A study of Free Convection in A solar Chimney Model

Dr. Sabah Tarik Ahmed* &Miqdam Tariq Chaichan*

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Abstract

A solar chimney is a hot air channel attached to a circular translucent roof opens at the periphery. The roof and the ground below it form an air collector. It enhances natural ventilation by employing air temperature difference between channal inlet and outlet. An experimental work was carried out for a designed and fabricated prototype solar chimney, in Baghdad-Iraq's autumn weather 2009. The chimney's tower hight was 4 m and the solar collector diameter was 6 m. A maximum air temperature differance attained was 22ºC at mid day through the solar chimney.

The study shows that Iraqi weathers are suitable for this system. Maximum heat transfer coeffecient (*h*) was 31.83 W/m^2K, maximum air volume flow rate achieved was 0.065 m^3/s, and maximum air velocity at the chimney outlet acquired was 2.309 m/s. Empirical equation that relates Nusselt and Rayleigh numbers was obtained.

Keywords: Solar chimney, free convection, solar collector, Nusselt number, Rayleigh number, Renold number

دراسة للحمل الحر في نموذج لمدخنة شمسية

الخلاصة

المدخنة الشمسية هي قناة هواء ساخن مربوطة إلى سطح دائري شفاف مفتوح من المحيط، هذا السطح مع الأرضية التي أسفله يشكلان المجمع الشمسي، وهو يعزز التهوية الطبيعية بتوظيف فرق درجات الحرارة للهواء عند مدخل ومخرج المدخنة. تمت التجارب على نموذج لمدخنة شمسية مصممه ومصنعه في اجواء بغداد- العراق خريف عام 2009. وكان ارتفاع المدخنة 4 م وقطر الجامع الشمسي 6 م. و تم التوصل لأكبر فرق في درجات الحرارة بحدود 22ºC عند منتصف اليوم عبر المدخنة الشمسية.

تبين الدراسة أن أجواء العراق مناسبة لهذا النوع من الأنظمة، إذ تم التوصل لأقصى معامل انتقال حرارة بالحمل (*h*) 31.83 W/m^2K، وأعظم معدل لتدفق هواء كان 0.065 m^3/s. أما أقصى سرعة هواء تم قياسها فكانت 2.309 m/s. وتم استنباط معادلة تجريبية تربط رقمي نسلت ورايلي.

Introduction

The solar tower's consist of three essential elements – solar air collector, chemney and wind turbines – have been familiar for centuries. Their combination to generate

* Machines & Equipment Engineering Department, University of Technology/Baghdad

electrcity has already been described in 1931 by Gunther [1, 2].

The principle can be described as in fig. (1): Air is heated by solar radiation under a low circular translucent roof opens at the periphery, the roof and the natural ground below it form an air collector. In the middle of the roof there is a vertical tower with large air inlets at its base. The joint between the roof and the tower base is airtight. As hot air is lighter than cold air it rises up the tower. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter. Thus solar radiation causes a constant updraft in the tower. The energy content in the updraft is converted into mechanical energy by pressure-staged turbines at the base of the tower, and into electrical energy by coventional generators [3, 4].

Hot air in the solar tower is produced by the greenhouse effect in a simple air collector consisting of a glass or plastic film glazing striched horizantally above the ground. The height of the glazing increases adjacent to the tower base, so that the air diverted to vertical movement with minimum friction loss. This glazing admits the solar radiation component and retains long wave re-radiation from the heated ground. Thus the ground under the roof heats up and transfers its heat to the air flowing radially above it from the outside to the tower [5].

According to the passive convection application by using a solar chimney system, determination of heat transfer coefficient *(h)* between the hot ground and the hot air in the channel, and Nusselt number (*Nu*) are important in the investigation of free convection, mathematical simulation and application of the system. The determination of the correlation between Nusselt (*Nu*) and Rayleigh (*Ra*) numbers in the vertical channel has been carried out in many research works [6]. The scaling analysis of the fluid with Prandtl number (*Pr*), $Pr<<1$ showed that *Nu* is scaled by $(Ra\ Pr)^{0.25}$ [7, 8].

However, the free convection in the open ended channel such as the application of solar chimney in the outdoor field has been rarely investigated. Frequently, the correlations derived from the laboratory research are used as the estimation of heat transfer coefficient [9, 10].

The tower (chimney) converts the heat flow produced by the collector into kinetic energy (convection current) and potential energy (pressure drop at the turbine). Thus the density difference of the air caused by the temperature rises in the collector works as a driving force [11, 12].

The tower itself is a plant's actual thermal engine. It is a pressure tube with low friction loss (like a hydro power station pressure tube or pen stock) because of its favorable servace-volume ratio. The updraft of the air heated in the collector is approximately proportional to the air temperature rise in the collector and to the volume, (i.e. the hieght and the diameter) or the tower [13]. In a large solar tower the collector rises the temperature of air about 30 to 35ºC. This produces about 15 m/s an updraft velocity in the tower at full load. It is thus possible to enter into an operatig solar tower plant for maintenance without danger from high air velocities [14, 15].

The objective of this paper is to determine the correlation of *Nu* number for a solar chimney in the outdoor field, where the temperature differences and *Ra* number values are different from the previous studies. By conducting the experiments on one solar chimney located outdoor, the new correlation between the *Nu number (Nu)* and the *Ra number (Ra)* is proposed. Also, this study shows the effect of variation of ambient temperatures on the range of *Ra* values. Taking into account those ambient conditions and the result of particular range of *Ra* values, the correlation between the *Nu* and *Ra* numbers are revised. Therefore, the present study is based on experimental investigation designed to develop an understanding of the airflow due to heat transfer by natural convection in a vertical channel for Iraqi weathers.

Expermintal setup

The solar tower's prototype was build as followed: Air is heated by solar radiation under a low circular transparent roof (6 meters diameter) opened at the periphery (2 cm high from ground); the roof and the ground below it form a solar air collector. In the middle of the roof there was a vertical tower (4 meters tall and 20cm diameter) with large air inlets at its base (10 cm hight from the ground). The joint between the roof and the tower base is airtight. As hot air is lighter than cold air it rises up the tower. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter. Continuous 24 hours - operation can be achieved by placing a thermal collector ground. For this purpose selective black colored concrete ground (to absorb more heat at daylight) was used.

The temperature of air under the transparent cover was measured by (6) six calibrated type K thermocouples distributed uniformly along the vertical chimney. Also, the rising air temperature through the chimney was measured by means of calibrated thermocouples. These thermocouples were fixed in scattered manners, to give acurate analysis for flowing air through the chimney. The last one introduced at the top of the chimny named (T_o) which represents leaving air temperature. The first thermocouple in the group represents collected air temperature (T_h). The temperature of the air entering the chimney (T_a) was measured by thermometer fixed away from the chimney. The black floor temperature (T_f) was measured also. Temperatures were perused by calibrated digital electronic thermometer, through a selector swich. Fig. (2) represents prototype dimensions and thermocouple distribution, while fig. (3) shows a photographic picture for tested prototype solar chimney.

The experiments were conducted in Iraqi autumn days, started at the first of August and finished at the end of November 2009. The tests were conducted in Saydia city west of Baghdad.

Mathematical calculations

The calculation used in this study employed Chungloo & Limmeechokchaib (2009) procedure. The *Nu* number is evaluated by:

$$Nu = h\,D/k \qquad (1)$$

Where:

$h=Q/ A_{eff} (T_h-T_a)$ (2)

$Q=m^{\circ} C_p (T_o-T_a)$ (3)

Where

$m^{\circ} = \rho. A_{chimney}. V$

The *Nu number* results will be correlated by the dimensionless group *Ra* number, theoretically evaluated by:

$Ra=[g. \beta.(T_h-T_a).L_c^3/\nu^2]. Pr$ (4)

Temperature of air at the inlet (T_a) was measured from chimneys outside. Temperature of air at the outlet T_o and temperature of T_h were measured experimentally. The mass flow rate of air in the solar chimney can be estimated by

$$V = C_D.r.\sqrt{g.L.\frac{(T_o - T_a)}{T_a}} \quad (5)$$

Where the value of the coefficient of discharge (C_D) was taken 0.4 in this study [8]. The Reynolds number is calculated from

$Re = (V D/\nu)$ (6)

The air volume flow rate (*VFR*) in the solar chimney can be estimated by

$VFR=C_D A_{cheminy} [g L (T_o - T_a)/T_a]^{½}$ (7)

Nu number is the non-dimensional expression of heat transfer coefficient, h, as $Nu = h D/k$. The relations between Nusselt number and Rayleigh number, is typically in the form

$Nu=C [Ra]^n$ (8)

Under the conditions of an Iraqi autumn climate, free convection was studied in a hot air channel of solar chimney. The investigation included collecting data of basement surface and air temperatures in the channel, analysing experimental data and determining the relation between the three nondimensional quantities *Nu*, *Ra*, and *Re* numbers. The effect of the ambient temperature on the temperature T_h and T_o were investigated. The calculated values of ($T_o - T_a$), *Q/A* and *VFR* using the equations and the calculated values of velocity (*V*) and convective coefficient (*h*), *Nu*, *Re*, and *Ra* numbers using the mentioned equations are summarized in Table 1.

This study was conducted in Baghdad city for the period from mid Septemper to mid November 2009. The reading temperatures were recorded once a week. All the readings were avaraged from data.

Results and discussions

Fig. (4) shows the avarage solar intensity taken from Iraqi Meteorology Organization for 24 hours of the tested period. The figure shows the effect of solar intensity on T_a, T_h and T_o for the whole 24 hours. The observation of prototype solar chimney showed that the temperatures T_a, T_h and T_o were behaving in the same manner as solar intensity with a time delay period about 1.5 hour in the daylight time. After sunset the studied temperatures reduced rapidly. It is clear that temperatures reduction rate at sunset is more than increment rate at daylight. Ambient temperature drop at night together with solar radiation degeneration, make the system depends on heat collected by the black floor collecter. This heat is limited due to prototype small diminsions. Low temperatures at daybreak may create unwanted negative ventilation and limiting air movements. To prevent this condition the collector diminsions and material must be considered as Chungloo (2009) illustrated in his article.

The high differance between T_a and T_h temperatures means higher heat collection of the blockaded air under solar collector. T_h was higher than T_o indicating some thermal losses from chimney walls.

The figure results illustrated that solar chimney if designed properly can maintain chimney air temperatures consistently above the outdoor temperature which would enhance the desired buoyancy-induced air flow through the chimney. The desired performance may be achieved with the solar "greenhouse" effect. Better performance could be obtained with a better solar radiation absorbing surface within the chimney.

Fig. (5) represents the variation of T_f, and T_h through 24 hours of daytime of the studied period. In the first morning both temperatures were adjacent then they separated. Both temperatures grow in high rate compared to T_a (as indicated in fig. 4). T_f increases due to floor material specific heat in addition to its black color which increases its absorption. T_h grows in higher rate compared to T_f by the action of transparency collector. The temperatures behave the same as solar intensity with a time delay about 1.5 hour for T_h, and 2 hours for T_f. T_h precedes T_f in avarage about 2 to 3°C until it reaches its maximum value then it starts to fall down. T_f maximum value which is higher than maximum T_h takes place after that.

High T_f indicates high solar energy storage. After sunset air temperatures reduced quickly while T_f reduced at a lower rate. The warm ground floor worked as a heating source for accumulated air in the collector. At daybreak unwanted negative ventilation occured which restricted air movements as illustrated earlier.

The relationships between day time and calculated heat transfer rate Q/A is shown in fig. (6). The solar radiation is the heat source of the solar chimney. Data analysis of Q/A was carried out as a function of T_a and T_h, because Q/A, T_h and T_o vary with ambient conditions. The curve indicates increasing rate with increasung collecting heat. In spite of thermal privation through chimney wall, the air velocity increased. Thermal gain in collector overcame thermal losses correlated with improvement in air natural convection. The influnce of solar radiation intinsity in Baghdad region appears clear by these observations.

Fig. (7) represents the influnce of day time on air volume flow rate VFR. Although the collecter heat loss increased as indicated by increasing T_h-T_o, the air volume flow rate increased also. Thermal gain increase with time progress, added to collecter black floor temperature increase. Hence, the volume flow rate of air increased starting from 7 AM to reach its maximum value at 2 PM. The volume flow rate of the buoyancy driven system depends on the T_o

and T_a temperature differences. The complicated interaction of solar intensity and ambient conditions and capability to induce air flow rate in a solar chimney are found to be more related to the heat source of the solar chimney than to the ambient conditions as Sakonidou (2008) mentioned.

Fig. (8) demonstrates the day time variation effect on air velocity through the chimney. The curve indicates increasing rate with collecting heat increase. In spite of thermal prevation through chimney wall, the air velocity increased. Thermal gain in collector overcame thermal losses correlated with improvement in air natural convection. The influnce of solar radiation intinsity in Baghdad region appears clear by these observations. Depending on these velocities *Re* was calculated for each velocity, as included in table 1. *Re* values indicates laminar flow through chimny.

The values of *Nu*, *Re* and *Ra* numbers shown in table 1 are computed for the range of temperature difference to display the airflow from the collector to the solar chimney. *Nu* number is the non-dimensional expression of heat transfer coefficient, *h*, as $Nu = h D/k$. The relations between Nusselt and Rayleigh numbers based on there values listed in table 1 was studied. The constants *C* and *n* are obtained by means of least square analysis of the logarithms of equation (9) as follows:

$$Nu=1.822[Ra]^{0.644} \qquad (10)$$

For calculation shown in table 1, the range of *Ra No.* is $18.2\times10^7 \le Ra \le 123.87\times10^7$, and the range of $(T_h - T_o)$ is $1\ ℃ \le (T_h - T_o) \le 2.31\ ℃$. The computational results for *Nu*, *Re* and *Ra* numbers are shown as solid lines in fig. (9) and fig. (10), respectively.

The relation between *Nu* and *Ra* numbers, and relation between *Re* and *Ra* numbers were derived and calculated for each day light hour. By using the relation between the nondimensional quantities, this study found the values of convective heat transfer coefficient of *15 to 33.9* W/m^2K and the calculated values of air flow rate of *118.8 to 234* $m^3/hour$ for $1℃ \le (T_h\text{-}T_o) \le 2.31℃$. Comparing to the value of heat transfer coefficient of *6.76 to 10.26* W/m^2K and ventilating airflow of *81.12 to 219.62* m^3/hour found in (Khedari, 2002) for $8.71\ ℃ \le (T_h - T_o) \le 37.42\ ℃$. In spite of the fact that practical results came from small dimensions prototype, this study shows higher values of heat transfer coefficient in Iraqi weathers. According to Bunnag et al (2004) the results of high ventilating airflow, as in this study, is related to the high value of heat transfer coefficient and the decrease of temperature difference $(T_h - T_o)$.

Comparison with Previous Correlations

The comparison of *Ra* values in table 2 shows that the range of *Ra* values in this study is higher than that found in the other studies. Since the *Ra* value is the function of $T_h\text{-}T_a$, this means higher temperature occurs in this study than that occurs in the previous studies. The present study provides higher values of *Nu numbers* when comparing with *Nu numbers* of

Azevedo & Sparrow (1985) and Gebhart (1971). While *Nu* of Chungloo (2009) and Khedari et al. (2002) provide higher values of this study *Nu*, both conditions relatively similar to Iraqi weathers but they were conducted in summer whereas this study was conducted in autumn.

It is also shown in the table (2) the significant impact of *Ra* value on the *Nu* value in each correlation. Since each of the correlations exists in the specific range of temperature, there is no direct comparison among these correlations. The proposed correlation here, therefore, increases the value of heat transfer coefficient (*h*) of the free convection heat transfer in the extended range of *Ra* value.

Conclusions

A fabricated passive solar cheminy based on the black concreate floor was tested on autumn days in Baghdad-Iraq - 2009. The air handling capacity of solar chimneys was predicted by computation and verified by measurements. Theoretical calculations were carried out to analyze the mechanism of natural convection inside the prototype solar chimneys constructed for this purpose. The conclusions are obtained as follows:

- The results obtained from the experimental solar chimney have illustrated that solar chimneys if designed properly can maintain chimney air temperatures consistently above the outdoor temperature which would enhance the desired buoyancy-induced air flow through the chimney.
- The desired performance was achieved with the solar "greenhouse" chimney studied.
- Better performance can be obtained by using better solar radiation absorbing surface within the chimney.
- Low temperatures at daybreak may create unwanted negative ventilation and limiting air movements.
- Optimum design parameters (height, width, length and material) of a vertical solar chimney can be deduced by comparing simulation results and results based on previous researchs.
- Mass flow rate is a strong function of heat input and the channel depth. Whereas, heat transfer coefficient is only function of the value of heat input and dependent of (T_h-T_a).
- The study proved that *Nu* and *Ra* numbers empirical relation is $Nu = 1.822[Ra]^{0.644}$.
- This kind of solar systems is suitable for Iraqi weathers. It will be able to generate adequate air flow rate cabable to sustain wind turbine works. Solar chimney with real diminsions can be used to generate electricity for long range of the day hours.

Referances

[1] Bunnag T, Khedari J, Hirunlabh J and Zeghmati B. “A field study of free convection in an inclined-roof solar chimney”, Science Asia, vol. 35, pp: 189–195, 2004.

[2] Najim R A. “Numerical Prediction of a Solar Chimney Performance Using CFD Technique”, Ph D thesis, Electromechanical Engineering

Department, University of Technology, Baghdad, Iraq, 2007.

[3] Schlaich J and Schiel W. "Solar chimneys", Encyclopedia of phesical science and technology, 3rd Edition, Acadimic press, England, 2001.

[4] Shyia A K. "Parametric study of solar chimney performance", M.Sc. thesis, University of AL-Mustansiriya, 2002.

[5] Afonso C and Oliveira A. "Solar Chimneys: simulation and experiment", Energy and Buildings, vol. 32, pp: 71-79, 2000.

[6] Ostrach S. "An analysis of laminar free convection flow and heat transfer about a flat plate parallel to the direction of the generating body force", Report 1111, National Advisory Committee for Aeronautics, 1953.

[7] Sakonidou E P, Karapantsios T D, Balouktsis A I and Chassapis D. "Modeling of the optimum tilt of a solar chimney for maximum air flow", Solar Energy, vol. 82, pp: 80–94, 2008.

[8] Chungloo S, Limmeechokchai B. "Application of passive cooling systems in the hot and humid climate: The case study of solar chimney and wetted roof in Thailand". Build Environ, vol. 42, pp: 3341–51, 2007.

[9] Kazansky S, Dubovsky V, Ziskind G and Letan R. "Chimney enhanced natural convection from a vertical plate: experiments and numerical calculations". International Journal of Heat and Mass Transfer, vol. 46, pp: 497–512, 2003.

[10] Susanti L, Homma H, Matsumoto H, Suzuki Y, Simizu M. "A laboratory experiment on natural ventilation through a roof cavity for reduction of solar heat gain". Energy Build, vol. 40, pp: 2196–206, 2008.

[11] Clito A. Solar Chimneys: Simulation and Experiment, Energy and Buildings, vol. 32, Pergamon Press., pp. 71–79, 2000.

[12] Ong K S, Chow C C. "Performance of a solar chimney", Solar Energy, vol. 74, pp:1–17, 2003.

[13] Khedari J, Yimsamerjit P and Hirunlabh J. "Experimental investigation of free convection in roof solar collector". Build Environ, vol. 37, pp: 455–459, 2002.

[14] Chungloo S. "The Field Investigation of Dimensionless Convection Heat Transfer coefficient in the Inclined Roof Solar Chimney", Journal of Architectural/Planning Research and Studies, vol. 6, Issue 1, 2009.

[15] Ding W, Hasemi Y, Yamada T. "Natural ventilation performance of a double-skin facade with a solar chimney". Energy and Buildings, vol. 37, pp: 411–418, 2005.

[16] Bergermann R, Schiel W and Weinrebe G. "Design of commercial solar tower systems-utilization of solar induced convective flows for power generation", Proceedings of ISEC 2003, International Solar Energy Conference Hawaii, 15-18 March, 2003.

[17] Chungloo S, Limmeechokchaib B. "Experimental investigation of free convection in an Open-ended inclined rectangular channel heated from the top". Int J Ambient Energ, vol. 25, pp: 151–62, 2009.

[18] Azevedo L F A & Sparrow E M. "Natural convection in open-

ended inclined channels", Journal of Heat Transfer, vol. 107, pp: 893-901, 1985.
[19] Gebhart B. "Heat transfer", 2nd ed., New York: McGraw-Hill, 1971.

Table (1) Expermintal data and calculated variables.

Time (hr)	7AM	8	9	10	11	12	1PM	2	3	4	5
Avarage solar radiation intensity (W/m^2)	17.5	125	250	400	500	520	540	480	400	220	85
T_o-T_a (℃)	3	4	6	13	15	19	21	22	18.7	13	11
Q/A *(W/m^2)*	26.08	38.69	70.6	161.72	208.66	278.66	310.85	325.64	271.6	160.6	135.6
VER *(m^3/s)*	0.033	0.037	0.043	0.055	0.055	0.061	0.0625	0.064	0.0605	0.053	0.05
V *(m/s)*	1.2773	1.428	1.743	1.915	2.057	2.264	2.298	2.309	2.244	1.899	1.87
h *($W/m^2.K$)*	26.08	20.525	23.533	26.95	29.8	30.96	31.83	29.6	30.96	29.86	23.9
Nu	397.56	312.89	358.73	410.82	454.26	471.95	485.21	451.21	467.57	404.21	426.219
Re (10^3)	0.033	0.03	0.044	0.049	0.052	0.058	0.059	0.059	0.0576	0.0487	0.048
Pr	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Ra (10^6)	18.2	24.3	36.05	75.88	86.226	108.17	119.144	123.87	105.31	74.3	61.87

Table (2) The calculated Nusselt and Rayleigh numbers for other researchers.

Reasercher	*Nu* number	*Ra* number	Empirical equation
Khedari et al., 2002	366.4-549	$(2\text{-}8)\times10^6$	$1.227[Ra]^{0.2916}$
Gebhart, 1971	23.8-81.2	1.5×10^5	$0.071[Ra]^{0.333}$
Azevedo & Sparrow, 1985	53.8-108.8	$6\times10^4\text{-}1\times10^6$	$0.645[Ra]^{0.25}$
Chungloo , 2009	475-610.5	$(1.5\text{-}4.2)\times10^7$	$1.44[Ra]^{0.249}$
This study	397.5-485.2	$(1.8\text{-}12.3)\times10^7$	$1.822[Ra]^{0.644}$

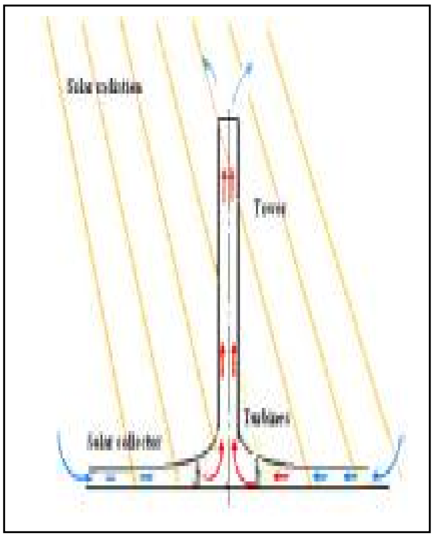

Figure (1) Solar Tower Principle [16]

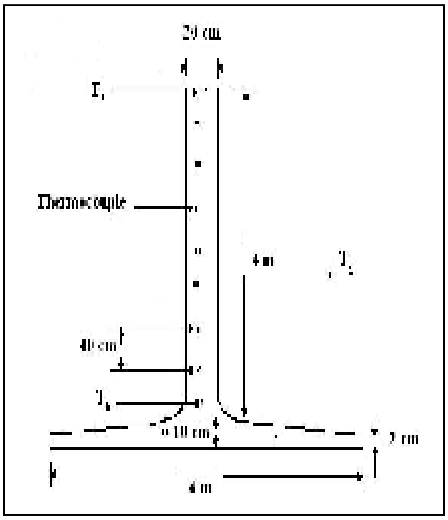

Figure (2) Schematic diagram of the solar chimney and thermocouples distribution

Figure (3) Photo for the solar chimney prototype

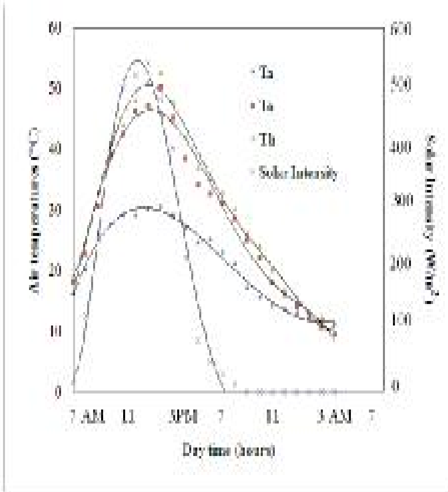

Figure (4) Variation of temperatures and solar intensity through 24 hours of day time

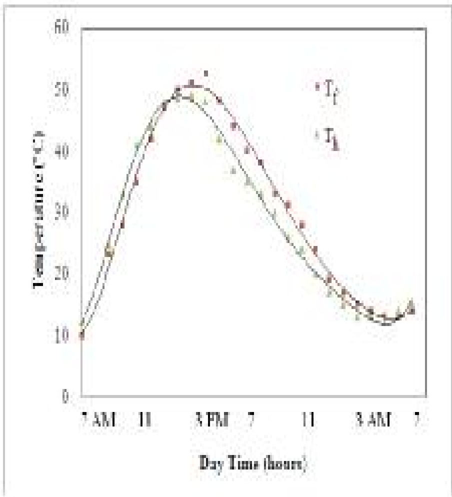

Figure (5) Variation of T_f &T_h temperatures through 24 hours of day time

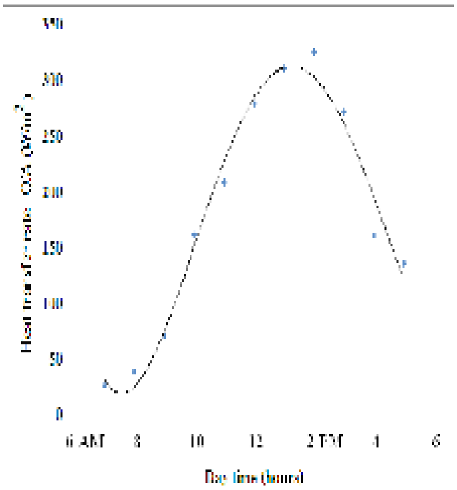

Figure (6) Variation of heat transfer rate through day time

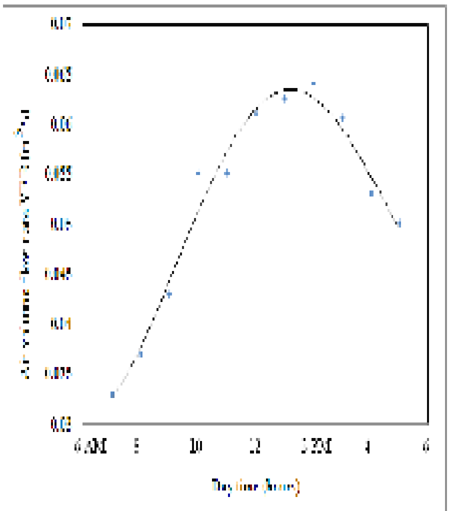

Figure (7) Variation of air volume flow rate through day time

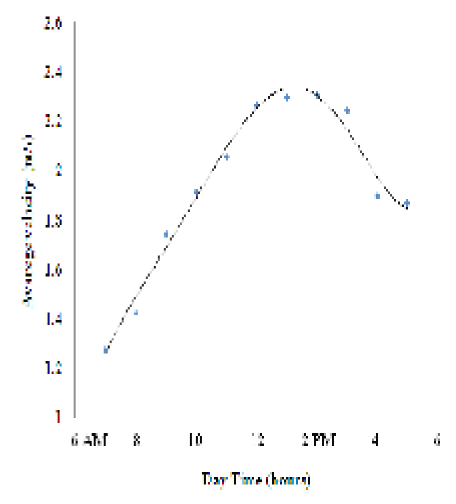

Figure (8) Variation of air avarage velocity through day time

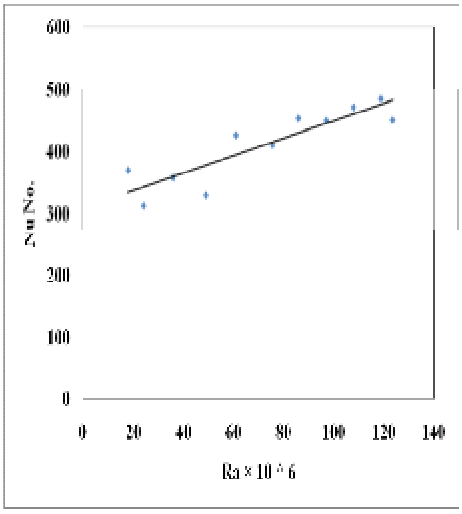

Figure (9) Variation of Nussult number with Rayleigh number

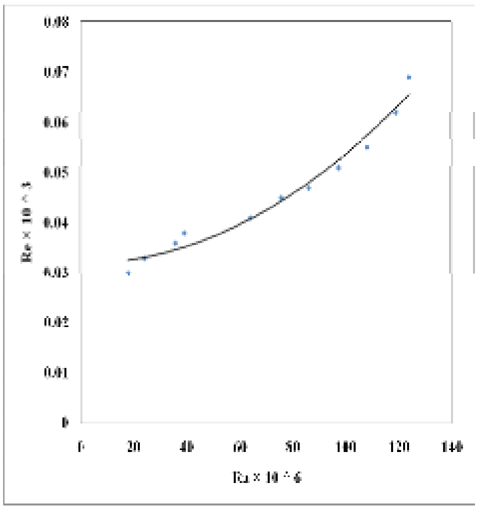

Figure (10) Variation of Reynolds number with Rayleigh number