UTILIZATION OF SAS LANGUAGE FOR MODELING THE ROCK BED PERFORMANCE

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ABSTRACT

Heated air by solar collector has high variation in temperature because it is depend on time. Therefore, a rock-bed was used to regulate the air temperature and to damp out the large fluctuation of air temperature, although it causes a change in the phase and the amplitude temperature of the inlet air. The rock-bed could be used then to store day-heat for night use.

The purpose of this paper was to mathematically model the rock-bed performance using SAS language. This modeling utilizes; (1) rock-bed characteristics, (2) Fourier series, and (3) statistical procedures for predicting the outlet air temperature. A computer program was developed to achieve this purpose. An air flow of 4.66 m^3/min was used to test the computer model and air temperatures at 0, 0.375, and 0.70 m of the rock bed height were recorded by time for 24 h.

It was found that Fourier series was more efficient for predicting the air temperature at any vertical location of the rock-bed. The correlation coefficient using the rock-bed characteristics and Fourier series was 0.905 for predicting the outlet air temperature. The determination coefficients were found to be above 0.98 between observed and predicted air temperatures at any vertical location of the rock-bed.

INTRODUCTION

A renewable energy-based on air heating system that does not require a conventional auxiliary heater, can still meet a daily load fraction exceeding 90% and supply hot air at a steady temperature and flow rate continuously for 24 hours a day (**Augustus and Kumar, 2007**).

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The utilization of air-rock or gravel packed beds is very important for heating or cooling a fluid by passing an air flow through it. Rocks are the materials, which are loosely packed in a store, take or give up heat from the air and have high energy storage capacity (**Paksoy et al., 1995 and Chandra and Willits, 1981**). The rock bed stores the thermal energy during the daytime and supplies heat during off-sunshine hours during day and night (**Augustus and Kumar, 2007**). Rock-bed is also considered to have the required characteristics such as higher thermal conductivity than those of water and phase change materials, rapid heat transfer, low cost and long life (**Chandra et al., 1981 and Garzoli, 1989**). The rock-beds are, in different meaning, used to damp out the large fluctuations of air temperature occurred when air is heated by a solar air collector or to alter the phase relationship between the input and output temperature (**Smith et al., 1984**). The rock-bed system kept the inside air temperature higher than that of outside air at night, even in an overcast day following a clear day (**Ahmet Kürklü, 2002**).

As the solar energy is intermittent, it needs to be stored in clear days to use the energy stored for heating at night (**Bouhdjar et al., 1996 and Walton, et al., 1979**).

Besides water and soil itself as the solar energy storage medium, 20–150 mm rocks are usually utilized to serve the same purpose (**Santamouris, et al., 1994 and Bredenbeck, 1984**).

Various researches showed that the rock-bed system could achieve an inside air temperature 4–20 °C higher than the outside air, in combination with a variety of energy conservation methods (**Bouhdjar et al., 1990**), and such systems could supply 20–70% of the annual heat requirement (**Bredenbeck, 1987**). Solar energy storage efficiencies of rock-bed systems varied from 8% to 19% (**Bouhdjar et al., 1996 and Willits and Peet, 1987**).

The response of the rock-beds to a periodic temperature variation has been studied by many researchers. An analytical solution to the output temperature of a packed bed exposed to a step input temperature was generally attributed to **Schumann, (1929)**. **Lattman and Sliva, (1970)** modified Schumann's model to be applicable in the region of small Reynolds numbers. **Hughes et al., (1976)** developed a thermal model to simulate solar heating systems where air is the transfer fluid through a packed gravel bed energy storage system. **Riaz, (1977)** presented a simple one-dimensional single phase conductivity model for transient analysis of a packed bed which accounts for the fluid convection motion, the air- rock heat transfer, axial bed conduction, and internal particle conduction in which air and rock are at the same temperature. **Eshleman et al., (1977)** developed a numerical model of heat transfer in rock beds. **Fujii, (1977)** performed a theoretical analysis concerning the behavior of heat storage capacity in pebbles and spheres exposed to a fluid with a periodic temperature variation.

A mathematical model was also developed to predict the discharge air temperature variation with time when rock bed storage was exposed to steady periodic air flow with sinusoidal temperature (**Abdel-Ghaffar, 1980 and 1996**). The model was derived from the fundamentals of heat and mass phenomena. A partial differential equation for the air temperature at any position at any time in the rock bed was developed as:

$$C\frac{\partial T_f}{\partial X} + D\frac{\partial^2 T_f}{\partial X\,\partial t} + E\frac{\partial T_f}{\partial t} = 0 \qquad (1)$$

Where; $C = q\,\rho_f\,C_f$,

$E = A_s\,\rho_s C_s$,

$D = (A_s\,\rho_s\,C_s)(q\,\rho_f\,C_f)/h_v = (E)(C)/h_v$

The volumetric heat transfer coefficient, h_v, was obtained from **Packer et al., (1980)** and **Abdel-Ghaffar, (1996)** as follows:

$$\mathbf{h_v = 2.12\left(\frac{G}{D_p}\right)^{0.543}} \qquad (2)$$

The partial differential equation was developed using three fundamental heat equations which explain the heat exchange between the air and solids as follows:

1- Energy equation for the air moving through the bed rock (x) representing the thermal and physical properties of the heated air,

2- Energy gain or loss to or from the solids (x) representing the physical and thermal properties of the solids,
3- The exchange of heat or energy transfer between the moving air and the solid including temperature of solids,
4- To develop one phase model energy balance only for air instead of two phase model (air and solids), it is important to eliminate the solid temperature by differentiate the partial differential equation with respect to the time (t) leading to the second order partial differential equation for the air temperature at any position (x) and at any time (t) in the limestone bed **(Abdel-ghaffar, 1980, Schuman, 1929 and Wylie, 1975).**

Wylie, (1975) presented a different model that relates the vertical height (x) and time (t) to the air temperature (T_f) at any location in the rock-bed. This model can be expressed as follows:

$$T_f(x,t) = T_{mean} + T_{amp}\ e^{-AX}\sin(\omega t - B\,X) \qquad (3)$$

Where; T_{amp} is the amplitude of the sinusoidal temperature function, A is the exponential decay coefficient, per unit length and B is the phase lag angle radian per unit length.

By differentiation of the **Wylie** equation's with respect to the position (x) and time (t) we get the following equations:

$$\frac{\partial T_f}{\partial x} = -T_{amp}\ A\,e^{-AX}\sin(\omega t - B\,X) - T_{amp}\ B e^{-AX}\ \cos(\omega t - BX) \qquad (4)$$

$$\frac{\partial^2 T_f}{\partial x \partial t} = -T_{amp}\ A\,e^{-AX}\omega\, cos(\omega t - B\,X) - T_{amp}\ B e^{-AX}\ (-\omega)\sin(\omega t - BX) \qquad (5)$$

$$\frac{\partial T_f}{\partial t} = T_{amp}\ e^{-AX}\omega\ \ cos(\omega t - B\,X) \qquad (6)$$

Substituting with the previous derivatives in the equation (1) with an identity for all x and t, since sin (ωt-BX) and cos (ωt-BX) ≠0.0, then the coefficients of sine and cosine must be zero, so the coefficients A and B could be determined and expressed in terms of the bed characteristics and the air velocity as follows **(Abdel-Ghaffar, 1980)**:

$$\mathbf{A} = \frac{\omega^2 \mathbf{D}\,\mathbf{E}}{\omega^2\,\mathbf{D}^2 + \mathbf{C}^2} \quad \text{and} \quad \mathbf{B} = \frac{\omega\,\mathbf{C}\,\mathbf{E}}{\omega^2\,\mathbf{D}^2 + \mathbf{C}^2}$$

Where ω is the angular velocity of sinusoidal temperature variation imposed on incoming air temperature, and it was determined as follows: $\omega = 2\pi / p$, where p is the period of oscillation in rad/hrs.

In this paper, a computer model was developed using SAS language to improve the prediction of limestone-bed performance. This program with the high capability of SAS procedures will improve Ezzat's model where 6 series of sine and cosine terms are used instead of 4 series in Ezzat's model. Thus, the objectives of this paper were then to:

1- Derive the system characteristics of limestone bed designed by **Ezzat, (1980)** that control the outlet air temperature from the limestone bed as a function of the air flow input to the system. These characteristics were mainly, the phase lag angle and the exponential decay coefficients.

2- Model the air temperature through the limestone bed mainly at; inlet gate, center of the bed height and outlet gate using Fourier series.

3- Develop the models that predict the outlet air temperature using the system characteristics and the inlet air temperature at two levels of air flow.

MATERIALS AND METHODS

The experimental unit consisted of a solar air heater and limestone bed. The unit was constructed at Agricultural and Biosystems Engineering in Alexandria University to obtain actual test data. It consisted of a wooden frame of 2.5 m long, 1.1 m wide and 0.265 m high. The aperture area of the solar air collector exposed to sun rays is 2.0 m^2 (2.0 m long and one meter wide). A flat galvanized sheet metal with a thickness of one mm. was installed fixed inside the wooden frame. The absorbing surface plate was painted by a black material to increase the solar collection efficiency. A glass sheet of 3mm thick was placed on the wooden frame at a distance of 12 cm. to form an upper passage was formed by the absorbing surface and an insulated bottom which was made of wood at a distance of 10 cm. the moving air stream picks up head from both sides of the absorber. The solar collector was connected to the rock bed storage system at one end and to a centrifugal fan at the other end through a set of pipes. The solar air heater was oriented toward the south direction. It was tilted by a movable steel frame. The tilt angle was about 20 degrees from the horizontal plane. 11 joints were sealed carefully to minimize leakage. **Fig. (1)** shows the cross section of experimental unit of solar rock bed storage system.

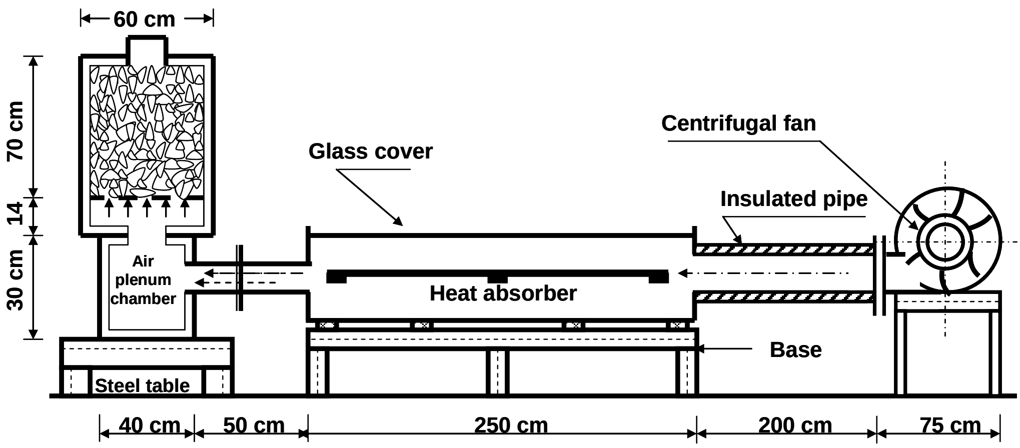


Figure (1): A diagrammatic sketch of the solar rock-bed storage system

EQUIPMENT

1- Rock bed:

A packed bed was constructed of 1 mm thick galvanized sheet with inside diameter of 1.13 m and a height of 1.02 m inlet chamber of same dimension was connected to the bed section. The bed was insulated with 20 mm thick of an insulated material. Limestone was placed in the bed and supported by steel plate of 20 mm holes at the bottom of the rock bed.

2- Solar air heater:

The solar air heater was constructed of 1 mm black galvanized sheet metal with 1.0 m wide and a length of 2.0 m. The aperture area of solar air heater was 2.0 m^2. A wooden frame with dimensions of 2.5 m long, 1.1 m wide and 0.265 m high was used to fix both solar energy a absorber and glass sheet. More details of solar air heater were presented by **Abdel-Ghaffar, (1986)**.

3- Centrifugal fan:

A Centrifugal fan was to supply air to the solar air heater and rock bed that were connected together by a 0.20 m inside diameter metal tube. This fan was connected to the solar collector by metal tube of 0.20 m inside diameter and 2.0 m long air flow adjusted by two gates constructed directly at fan exit.

4- Instrumentation:

The heated air temperature passing through the solar air heater and rock bed were measured at half hour interval time. The air flow rate was measured by a Pitot tube and an inclined manometer that had accuracy of 0.005 inch water.

PROCEDURE

Before staring the test, the equivalent spherical diameter, the true and apparent density of the material, and the void fraction of the bed were all measured. The equivalent spherical diameter, Dp, of the particles was calculated from the following formula suggested by **Löf and Hawley, (1948)**:

$$\mathrm{D}_P = \left[\frac{6}{\pi} \frac{net\, volume of\ particles\ in\, cm^3}{number\, of\ particles} \right]^{\frac{1}{3}} \qquad (7)$$

The void fraction, e was determined from the following relation:

$$\mathbf{e = 1 - \rho_b / \rho_s} \qquad \mathbf{(8)}$$

Where, ρ_b is the bulk density of limestone in bed and ρ_s is the solid density or true density of limestone. The bulk density of limestone in bed was measured by weighing the limestone in the test section divided by the volume of the bed under test **(Löf and Hawley, 1948)**.

About 830 kg of limestone were placed in the bed up to 0.70 m depth. The equivalent spherical diameter of stone was determined. The particles and apparent density of the limestone as well as the void fraction of the material inside the bed were also determined according to the methods published by **Smith et al., (1984)** and **Abdel-Ghaffar, (1986)**. **Table (1)** shows the physical properties of limestone and the characteristics of rock- bed used in this study.

Heated air temperatures were measured in the rock bed at 0, 0.375 and 0.70 m. above the bed bottom. Temperature was recorded every half hour for 2-3 days at the air flow rate of 4.66 m^3/min.

Statistical procedures were used to predict the temperatures T_1, T_2 and T_3 for the three heights mentioned above, respectively. This prediction was based on fitting the observed data to expansion of Fourier series.

At least the first six harmonic terms for "sin and cos" were considered to give an accurate prediction for each function. Basically, the general temperature function takes the following expression:

$$\begin{aligned} \mathbf{F(t_i) = A_o + A_1 \cos(\omega\, t) + A_2 \cos(2\omega\, t) + A_3 \cos(3\omega\, t) + \ldots + A_6 \cos(6\omega t)} \\ \mathbf{+ B_1 \sin(\omega\, t) + B_2 \sin(2\omega\, t) + B_3 \sin(3\omega\, t) + \ldots. + B_6 \sin(6\omega t)} \qquad (9) \end{aligned}$$

Where A_0, A_1, A_2, A_3, .., A_6, and B_1, B_2, B_3, ..., B_6 are the Fourier series coefficients. The statistical methods provide the estimate values of these coefficients with the significance test of each.

Table (1): Characteristics of limestone bed and physical properties of crushed limestone.

Characteristics	Symbol	Units	Value
1-Rock-Bed Characteristics			
Diameter	d	m	1.13
Height	H	m	0.70
Volume	V	m^3	0.702
Cross Sectional Area	a	m^2	1.003
2-Solid Characteristics			
Limestone weight	m	kg	831.51
Solid density	ρ_s	kg/m^3	2435.5
Diameter of particle	D_p	cm	4.791
Void fraction	e	-	51.5%
Mean length of particle	-	cm	7.72
Mean width of particle	-	cm	5.35
Mean thickness of particle	-	cm	3.63

Table (2) shows the physical and thermal properties of limestone and solar heated air required for predicting the temperature distribution at the outlet of the limestone bed. It shows also the values of all variables input to the model for only the low air flow (4.66 m^3/min).

Using the design characteristics of the rock-bed including the coefficients; A, and B as shown in **Table (2)**, a new Fourier series coefficients were computed in order to predict the temperature of air at any height and time. A computer program using language SAS was developed to estimate the new model of limestone performance to predict the temperature of air as a function of height and time. The program determines also the coefficients of A and B.

Table (2): The physical and thermal properties of limestone and solar heated air required for predicting the temperature distribution at the outlet of the limestone bed.

Characteristics	Symbol	Units	Values
Void fraction	e	-	0.515
Air mean temp.	T_{mean}	C^o	35
Air density	ρ_f	kg/m^3	1.127
Air specific heat	C_F	kJ/kg.K^o	1.007
Length of rock bed	L	m	0.7
Air flow rate	Q	m^3/hr	280
Solid area as % of cross section	A_s	m^2	0.485
Limestone density	ρ_s	kg/m^3	2435.5
Limestone specific heat	C_s	kJ/kg.K^o	0.9085
Equivalent spherical diameter	D_p	cm	4.714
Superficial mass velocity per unit cross section of limestone bed	G	kg/hr.m^2	320
Volumetric heat transfer coeff.	h_v	kJ/hr.m^3.C^o	3732.9
Time	t	hr	-
Periodic of oscillation	p	hr	24
Heat capacity of air	C	kJ/hr.C^o	317.8
Heat capacity of limestone	E	kJ/m.C	1073.1
C*E/h_v	D	kJ/m.C	91.35
Angular velocity	ω	rad/hr	0.2618
Exponential decay coefficient	A	1/m	0.39299
Phase lag coefficient	B	rad/m	0.68614

RESULTS AND DISCUSSION

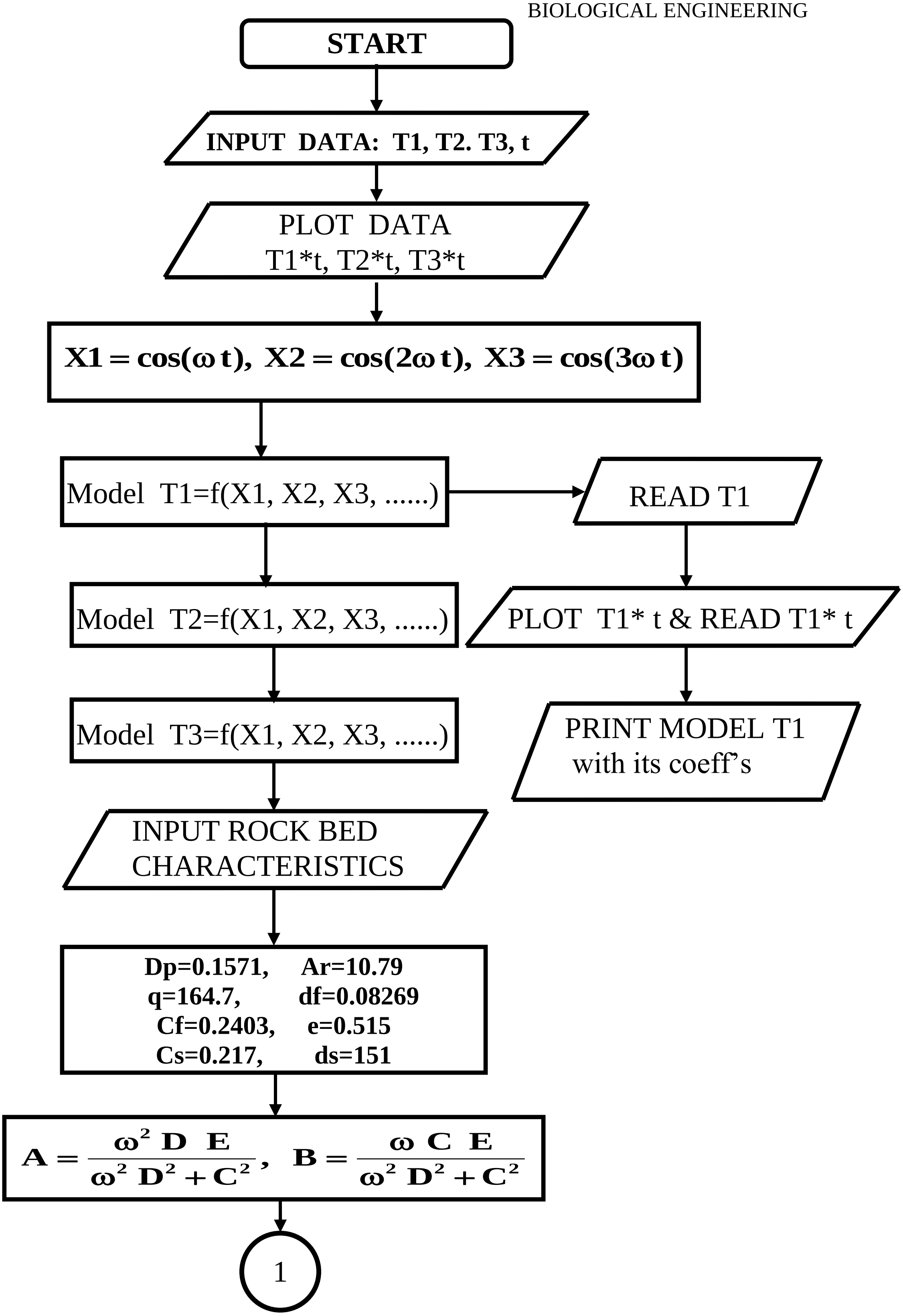
Figure 2 shows the flow chart of the computer program used for predicting the limestone bed performance. The program utilizes SAS language and Fourier series in order to determine the temperature distribution at the three heights mentioned above and to find the coefficients A and B.

The program also prints the predicted values of the temperatures T1, T2 and T3 with the related correlation coefficient. The output of this program is shown in **Tables (3)** through **(11)**.

Tables (3), (4) and **(5)** show the statistical analysis of T1. **Table (3)** gives the results of the general linear models (GLM) procedure of the dependent variable T1 and **Table (4)** gives the test of significance of the variables of Fourier series of T1 while **Table (5)** gives the estimate values and its significance test of the Fourier series variables of T1. As shown in **Table (3)**, the determination coefficient is above 0.99. The estimate values of first twelve harmonic terms of Fourier series are later used by the computer program to predict the temperature distribution of the limestone at the outlet.

Table (3): The results of GLM procedure of the dependent variable T1.

General Linear Models Procedure of Dependent Variable: T1 Number of observations in data set = 145					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	12	8030.309	669.19242	3209.28	0.0001
Error	84	17.515	0.20852		
Corrected Total	96	8047.824			
R-Square 0.9978	**C.V.** 1.531		**Root MSE** 0.457	**Mean of T1** 29.822	


START
INPUT DATA: T1, T2. T3, t
PLOT DATA
T1*t, T2*t, T3*t
$X1 = \cos(\omega t),\ X2 = \cos(2\omega t),\ X3 = \cos(3\omega t)$
Model T1=f(X1, X2, X3, ...)
READ T1
Model T2=f(X1, X2, X3, ...)
PLOT T1* t & READ T1* t
Model T3=f(X1, X2, X3, ...)
PRINT MODEL T1
with its coeff's
INPUT ROCK BED
CHARACTERISTICS
Dp=0.1571, Ar=10.79
q=164.7, df=0.08269
Cf=0.2403, e=0.515
Cs=0.217, ds=151
$A = \frac{\omega^2 D\ E}{\omega^2 D^2 + C^2},\quad B = \frac{\omega\ C\ E}{\omega^2 D^2 + C^2}$
1

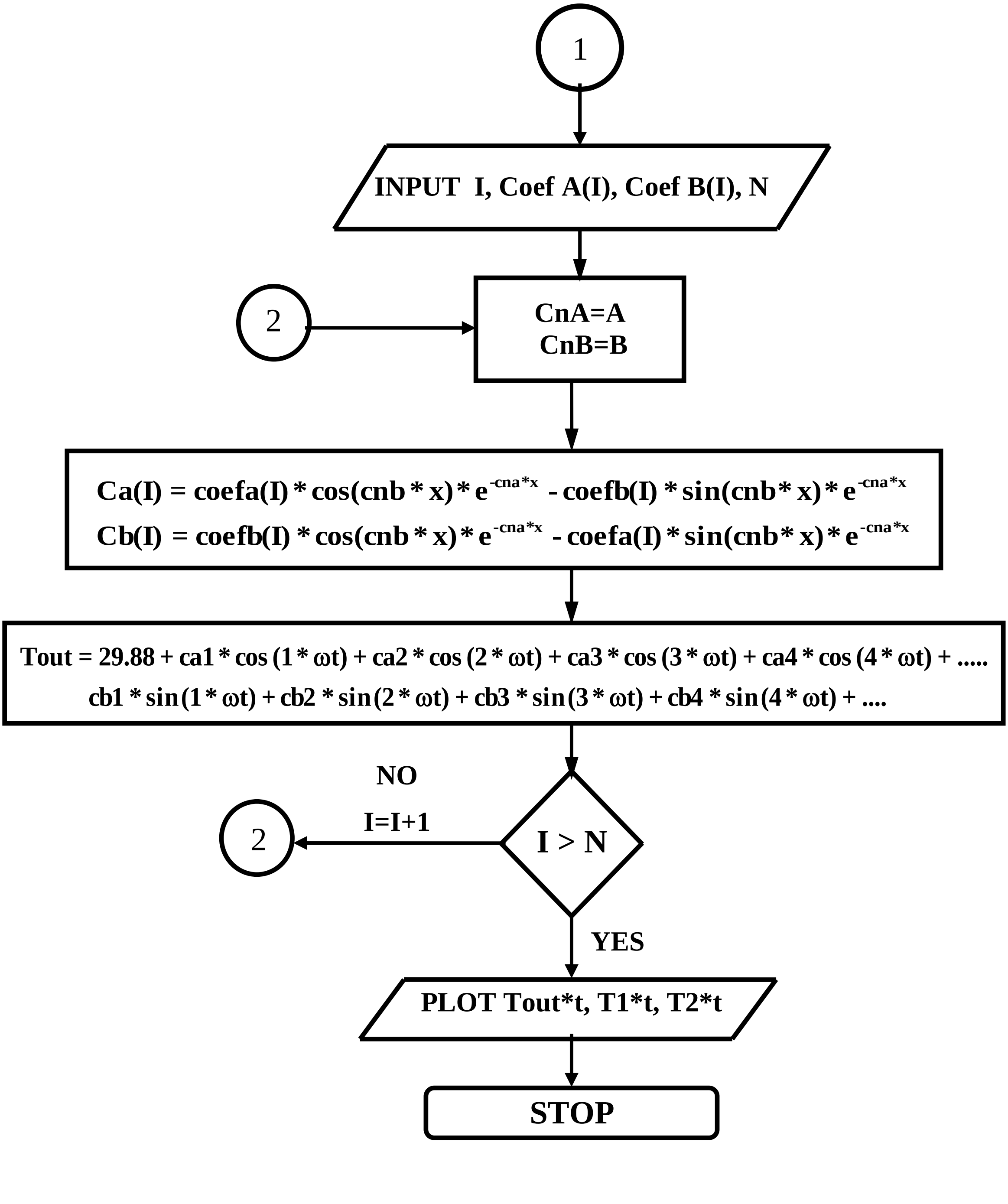


Figure (2): Flow chart of the computer SAS program used for predicting the limestone bed performance.

Table (4): The test of significance of the variables of Fourier series of T1.

Variable	DF	Type III SS	Mean Square	F value	Pr > F
x1	1	7.78785	7.78785	37.35	0.0001
x2	1	885.2738	885.2738	4245.55	0.0001
x3	1	1.71247	1.71247	8.21	0.0053
x4	1	17.4089	17.4089	83.49	0.0001
x5	1	0.88160	0.88160	4.23	0.0429
x6	1	2.12800	2.12800	10.21	0.0020
x7	1	7082.25	7082.25	33964.73	0.0001
x8	1	14.6874	14.6874	70.44	0.0001
x9	1	0.44872	0.44872	2.15	0.1461
x10	1	0.98588	0.98588	4.73	0.0325
x11	1	0.18714	0.18714	0.90	0.3462
x12	1	0.27395	0.27395	1.31	0.2550

Table (5): The estimate values and its significance test of the Fourier series variables of T1.

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	STD ERROR of Estimate
INTERCEPT	29.88126	644.12	0.0001	0.04639
X1	-0.39909	-6.11	0.0001	0.06530
X2	-4.25497	-65.16	0.0001	0.06530
X3	-0.18714	-2.87	0.0053	0.06530
X4	-0.59668	-9.14	0.0001	0.06530
X5	-0.13427	-2.06	0.0429	0.06530
X6	-0.20861	-3.19	0.0020	0.06530
X7	12.14690	184.30	0.0001	0.06591
X8	0.55316	8.39	0.0001	0.06591
X9	0.09669	1.47	0.1461	0.06591
X10	0.14331	2.17	0.0325	0.06591
X11	0.06244	0.95	0.3462	0.06591
X12	0.07554	1.15	0.2550	0.06591

Figure (3) shows the temperature distribution of the measured T1, T2, and T3 at rock-bed heights of 0.0, 0.375 and 0.7 m respectively for airflow rate of 4.66 m^3/min.

Tables (6) through (**11)** show the statistical analysis for T2 and T3 with the same manner as for T1. **Figures (4), (5)** and (**6)** show the temperature distribution of measured and predicted T1, T2 and T3 respectively.

The correlation coefficient, r, between the measured T3 and predicted T3 (namely T_{out}) using the computer model explained above by applying Fourier series technique and the design thermal characteristics of the limestone-bed was also shown in **Table (12)**. It reached 0.90. The graph on **Figure (7)** shows the temperature distribution at the inlet (T1) and outlet (T3) of the rock-bed as well as the predicted temperature distribution (T_{out}). The computed coefficients A and B are shown in **Table (2)**.

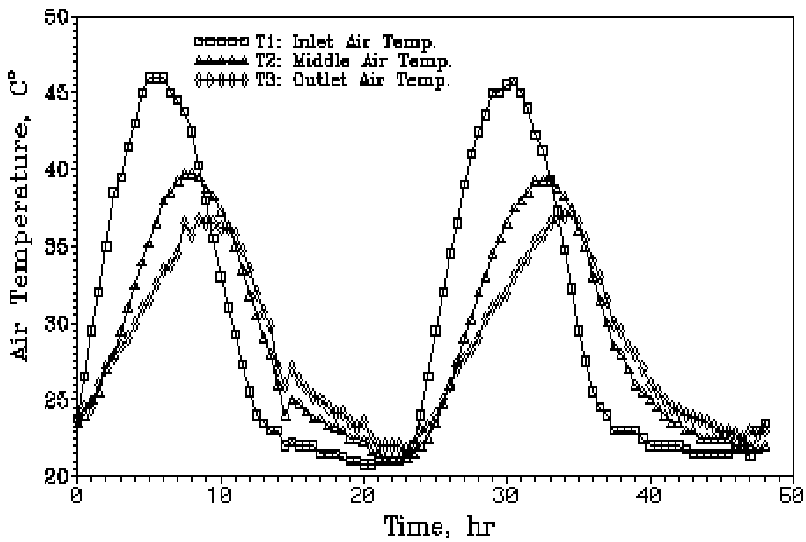


Figure (3): Temperature distribution; T1, T2, T3 at the inlet, middle height, and outlet of the limestone-bed respectively.

Table (6): The results of GLM procedure of the dependent variable T2.

General Linear Models Procedure of Dependent Variable: T2 Number of observations in data set = 145					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	12	3878.00266	323.16689	1024.62	0.0001
Error	84	26.49363	0.31540		
Corrected total	96	3904.49629			
R-Square 0.9932	**C.V.**	1.9496	**Root MSE** 0.562	**T1 Mean** 28.806	

Table (7): The test of significance of the variables of Fourier series of T2.

Variable	DF	Type III SS	Mean Square	F value	Pr > F
x1	1	1165.008	1165.008	3693.74	0.0001
x2	1	92.487	92.487	293.24	0.0001
x3	1	0.71636	0.71636	2.27	0.1355
x4	1	0.4403	0.4403	0.14	0.7096
x5	1	0.27801	0.27801	0.88	0.3505
x6	1	0.09012	0.09012	0.29	0.5944
x7	1	2475.473	2475.473	7848.67	0.0001
x8	1	120.2065	120.2065	381.12	0.0001
x9	1	4.68534	4.6853	14.86	0.0002
x10	1	0.65762	0.65762	2.09	0.1525
x11	1	0.35241	0.35241	1.12	0.2935
x12	1	0.04941	0.04941	0.16	0.6933

Table (8): The estimate values and its significance test of the Fourier series variables of T2.

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	STD ERROR of Estimate
INTERCEPT	28.87259	506.05	0.0001	0.05706
X1	-4.8811	-60.78	0.0001	0.08031
X2	-1.3753	-17.12	0.0001	0.08031
X3	-0.1210	-1.51	0.1355	0.08031
X4	-0.0300	-0.37	0.7096	0.08031
X5	-0.0754	-0.94	0.3505	0.08031
X6	0.0429	0.53	0.5944	0.08031
X7	7.1814	88.59	0.0001	0.08106
X8	-1.5825	-19.52	0.0001	0.08106
X9	0.3124	3.85	0.0002	0.08106
X10	-0.1170	-1.44	0.1525	0.08106
X11	0.08568	1.06	0.2935	0.08106
X12	0.03208	0.40	0.6933	0.08106

Table (9): The results of GLM procedure of the dependent variable T3.

General Linear Models Procedure of Dependent Variable: T3 Number of observations in data set = 145					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	12	2368.94082	197.41174	669.44	0.0001
Error	84	24.77098	0.29489		
Corrected total	96	2393.71180			
R-Square 0.99	**C.V.** 1.906		**Root MSE** 0.543	**T1 Mean** 28.484	

Table (10): The test of significance of the variables of Fourier series of T3.

Variable	DF	Type III SS	Mean Square	F value	Pr > F
x1	1	1189.675	1189.675	4034.27	0.0001
x2	1	0.08315	0.08315	0.28	0.5968
x3	1	6.18475	6.18475	20.97	0.0001
x4	1	0.07562	0.07562	0.26	0.6139
x5	1	0.44300	0.44300	1.50	0.2238
x6	1	0.17830	0.17830	0.60	0.4390
x7	1	1088.639	1088.639	3691.65	0.0001
x8	1	55.32666	55.32666	187.62	0.0001
x9	1	19.48454	19.48454	66.07	0.0001
x10	1	0.76984	0.76984	2.61	0.1099
x11	1	0.96219	0.96219	3.26	0.0744
x12	1	0.17561	0.17561	0.60	0.4425

Table (11): The estimate values and its significance test of the Fourier series variables of T3.

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	STD ERROR of Estimate
INTERCEPT	28.5402547	517.32	0.0001	0.05516899
X1	-4.93255592	-63.52	0.0001	0.07765862
X2	-0.04123728	-0.53	0.5968	0.07765862
X3	-0.35564668	-4.58	0.0001	0.07765862
X4	-0.03932694	-0.51	0.6139	0.07765863
X5	-0.09518286	-1.23	0.2238	0.07765863
X6	0.06038520	0.78	0.4390	0.07765864
X7	4.76235646	60.76	0.0001	0.07838119
X8	-1.07361141	-13.70	0.0001	0.07838119
X9	0.63712544	8.13	0.0001	0.07838118
X10	-0.12664232	-1.62	0.1099	0.07838118
X11	0.14158297	1.81	0.0744	0.07838117
X12	-0.06048629	-0.77	0.4425	0.07838117

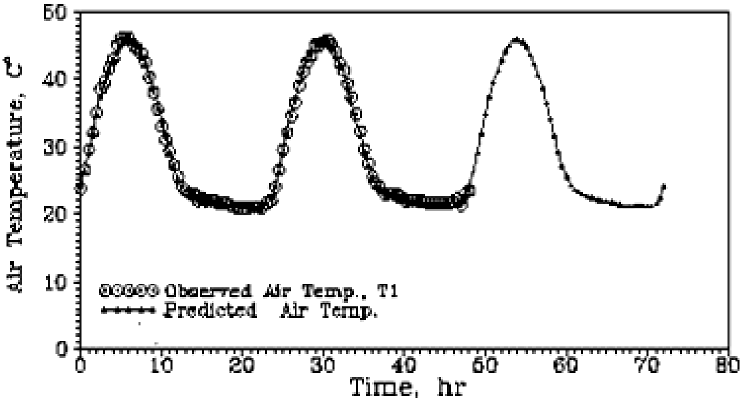


Figure (4): Measured and predicted (fitted) temperature at the inlet of the limestone-bed; T1

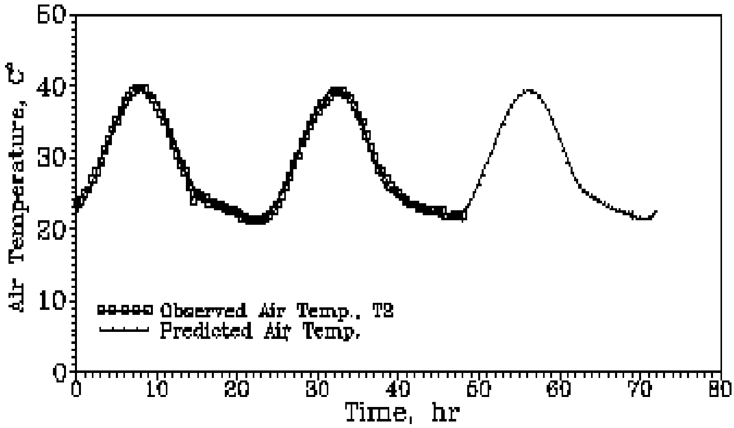


Figure (5): Measured and predicted (fitted) temperature at the middle of the limestone-bed; T2.

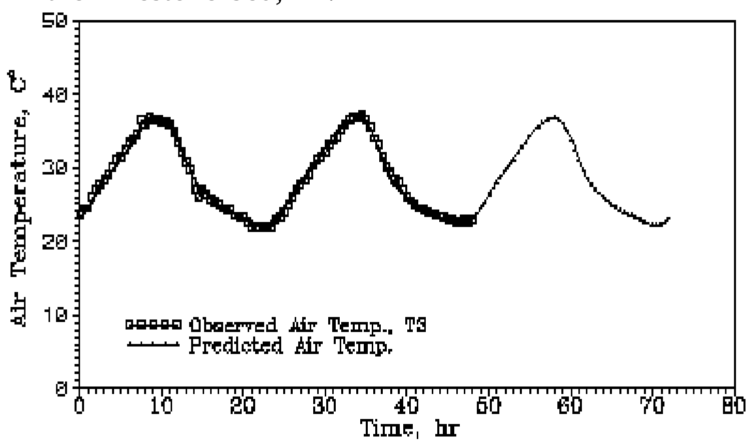


Figure (6): Measured and predicted (fitted) temperature at the outlet of the limestone-bed; T3.

Table (12): The correlation analysis for variables T3 and Tout computed from limestone bed characteristics.

Variable	N	Mean	Std Dev	Minimum	Maximum
T_{out}	388	29.795	7.384	20.803	42.4656
T3	388	28.485	4.9741	21.750	37.2500
Pearson Correlation Coefficient, r, between T_{out} and T3 = 0.90287					

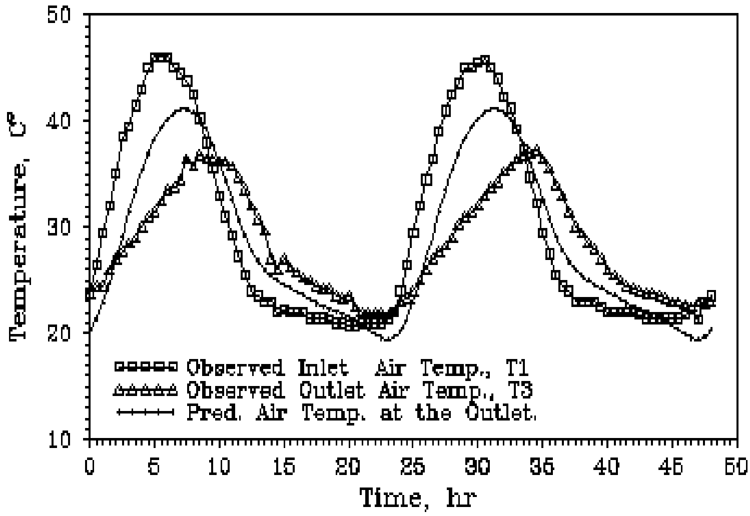


Figure (7): The temperature distribution of the inlet, T1 and the outlet, T3, of the limestone-bed as well as temperature distribution of T_{out} that calculated by the model.

CONCLUSIONS

From the obtained results, it could generally conclude that:

1- A mathematical model was established and developed to predict the discharge air temperature variation with time.

2- A mathematical equation could be obtained and it was powerful to express the performance of the bed-rock.

3- Good agreement was found between the observed and predicted (fitted) data of air temperature at any rock-bed height. Therefore, the use of the system characteristics and Fourier series was not only successful to predict the temperature distribution at any rock-bed height but also to compute the exponential decay coefficient (A) and the lag phase coefficient (B).

4- The difference between the mean air temperature for the inlet and outlet of the rock bed was found to be insignificant. The correlation coefficient between the outlet temperature and the computed temperature by the model was above 0.90.

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الملخص العربى

الاستفادة من لغة الساس فى عمل نموذج رياضى لاختبار أداء مرقد من الحجرالجيرى

عزت عبد المنعم عبد الغفار   خيرى مصباح اسماعيل**   محمد أبو الحمد رشوان***

من المعروف أن عملية تسخين الهواء باستخدام المجمعات الشمسية عادة ما يكون فيها تباين كبير فى درجات الحرارة و يرجع ذلك الى تفاوت درجات الحرارة على مدار اليوم. وعلى ذلك فان استخدام مرقد الحجرالجيرى من شأنه عمل تقليل للتذبذبات العالية فى درجة حرارة الهواء، وبالتالى أمكن استخدام مرقد الحجر الجيرى فى تخزين الحرارة المتجمعة خلال ساعات النهار للاستفادة بها خلال ساعات الليل.

وعلى ذلك فان الهدف الرئيسى من هذا البحث هو عمل نموذج رياضى لمرقد الحجرالجيرى باستخدام لغة الساس ومن خلال هذا النموذج يمكن الاستفادة من خواص المرقد الحجرى، متسلسلة فورير واستخدام الطرق الاحصائية لاستنتاج درجة حرارة خروج الهواء.

وقد تم تطوير برنامج كومبيوتر لتحقيق هذا الغرض وقد استخدم معدل هواء مدفوع للمرقد بمقدار ٤.٦٦ متر^{٣}/دقيقة لاختبار النموذج الرياضى وقد تم تسجيل درجة حرارة الهواء الخارج من المرقد عند ارتفاعات: صفر، ٠.٣٧٥ و ٠.٧٠ مترمن بداية المرقد لمدة ٢٤ ساعة.

وقد وجد أن متسلسلة فورير أكثر كفاءة فى استنتاج درجة حرارة الهواء عند أى ارتفاع للمرقد كما أن معامل الارتباط الناتج باستخدام خصائص المرقد عند استنتاج درجة حرارة الهواء الخارج من المرقد كان ٠.٩٠٥. كذلك تم ايجاد معامل التقدير بين درجة حرارة الهواء الملاحظة والمستنتجة حيث كانت ٠.٩٨ عند أى ارتفاع للمرقد.

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