kinetic energy	m^2/s^3	TSM	Thermal storage material

CONCLUSION

From the experimental and numerical results, a following conclusion can be done:

1- Employing the sun irradiance for heating effect by using the phase change material and foam matrix as a thermal energy storage material, made more successfully comfortable zone, and not for heating the zone but for make a good control to room temperature.

2- The heating effect still for long time after sun-set, where heat storage as a latent heat of fusion with small different in temperature. And that mean this design of solar chimney effective not in day time but in night time also.

3- Numerical simulation results appear acceptable accuracy in velocity and temperature profile comparing with the experimental results, and that lead to expanded to use the simulation program before run out the design.

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