"OPTIMIZATION OF THICKNESS OF PACKED BED SOLAR AIR HEATER USING STONE PEBBLES AS MATRICES"

Dissertation Submitted in the Partial Fulfillment of the Requirement in the Award of the Degree of

MASTER OF TECHNOLOGY

(RENEWABLE ENERGY TECHNOLOGY)

By

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Declaration

I hereby declare that the thesis entitled "**OPTIMIZATION OF THICKNESS OF PACKED BED SOLAR AIR HEATER USING STONE PEBBLES AS MATRICES"** is an original work carried out by me under the supervision of Mr. Naushad Ahmad Ansari, Department of Mechanical Engineering, Delhi Technological University, Delhi. This thesis has been prepared in conformity with rules and regulations of the Delhi Technological University, Delhi. The research work reported and results presented in the thesis have not been submitted either in part or full to any other university or institute for the award of any degree or diploma.

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Certificate

This is to certify that the project captioned "OPTIMIZATION OF THICKNESS OF PACKED BED SOLAR AIR HEATER USING STONE PEBBLES AS MATRICES" factual record of the work done by MRADUL GAUTAM in partial fulfilment of the requirement for the award of Degree of Master of Technology in Renewable Energy Technology of Delhi Technological University.

This is also certified that the above student have completed this work during the academic session 2016-2017 under my guidance and supervision.

NAUSHAD AHMAD ANSARI

(Assistant Professor)

ABSTRACT

The principal applications in which solar air heaters are being used are drying for agricultural and industrial purposes. Solar air heater have been used for many application requiring low to medium grade thermal energy. Like space heating and cooling, agriculture drying, timber seasoning chemical processes and powder generation. It is mainly due to their low manufacturing cost, simple design, operation and maintenance. Their usefulness as quantitative energy collection has been limited because of lower thermal efficiency primarily as result of lower convective heat transfer coefficient between the absorber plate and air, leading to higher plate temperature, due to which greater thermal losses. Several methods for the enhancement of heat transfer coefficient and hence the improvement of thermal performance of solar air heater have been proposed and investigated by a number by a number of investigator. One of the method of improving the thermal performance of the solar air heater is to enhance the heat transfer rate to the air by packing the duct of solar air heater by stone pebbles, such a system absorbs solar air radiation in depth and has a ratio of heat transfer area to volume and hence high transfer capability, resulting in an increase in thermal efficiency of the collector.

Packed beds are generally used for storage of thermal energy from solar air heaters. In this paper experimental study has been conducted on a porous packed bed solar air heater using stone pebbles as packing material. The effect of air massflow rates and bed porosity on the thermal performance of packed bed solar air heaters are investigated. It is seen that heat transfer coefficient and friction factor are strong functions of geometrical parameters of the porous packed bed. The results of a packed bed solar air heater shows a substantial enhancement in the thermal performance as compared to the conventional collector also a decrease in porosity increases the volumetric heat transfer coefficient.

Content

CHAPTER 1

(INTRODUCTION)

1. INTRODUCTION

Energy consumption is on increase and the fossil fuels cannot last forever. Extensive fossil fuel consumption by human beings has led to some undesirable phenomena such as atmospheric and environmental pollutions [17]. Consequently, global warming, greenhouse effect, climate change, ozone layer depletion and acid rain terminologies started to appear in the literature frequently. So, it has become the need of an hour to use the energy resource which is clean and ecofriendly. Solar energy is one of the better options for clean energy. Solar air heating is a heating technology used to heat or condition air for buildings or process heat applications. It is typically the most cost-effective out of all the solar technologies, especially in commercial and industrial applications, and it addresses the largest usage of building energy in heating climates, which is space heating and industrial process heating.

1.1 Energy Crisis

Developed countries fulfill up to 90% of their energy demand by fossil fuels and balance comes from other resource , while the under developed countries fulfill about 50 % of their demand by fossil fuels which resulted in sharp rise in the price of these fuels[21]. This came to know as energy crisis this crisis affected:

(i) A major drain of foreign exchange

(ii) Cutting down the needs

(iii) Uncertain future development

1.2 Classification of Energy Resources

Energy resource can be classified into two categories[36]:

(i) Conventional Resources: These Include fossil fuels e.g. oil, coal, and natural gas.

(ii) Non- Conventional Resources: These could be:

(a) Renewable: These are non – conventional resource which is renewed over a short span of time e.g. solar energy , wind energy, hydro energy, tidal energy, biomass and geothermal energy.

(b) Non- Renewable: Such source of fossil fuels nature which has not been exploited so far due to economic reasons e.g. peat and oil shale.

1.3 Origin of Solar Energy:

The Sun's total output is $3.8 * 10^6$ W, which is equal to 63 MW from every square meter of its surface. This energy radiates outward in all directions from nearly spherical sun . The earth intercept only a tiny fraction of the total, about over to billions [20].

The earth moves around the sun in an orbit that is slightly elliptical in shape. As a result of this shape the earth is a little farther from the sun in July than it is in January. This cause a small variation in the 90mm of water amount of solar energy the earth received about 6 % more in January than in July , a variation which is equally ignored in the solar energy.

The solar radiation that reaches the earth's surface consists of wavelength ranging from 0.3 to 0.4 micro meters. For most solar energy application the radiations in the visible range 0.38 to 0.78 micrometer and the near infrared 0.78 to 2.0 is the most [20].

Almost half of the solar radiation absorbed is reflected and scattered by cloud and small particles.

1.4 Solar Energy Applications:

The Important application of solar energy are given below:

(i) Water Heating

(ii) Air Heating for agriculture and industrial applications

(iii) Heating and cooling for space

(iv) Solar refrigeration

(v) Cooking for food

(vi) Distillation of water

(vii) Solar furnaces

(viii) Power generation and solar cell

(ix) Photochemical and Photo biological conversion

(a) WATER HEATER:

These system use the sun to heat either water in collector generally mounted on a roof. The heated water is stored in tanks. Some system use electric pump to circulate the fluid through the collector[42]. Solar system use electric pump to circulate the fluid through the collector. Solar Water Heater can operate in any climate. Performance varies depending in part, on how much solar is available at the site, but also on how cold the water coming into the system. In almost climates, you will need a conventional water heater as the backup.

(b) Heating and cooling for space:

Solar air heating system has the space above or below the absorber plate that can be serve as conduit. Solar air heater designs are relatively simple and eliminate corrosion and leakage problems, which may difficult and costly to overcome [36]. The cost of the air heater could be substantially lower than that of liquid system.

(c)Solar furnace:

The solar furnace relies on the power of the sun. This is use to power a furnace producing steel from iron ore. The production of steel and aluminum requires very large amount of energy[36]. This is normally provided by electricity, gas, or fossil fuels. The ore is heated to a very high temperature until it become molten then it is poured. Pollution is kept to a minimum as solar power its clean source of energy.

(d) Photovoltaic:

Photovoltaic is the energy conversion of sunlight into electricity through a photovoltaic (PVs) cell, commonly called a solar cell. A photovoltaic cell is a non- mechanical device usually made of silicon alloys [36]. The performance of photovoltaic array is dependent on sunlight. Climate conditions (e.g. Cloud fog) have a significant effect on the amount of solar energy received by a PV array and, in turn, its performance.

(e) Solar Cooker:

The solar oven is useful and well proved alternative to burning wood. It is an extremely simple cooker which relies exclusively on the direct radiation of the sun. Most dishes can be cooked in it and this without additional work, quite the contrary! Cooking with the solar-oven does not need supervision because stirring the pan is not necessary. The solar-oven functions according to the greenhouse effect, i.e. the light rays from the sun (not heat rays)[36].

(f) Power Generation:

Solar Power Plant are composed of sun tracking collectors, which concentrate sun light on the steel pipes that contain a heat transfer fluid(HFT) . This fluid is pumped through heat generate steam up to 400degree C., which in turn power a turbine to produce electricity . In addition to electricity, the hot water emitted can be reduced for cooling machines or hot water[36].

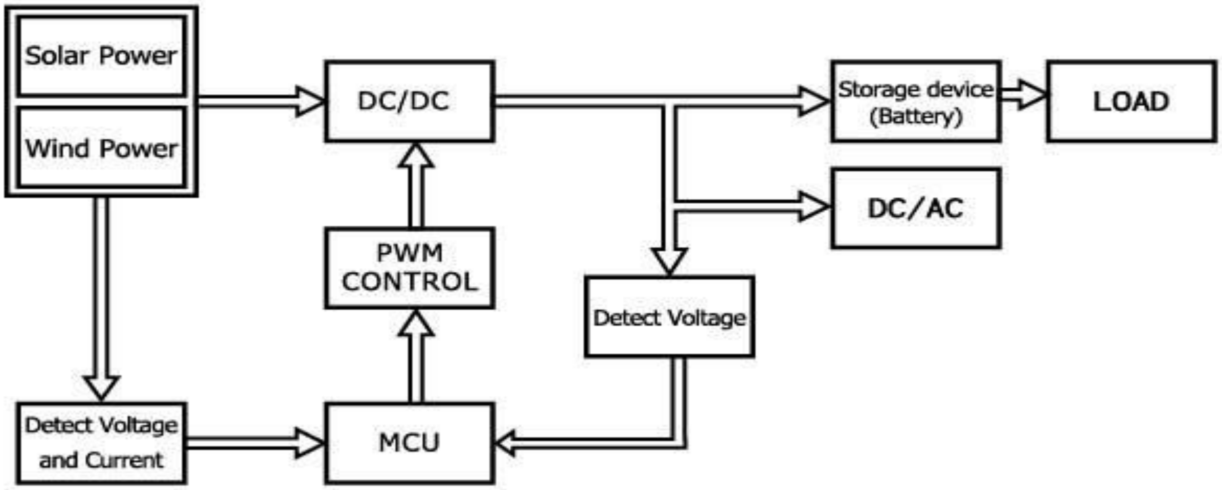

Figure 1.5: Solar Power Generation block diagram[44]

1.5 Solar Air Heater:

Solar air heating system has the space above or below the absorber plate that can be serve as conduit as shown in figure.1.2. Solar Air Heater designs are relatively simple and eliminate corrosion and leakage probems, which may difficult and costly to overcome. The cost of the air heater could be substantially lower than that of liquid system [36].

Figure 1.2: Solar Air Heater [40]

1.5.1 Method of Enhancement of Performance of Collector:

The Following methods have been proposed by the investigation to achieve enhancement of thermal efficiency of the solar air heaters.

(i) Packed Bed:

The thermal performance of solar air heaters can be improved by enhancing the heat transfer to air by packing its duct with blackened stone pebbles matrices. In a packed bed system, there is heat transfer between the flowing fluid and the packing material. Two categories of packed bed exists, regular and random packaging arrangement

Regular packaging provides complete control of the bed void age and surface area depending upon the method of assembly. It has been found that the efficiency of collectors with packed bed is substantially higher as compared to that of conventional solar air heater operating under similar conditions.[37]

Figure 1.3: Solar Air Heater (Packed Bed) [40]

(ii) Selective Coatings:

Solar collectors most have high absorptance for radiation in the solar energy spectrum. At the same time, they lose energy by the combination of mechanism including thermal radiation from the absorbing surface, and it is desirable to have the long wave remittance of the surface as low as possible, to reduce losses. So it is possible to devise surfaces having high solar absorptance and low long wave emittance, that is, selective coating[1].

(iii) Number of Glass Covers:

Larger number of glass covers reduces the thermal loss but lead in a fall in the effective transmissivity in lower temperature region. At high temperature, three plate cover superior to one. Thus the number of covers depend upon the desired output and hence absorber temperature. And low value of glass cover emissivity result in low thermal losses and thus better efficiency.

(iv) Artificial Roughness:

The use of artificial roughness on the underside of the absorber plate can substantially enhance the performance of the solar air heater due to increase in heat transfer coefficient from the plate to air.

1.5.2 Design Variation of Solar Air Heater:

Absorber of solar air heater cab be classified as :

(i) Non-Porous Absorbers:

In such a system, air may flow above, below on the both side of the absorber. Performance of such a system may be improved by using modified non-porous absorbers like corrugated iron sheet fin structure or V- shaped troughs[1].

(ii) Porous Absorbers:

In such system, the absorber may have slit and expanded metal , metal chip, wire woven screens, pebbles, glass tubes or spheres as absorbing material. The presence of such a bed has been found to result in considerable enhancement of performance as solar radiation penetrates in the bed and is absorbed gradually depending on the matrix density in addition, it has high ratio of heat transfer area to volume and hence high heat transfer capability, resulting in an increase in thermal efficiency of the system.

1.5.3 Study of Plane and Packed bed Solar air heater:

Two dimensional flows were obtained by drawing atmosphere through flow straighter 1. the air passes through the test section 2 and 3 i.e. Solar air heater each having rectangular channel of size 150*49*5 cm^2 one with plane and other with packed be collector and the flow is metered before exhausting into the atmosphere. The side and middle wall of the channel has a 24 gauge M.S. sheet over a 50mm of glass wool insulation supported on a sal wood sheet. A mild steel sheet acted as an absorber in plane collector, on the lower side of which air flow was maintained between absorber plate and the glass cover, where as in packed bed, bottom M.S. sheet and glass cover. The M.S. and the absorber matrices were painted black with black board point to the sun facing side and exposed area of each plate is 0.735 m^2 . [40]

The whole assembly was mounted on stand such that suction side of the air blower gets aligned with the axes of the twin air heater and flow straighteners in horizontal position[40]. The mass flow rate of air through the twin air heater was maintained constant with the help of by-pass and control valves and measured by two orifice meters provided in the air flow circuit.[40]

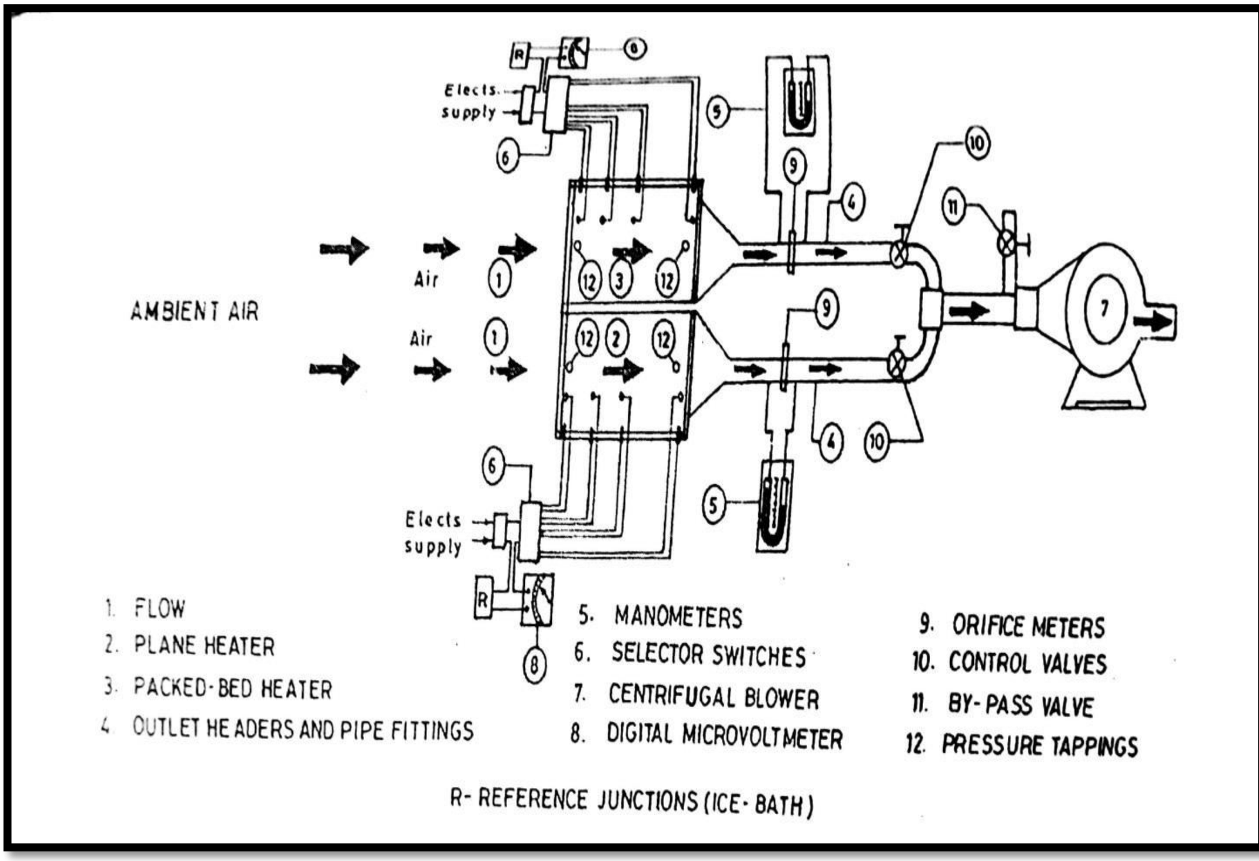

Figure 1.4: The schematic diagram of the experimental set-up [40]

CHAPTER 2

(LITERATURE REVIEW)

2. Literature Review

It is important to learn and understand the existing knowledge to create the new one. In this chapter, an effort has been made to compile the available information on solar air heater and the effect of various parameters on efficiency and the investigations performed to enhance the system. The wide area of information on the subject has been abridged to formulate the objectives of the present study.

The consolidate report of the investigations carried out in relevance to packed bed solar air heaters.

Jain D. et al. [17] presented a periodical analysis of multi-tray crop drying using an inclined multi-pass solar air heater with in-built thermal storage. The performance of multi-tray drying integrated with a solar air heater was evaluated for drying of the paddy crop. The effect of change in the tilt angle, length and breadth of a collector and mass flow rate on the temperature of crop was studied. It has been observed that the crop moisture content decreases with the drying time of the day and the thermal efficiency of the drying increases with increase in mass of the crop.

Ozturk H.H. et al.[27] investigated experimentally energy and exergy efficiency of a packed-bed heat storage unit for greenhouse heating. In this research, solar energy was stored daily using the volcanic material with the sensible heat technique for heating the tunnel greenhouse of 120 m2. The packed bed heat storage unit was built under the soil at the centre of the tunnel greenhouse. It was found that the net energy and energy efficiencies in the charging periods were 39.7 and 2.03% respectively. The results showed that 18.9% of the total heating requirement of tunnel greenhouse was obtained from the heat storage unit.

Fath Hassan et al.[12] presented the thermal performance of a simple design solar air heater with built-in thermal energy storage system. The conventional flat plate absorber is replaced by a set of tubes filled with a thermal energy storage material. The proposed integrated system heat transfer area and heat transfer coefficient are increased and the heat loss is decreased.

Based on a simple transient analysis, explicit expression for the heater absorber and glass cover temperatures, effective heat gained, outlet temperature, and the heater efficiency have been developed as a function of time. The integrated system performance curves were presented and a marked improvement in the system performance was noticed over the conventional flat plate heater system.

In air based solar energy utilization systems, storage of hot air is not possible due to low density of air. Such air heaters have low thermal efficiency because of low convective heat transfer coefficient, which results in higher heat losses to the surroundings. For the purpose of minimizing the energy losses and maximum utilization of solar energy to increase the thermal performance of the solar air heater. Several methods including the use of packing of porous materials like pebbles, rocks, hollow spheres, glass beads, wire mesh, cross rod matrices and slit-and-aluminum- foil matrices in the duct of solar air heater have been proposed. Also various designs of solar air heater with different

Configurations have been proposed to enhance thermal performance of solar air heater. Several experimental and

Theoretical studies have done to obtain detailed information on the heat transfer mechanism by using a porous packing in an air duct.

Kays and London et al. [19] have done a detailed study on heat transfer and flow friction using wire screens inside the heat exchanger tubes.

Hamid and Beckman et al.[15] have studied the thermal behavior of air-cooled radiatively heated and randomly stacked copper wire mesh screen matrices in a bed.

Chiou et al. [5] experimentally investigated the volumetric heat transfer coefficient and friction factor for a collector duct packed with slit and expanded aluminum foil matrices and found that the volumetric heat transfer coefficient is generallyhigher for beds with lower porosities.

Hasatani et al. [16] have investigated theoretically and experimentally about the collection and storage characteristics of solar collector packed with semi-transparent material.

Choudhary et al. [6] have done an experimental study on the comparative theoretical performance analysis of solar air heater packed with different materials like cylinder, ring, sphere and crushed materials; and without packing in the flow passage.

Varshney and Saini et al. [41] carried out experimental investigations on heat transfer and fluid flow characteristics of a solar air heater having its duct packed with wire mesh screen matrices. The investigations covered a wide range of geometrical parameters of wire mesh screen matrix (wire diameter, pitch and number of layers).

Thakur et al.[38] carried out experimental investigation on a low porosity packed bed solar air heater. Investigation covers a wide range of geometrical parameters of wire screen matrix. The correlations have been developed for the Colburn j factor and friction factor for a low range of porosities from 0.667 to 0.880 and packing Reynolds number range from 182 to 1168.

Tian et al. [39] experimentally investigated the various configurations of copper screen meshes to identify the preferable orientation for maximizing thermal performance under steady state forced air convection. Results show that the overall heat transfer depends on porosity and surface area density but weakly on orientation.

Singh et al. [35] carried out experimental investigation on the effect of system and operating parameters on heattransfer and pressure drop characteristics of packed bed solar energy storage system with large sized elements of storage material. Five different shapes of elements of storage material were investigated. Correlations were developed for Nusselt number and friction factor as function of Reynolds number, sphericity and void fraction.

Mittal and Varshney et al.[22] have done a thermo-hydraulic investigation of a solar air heater packed with blackenedwire screen matrices for different geometrical parameters and developed a design criterion to select a matrix which would result in best thermal performance with minimum pumping power penalty.

Ramadan et al. [30] carried out experimental investigations on thermal performance of a double-pass solar air heater packed with lime stones and gravels and observed that the thermo-hydraulic efficiency was found to increase with increasing mass flow rate until a typical value of 0.05 kg/s beyond which increase in thermo-hydraulic efficiency becomes insignificant.

Prasad et al. [29] carried out experimental investigation on a packed bed solar air heater using wire mesh as packing material for eight sets of matrices with varying geometrical parameters.

Dhiman et al. [7] investigated theoretically and experimentally thermaland thermo hydraulic performance of counter and parallel flow packed bed solar air heaters.

P.Tiwari et al. [40] investigated theoretically and experimentally on heat transferand fluid flow characteristics.

2.2 Research Gap:

Going through the above literature work published in various sources. I have not found any researcher investigating the optimum parameters related to the thickness of the stone pebbles bed and its effect on the performance of the solar air heater in both the cases i.e. plane nad packed bed solar air heater. Analysis has been conducted under identical and actual outdoors conditions in order to compare their thermal performance.

2.3 Problem Statement:

In the light of the comprehensive and the valuable literature review, it is clear that the efficiency of the solar air heater enhance by the different methods used by the researchers by studying the various parameters. The research on parameter "thickness of the stone pebbles" in packed bed solar air heater is not done by any researcher to enhance the efficiency. So, I have to make my keen interest on the thickness parameter. Therefore, the aim of my investigation to find out the optimum thickness of layer of stone pebbles of packed bed solar air heater.

CHAPTER 3

(GOVERNING EQUATIONS)

3.1 Energy Balance Equation:

The solar radiation absorb by a collector is equal to the difference between the incident solar radiation and the optical losses. The thermal energy lost from the colllector to the surrounding by conduction, convection, and infrared radiation can be represented by the difference between the mean absorber plate temperatures, Tpm and the ambient temperature Ta. In the steady state, the use of full energy output of a collector is the difference between the absorbed solar radiation and the thermal loss. [36]

$$Q_u = A_c\, F_R\, [S - U_L\, (T_{fi} - T_a)] \tag{3.1}$$

Where,

Q_u = Useful Heat Gain

A_c = Area of Collector plate (m2)

F_R = Collector heat removal factor

S = Solar flux absorbed

U_L = Loss Coefficient

T_{fi} = Fluid Inlet Temperature

T_a = Ambient Temperature

The above equation is useful energy equation for the determination of performance.

Expreesions have been developed for conventional collector performance parameter, namely:

- Collector Efficiency
- Collector Efficiency Factor
- Collector Heat Removal Factor (F_R)
- Collector Flow Factor($F^* = F_R/F$)

Consider a conventional solar air heater having absorber plate length L_1 and Width L_2. The air flow in parallel plate passage below the absorber plate.

Consider a slice of width L_2 and thickness dx at a distance from the outlet.

We assume that :

- Quasi Steady State condition exists.
- The bulk mean temperature of the air change from T_f to T_f+dT_f as it follows through the distance dx.
- The air mass flow rate (m) is constant.
- The mean temperature of the absorber plate and the plate below are T_{pm} and T_{bm} respectively and their variation may be neglected.
- The side losses are neglected.

The following energy equations are obtained:

(i) For Absorber Plate:

$$SL_2\,dx=U_1L_2dx(T_{pm}-T_a)+\underline{h_{fi}}L_2dx(T_{pm}-T_f)+(\sigma L_2dx(T_{pm}^4-T_{bm}^4))/1/\varepsilon_p+1/\varepsilon_b-1 \qquad (3.2)$$

Where,

$\varepsilon_{p=}$ emissivity of collector absorber plate

$\varepsilon_{b=}$ Emissivity of the bottom plate

T_{pm} = Mean temperature of absorber plate

$T_{bm=}$ Mean temperature of back plate

H_{fi} = Heat transfer coefficient of the back plate

(2) For bottom plate:

$$(\sigma L_2 dx\ (T_{pm}^4 - T_{bm}^4))/(1/\varepsilon_p + 1/\varepsilon_b - 1) = U_l L_2 dx(T_{pm} - T_a) + h_{fi} L_2 dx(T_{pm} - T_f) \quad (3.3)$$

(3) For Air Stream:

$$mC_p dT_f = h_{fp} L_2 dx(T_{pm} - T_f) + h_{fp} L_2 dx(T_{bm} - T_f) \quad (3.4)$$

3.2 Representation of Thermal Performance:

(i) Collector Efficiency:

A measure of collector performance defined as the useful gain over some specified time period to the incident solar energy over the same time period.

$$\eta = \int Q_u\, dt / A_c \int G_r \quad (3.5)$$

(ii) Collector Efficiency Factor:

$$F = (1 + U_l/h_c)^{-1} \quad (3.6)$$

$$h_c = h_{fp} + h_r h_{fb}/(h_r + h_{fp}) \quad (3.7)$$

h_{fp} = convective heat transfer coefficient between the absorber plate and the air stream

h_{fb} = convective heat transfer coefficient between the bottom plate and the air stream

h_r = Equivalent radiated heat transfer coefficient.

It represents the ratio of actual useful energy gain to the useful energy gain that would result if the collector absorbing surface has been at the local fluid temperature.

(iii) Collector Heat Removal factor:

$$F = (mC_pU_1A_p)[1\text{-}\exp\{-FU_1A_p/C_p\}] \qquad (3.8)$$

It is an important design parameter since it is a measure of the thermal resistance encountered by absorbs solar radiation in reaching the collector fluid. From the above equation it can be shown that F_R represent the ratio of the actual useful heat gain rate to the gain which would occur if the collector absorbser plate were at the fluid inlet temperature T_s everywhere. As such its value ranges between 0 & 1.

(iv) Collector Flow Factor:

$$F = F_R/F = (mC_pU_1A_p)[1\text{-}\exp\{-FU_1A_p/C_p\}] \qquad (3.9)$$

This collector flow factor is a fraction of the single variable; the dimensional collector capacitance is (mC_p/U_1A_cF).

(v) Expression For collector Efficiency:

The performance of the flat plate collector operating under assumed steady conditions can be described by the following equation.

$$\eta = F_R\,[(\tau\alpha)e\text{-}U_1\,(T_{fi}\text{-}T_a)/I] \qquad (3.10)$$

However, for solar air heaters, it is helpful to utilize the following equation to express efficiency

$$\eta = F_R\,[(\tau\alpha)e\text{-}U_1\,(T_o\text{-}T_a)/I] \qquad (3.11)$$

Thermal efficiency can also be expressed by the another equation in terms of temperature rise working fluids (air) as:

$$\eta = GC_p(T_o-T_{fi})/I \quad (3.12)$$

Where, G is the mass flow rate per unit area

Infact, when the collector work on an open cycle, drawing external air, a configuration often utilized for air heaters only, inlet temperature coincides with the environmental temperature(T-T). Under this working condition, eqn.(3.10) cannot be very useful since the equation of the efficiency reduces to, $\eta= F_R(\tau\alpha)e$. Indeed, this expression does not allow the areal operative temperature to be show and it therefore proves to be less efficiency's than eq. (3.11).

For an open cycle air heater temperature rise parameter contained in eq. (3.11) as well as eq.(3.12) coincide, $(T_o-T_a)/I = (T_o-T_{fi})/I$. Thus eq. (3.11) and (3.12) can be represented on a single diagram having shown the typical performance η and $(T_o-T_{fi})/I$ for variation of G. The most suitable way to describe the working behaviour of air heaters.

Such plots apparently are efficiency versus efficiency and these are straight lines with a slope of constant fluid capacitance rate (i.e.GC_p, the flow rate per unit area time's specific heat) but the actual location of point is important . The designer has to use the actual operating conditions.

In the case of air recycling (i.e.$T_{fi}>T_a$), a series of efficiency curves are obtained for different mass flow rate but for the case when there is no air recycling all the performance curve is obtained as a result of bet curve of the experimental data.

CHAPTER 4

(RESEARCH TOOL)

Response Surface Methodology

4.1 Response Surface Methodology (R.S.M.)

Response surface methodology (RSM) is a collection of mathematical and statistical techniques useful for analyzing problems in which several independent variables influence a dependent variable or response, and the goal is to optimize this response [29]. In many experimental conditions, it is possible to represent independent factors in quantitative form as given in Equation 4.4. Then these factors can be thought of as having a functional relationship with a response as follows:

$Y = \phi(x_1, x_2, \ldots\ldots\ldots\ldots, x_k) \pm e_r$	**(4.1)**

This represents the relation between response Y and x_1, $x_2, \ldots, x_k$ of k quantitative factors. The function Φ is called response surface or response function. The residual e_r measures the experimental errors [15]. For a given set of independent variables, a characteristic surface is responded. When the mathematical form of Φ is not known, it can be approximated satisfactorily within the experimental region by a polynomial. Higher the degree of the polynomial, better is the correlation but at the same time costs of experimentation become higher.

For the present work, RSM has been applied for developing the mathematical models in the form of multiple regression equations for the efficiency of solar air heater. In applying the response surface methodology, the dependent variable is seen as a surface to which a mathematical model is fitted. For the development of regression equations related to various parameters effecting the efficiency of solar air heater, the second order response surface has been assumed as: “

"This assumed surface Y contains linear, squared and cross product terms of variables x_i"s. In order to estimate the regression coefficients, a number of experimental design techniques are available. Box and Hunter have proposed that the scheme based on central composite rotatable design fits the second-order response surfaces quite accurately[25]. "

4.2 Central Composite Second order Rotatable Design

In this design, the standard error remains the same at all the points which are middle from the center of the region. This criterion of rotatability could be explained as follows: Let the point (0, 0, ---, 0) symbolize the center of the region in which the relation between Y and X is under investigation. From the results of any experiment, the standard error, e_r of Y can be computed at any point on the fitted surface. This standard error acts as a meaning of the co-ordinates x_i"s of the point[30]. Because of rotatability form, this standard error is same at all equidistant points with the distance ρ from the center of region i.e. for all points, which satisfy the following equation:

$$X_1^2 + X_2^2 + \ldots\ldots\ldots\ldots\ldots + X_k^2 = \rho^2 = \text{constant} \quad \textbf{(4.2)}$$

The Central composite rotatable design is subdivided into the following three parts:

- Points related to 2^k design, where k is the number of parameters and 2 is the number of levels at which the parameters is kept during testing
- Extra points called star points positioned on the co-ordinates axes to form a central composite design with a star arm of size α
- Few more points added at the center to give roughly equal precision for response Y with a circle of radius one

The factor α is the radius of the circle or sphere on which the star points lie. With k ≥5 the experimental size is reduced by using half replication of 2^k factorial design. With half replication, α become $2^{(k-1)/4}$. Also, no duplication is needed to find error mean square since this can be found out by replicating the center points. The components of middle composite second order rotatable design for a different number of variables are given in Table 4.1.[22]

Table 4.1: Components of Central Composite Second Order Rotatable Design (Cochran and Cox, 1962)

Variables (k)	Factorial Point (2^k)	Star Point (2k)	Center Points (n)	Total (N)	Value of α
3	8	6	6	20	1.682
4**	8*	8	5	21	1.682
5	16	10	6	32	2.000
6	32	12	9	53	2.378
*Small repletion, ** This row is used in present work					

4.3 Estimation of the Coefficients

As stated earlier the regression equation demonstrating second order response surface has been assumed as (Eq. 4.13):

Where Y is the estimated response, b‟s are the coefficients and x_i‟s are the independent variables.

The method of least squares may be used to estimate the regression coefficients [16]Letx_{qi} denotes the q^{th} observation of the variable x_i and N the total number of observations. Then the data for N observations in terms of various variables will appear as shown below:

Y	X_1	X_2	X_k	x_1^2	$x_2^{2..}$	x_k^2	$x_1x_2\ldots$	$x_{k-1}x_k$
Y_1	X_{11}	X_{12}	X_{1k}	X_{11}^2	X_{12}^2	X_{1k}^2	$X_{11}X_{12}$	$X_{1k-1}X_{1k}$
Y_2	X_{21}	X_{22}	X_{2k}	X_{21}^2	X_{22}^2	X_{2k}^2	$X_{21}\ X_{22}$	$X_{2k-1}X_{2k}$
Y_N	x_{N1}	x_{N2}	x_{Nk}	x_{N1}^2	x_{N2}^2	x_{Nk}^2	$x_{N1}x_{N2}$	$x_{Nk-1}x_{Nk}$

In terms of the q^{th} observation the Equation 4.5 can be written as:

Or

Where, q = 1, 2… N

The least square function is,

This function L is to be minimized with respect to b_0, b_1… This least square estimate of b_0, b_i, b_{ii} and b_{ij} must satisfy the following set of equations:

There are P = k+1 normal equations, one for each unknown regression equation coefficient. Hence, by solving the above equations the coefficients of the regression equation can be obtained.

It is simpler to solve the normal equations if they are expressed in matrix form. The second order response surface in matrix form may be written as:

$Y = \beta X + \varepsilon$	

Where

N = Total number of investigations P =

Total number of coefficients

Y is an (N × 1) vector of the observations, X is an (N × P) matrix of the levels of the independent variables, β is a (P × 1) vector of the regression coefficients and ε is a (N×1) vector of random errors.

The least square estimates must satisfy. This on simplification yields the values of different coefficients of regression.

4.4 Analysis of Variance

For the analysis of variance, the total sum of squares may be divided into four parts:

- The contribution due to the first order terms
- The contribution due to the second order terms
- A"Lack of fit" component which measures the deviations of the response from the fitted surface
- Experimental error which is obtained from the center points

The general formulae for the sum of squares are given in Table 5.2 .where, N is the total number of experimental points, n_0, Y_s, Y_0 represent a total number of observations, s^{th} response value and mean value of response respectively at the center points of the experimental region. The design matrix for five independent variables is shown in Table 4.3.

4.5 Significance Testing of the Coefficients

In order to determine the individual coefficients for significance, one has to set up a null hypothesis, which tests the estimated coefficients for the difference from its mean value using the student's t-test [16]. Where design is completely randomized, it may be shown that the analysis of variance could be used in place of t-test to compare two treatments. This is due to the reason that the one-tailed F-test with 1 and n degree of freedom (DOF) corresponds to the twotailed t-test with n degree of freedom i.e. $t^2 = F$ for 1 DOF. Hence, for the significance testing of individual coefficients, F-test with 1 and n_0 degree of freedom has been used, where n_0 is the total number of observations of the center point.

Table 4.2: Analysis of Variance for Central Composite Second Order Rotatable Design (Peng, 1967)

S No.	**Source**	**Sum of Square**	**Degree of Freedom**
1	First order terms		K
2	Second order terms		
3	Lack of fit	Found by subtraction	
4	Experimental Error		
5	Total		

The F ratio is given by:

Where,

= Regression coefficients 'ib

cii = Element of the error matrix 1' (−XX)

Se = Standard deviations of experimental error calculated from replicating observations at zero level as:

Where

$Y_s = s^{th}$ response value at the center

This calculated value of F can be compared with the theoretical value of F at 95% confidence level. If for a coefficient the computed value of F is greater than the theoretical value, then the effect of that term is significant. The insignificant second order terms can be deleted from the equations and remaining coefficients can be recalculated.

4.6 Adequacy of the Model

Once the co-efficient have been estimated and tested for their significance, the estimated regression equation is then tested for the adequacy of fit as follows

1. Find the residual sum of squares as:

Where yq"s are the observations at experimental points and is the mean of all observations. N is the total number of observations and k is the total number of variables. The number of degree of freedom for residual sum of squares will be:

2. From repeated observations at the center point, the error sum of squares can be found as

Where ys is the S^{th} response value at the center point is the mean of all the responses at the center point and n0 is the total number of experimental points at the center? The degree of freedom for error sum of squares is f2 = n0-1.

3. Find the inadequacy of fit sum of squares for which the number of degree of freedom is

4. Apply F- test to test the adequacy of fit as below

The estimated regression equation fits the data adequately if F<F0.05 (f3, f2) at 95% confidence level or if F< F0.99 (f3, f2) at 99% confidence level.

As intended earlier, both the stages of solar air heater i.e. plane bed and pack bed would be optimized. The independent variables were chosen from the preliminary studies conducted earlier which identified the most important factors affecting the efficiency of solar air heater. For the efficiency of plane and packed bed both, mass flow rate per unit area, outlet temperature, inlet temperature, insolation (in case of packed bed thickness of pebbles matrices) were considered as the parameters of importance. The design variables and levels are presented in table 4.3 & 4.4 for the finding the efficiency of solar air heater plane and packed bed both.

Table 4.3: Process Parameters and Their levels

Coded Factors	**Real factors**	**Parameters**	**Levels**				
			(-1.682)	(-1)	(0)	(+1)	(+1.682)
X_1	A	Mass Flow Rate Per Unit Area(kg/s-m^2)	1.62	3.5	6.25	9	10.87
X_2	B	Outlet Temperature (^{o}C)	0.16	0.5	1	1.5	1.84
X_3	C	Inlet Temperature (^{o}C)	19.54	40	70	100	120.45
X_4	D	Insolation (W/m^2)	31.47	40	52.5	65	73.52

Table 4.4: Process Parameters and Their Levels For Packedbed

Coded Factors	**Real factors**	**Parameters.**	**1**	**Levels**			
			(-1.682)	(-1)	(0)	(+1)	(+1.682)
X_1	A	Mass Flow Rate Per Unit Area(kg/s-m^2)	0.6	3.5	7.75	12	14.89
X_2	B	Outlet Temperature (°C)	0.16	0.5	1	1.5	1.84
X_3	C	Inlet Temperature (°C)	28.06	40	57.5	75	86.93
X_4	D	Insolation (W/m^2)	9.54	30	60	90	110.45
X_5	E	Thickness (mm)					

CHAPTER 5

(RESULTS AND DISCUSSION)

5. Result and Discussion:

A Total number of 21 and 26 investigations for plane and packed bed solar air heater respectively are performed and data are optimized using Response Surface Methodology (RSM). Process parameters such as mass flow rate per unit area, outlet temperature, inlet temperature and insolation, thickness for both plane and packed bed have been optimized. The studies on the efficiency of plane bed and packed bed solar air heater have been presented. The effect of thickness of the stone pebbles in packed bed plays a crucial role.

5.1 Optimization Results for Plane Bed:

As discussed in the previous section, mass flow rate per unit area, outlet temperature, inlet temperature and insolation are been considered as the factors and efficiency as the response in solar air heater.

A total number of 21 investigations were performed with various permutation and combinations of the factor s as indicated by the test matrix generated from the design experiment software. The results so obtained in the investigations were fed to the software again and the analysis of variance (ANOVA) table are generated.

Table 5.1: Analysis of Variance for Efficiency (Plane Bed)

ANOVA for Response Surface Reduced Quadratic model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		**Mean**	**F**	**p-value**	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	566.84	9	62.98	4.99	0.0075	significant
A-Mass flow rate per unit area	*24.06*	*1*	*24.06*	*1.91*	*0.1947*	
B-Outlet temperature	*118.34*	*1*	*118.34*	*9.38*	*0.0108*	
C-Inlet temperature	*13.75*	*1*	*13.75*	*1.09*	*0.3190*	
D-Insolation	*2.70*	*1*	*2.70*	*0.21*	*0.6529*	
AB	*2.39*	*1*	*2.39*	*0.19*	*0.6721*	
BD	*127.30*	*1*	*127.30*	*10.09*	*0.0088*	
A^2	*54.06*	*1*	*54.06*	*4.28*	*0.0628*	
C^2	*1.821E-004*	*1*	*1.821E-004*	*1.443E-005*	*0.9970*	
D^2	*7.82*	*1*	*7.82*	*0.62*	*0.4479*	
Residual	138.81	11	12.62			
Lack of Fit	*124.01*	*7*	*17.72*	*4.79*	*0.0746*	*not significant*
Pure Error	*14.80*	*4*	*3.70*			
Cor Total	705.65	20				

The Model F-value of 4.99 implies the model is significant. There is onlya 0.75% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case B, BD are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 4.79 implies there is a 7.46% chance that a "Lack of Fit F- value" this large could occur due to noise. Lack of fit is bad -- we want the model to fit. This relatively low probability (<10%) is troubling.

Table 5.4: Statistical values of the Efficiency of solar air heater (Plane Bed)

Std. Dev.	**3.55**		**R-Squared**	**0.8033**
Mean	49.50		Adj R-Squared	0.6423
C.V. %	7.18		Pred R-Squared	-0.8925
PRESS	1335.47		Adeq Precision	8.641
-2 Log Likelihood	99.26		BIC	129.70
			AICc	141.26

A negative "Pred R-Squared" implies that the overall mean may be a better predictor of your response than the current model. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Hence the ratio of 8.641 indicates an adequate signal. This model can be used to navigate the design space.

5.1.1. Final Equation in Terms of Coded Factors:

$$\text{Efficiency} = +47.68+2.00 * A +4.51* B +1.22 * C -0.99* D +1.15 * AB +6.87* BD +1.91* A^2 - 3.770E\text{-}003* C^2 +1.06 * D^2 \quad (6.1)$$

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels of the factors are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

5.1.2 Final Equation in Terms of Actual Factors:

$$\text{Efficiency} = +217.94305 - 1893.51453 * A - 3.90110 * B + 0.25121 * C - 0.22660 * D + 15.72519 * AB + 5.10530E\text{-}003 * BD + 20048.05405 * A^2 - 1.50796E\text{-}004 * C^2 + 3.28951E\text{-}005 * D^2 \qquad (6.2)$$

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space.

Proceed to Diagnostic Plots (the next icon in progression). Be sure to look at the:

1) Normal probability plot of the studentized residuals to check for normality of residuals.

2) Studentized residuals versus predicted values to check for constant error.

3) Externally Studentized Residuals to look for outliers, i.e., influential values.

4) Box-Cox plot for power transformations.

If all the model statistics and diagnostic plots are OK, finish up with the Model Graphs icons

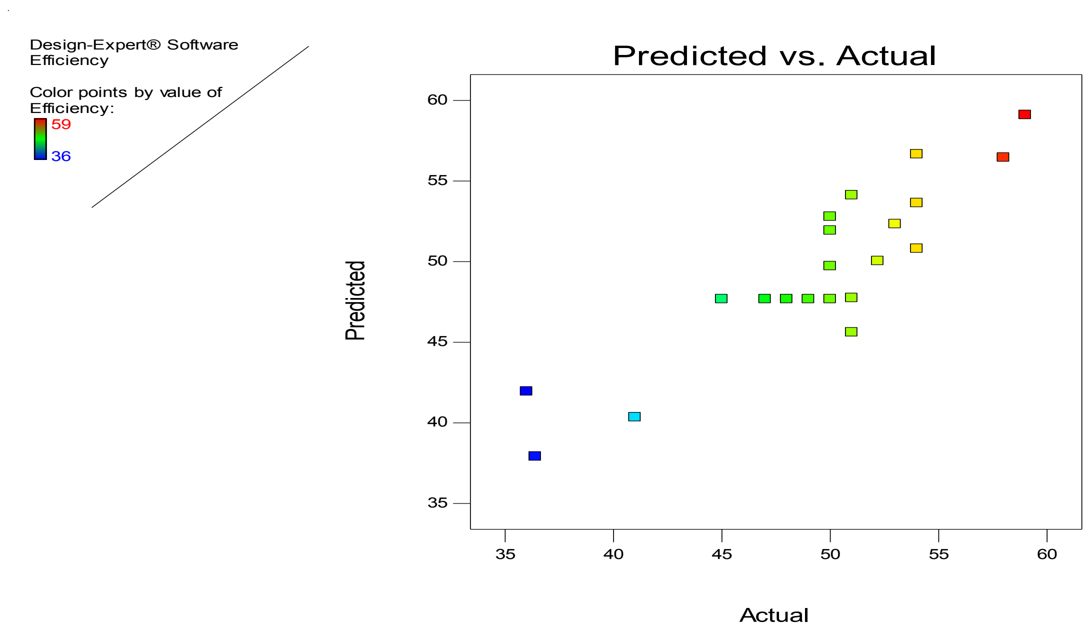

Figure 5.1: Predicted and observed Values for Efficiency of Plane Bed Solar air Heater

5.1.3 Comparison between Actual and Predicted Responses:

Figure 5.1 shows, the actual experimental values obtained and the predicted values from the surface response method for the plane bed solar air heater. From the figure 6.1, the percentage of error for all data is in the range of 14 %. Hence it is concluded that the experimental values ranges from each response. The advantageous range leads close to zero (because the zero value mean the predicted equals to the actual value obtained).The focus was for maximizing the efficiency for the plane bed solar air heater. Taken the journey from the actual condition , I reached to diminishes the losses against the system and I finally reach close to the range of 14% desirability.

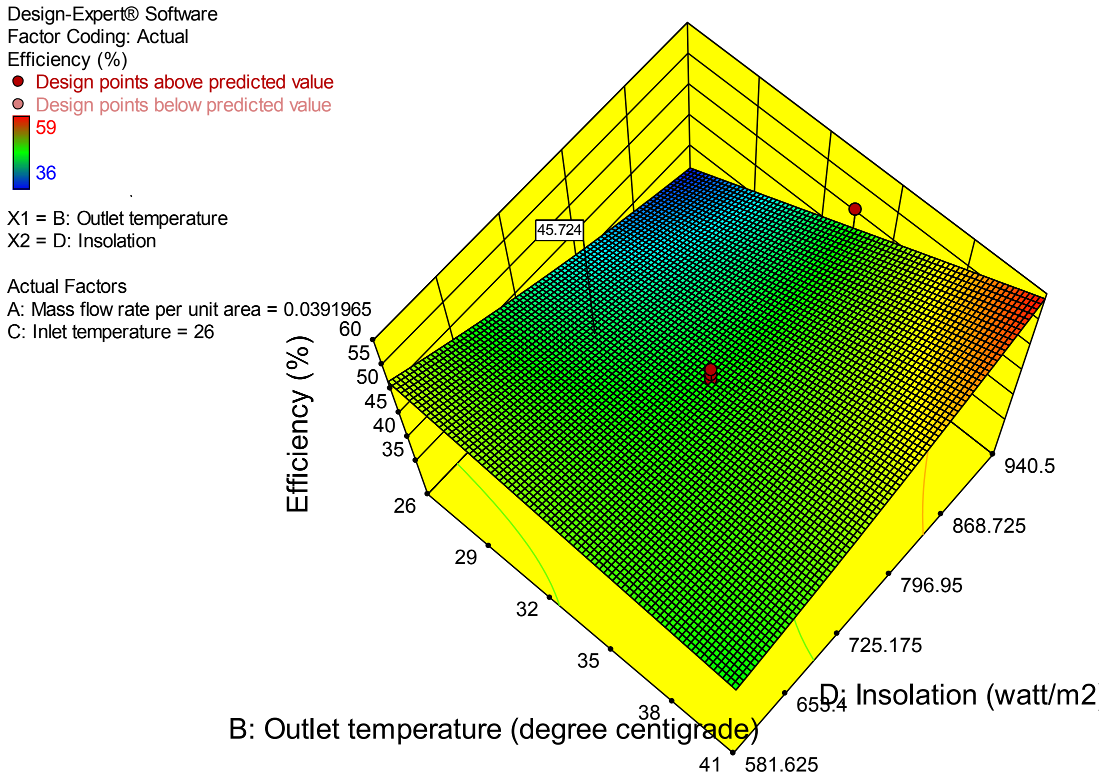

Figure 5.2: Response Plot For outlet Temperature and Insolation on Efficiency

5.1.4 Effect of Mass Flow Rate on Efficiency:

The Result of mass flow rate per unit area per unit time in the plane bed solar air heater on efficiency as shown in figure 5.2. It is apparent that as the mass flow rate increases, the efficiency of the solar air heater of plane bed increases. This is due to the fact that concomitant increases in pressure drop, proportional to the velocity which in turn increases the mass flow rate.

The optimum value obtained for the mass flow rate corresponding to the efficiency and outlet temperature is in between 0.0391965 kg/m^2-s.

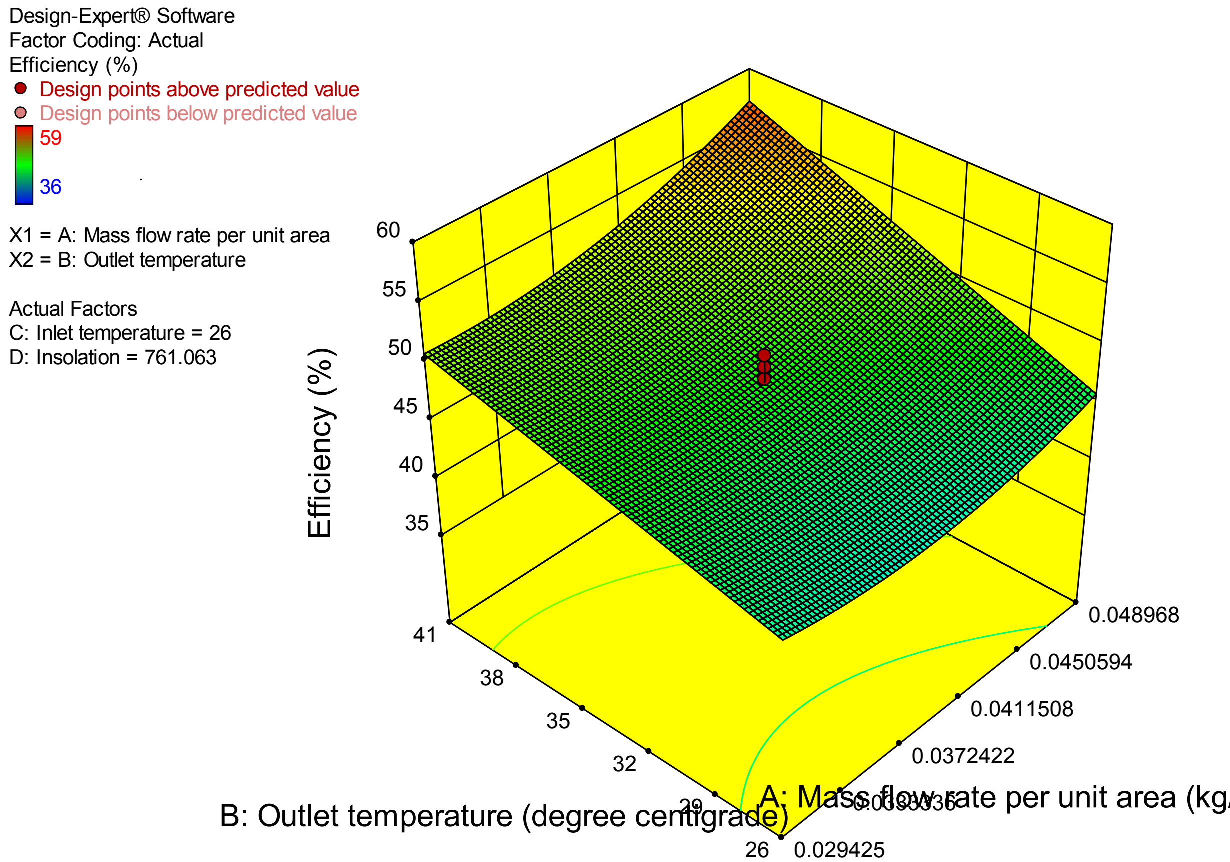

Figure 5.3: Response Plot For Effect of outlet Temperature and Mass Flow Rate on Efficiency

5.1.5 Effect of outlet Temperature on Efficiency:

The Effect of outlet temperature on efficiency in the plane bed solar air heater a shown in figure 5.3. It is apparent that as the outlet temperature increases, the efficiency of the system increases. This is due to the fact that as the outlet temperature increases kept the inlet temperature constant, the temperature difference in the efficiency term increases which in turn increases the heat gain by the flowing air or we can say that the increase in in the available energy of the flowing air, This leads to the increase in efficiency of the plane bed solar air heater.

The optimum value obtained for the outlet temperature with respect to the efficiency, mass flow rate per unit area per unit time and insolation is around 35°C.

5.1.6 Effect of Insolation on Efficiency:

The effect of insolation on efficiency as shown in figure 5.3. Insolation is the amount of the solar radiation reaches on given surface area. As the insolation , the efficiency of the system decreases , this is due to the fact that , the insolation has the inverse relationship with respect to the efficiency , here we put the input source in the form of insolation to transfer the energy into flowing medium. Insolation is lost due to various factors such as absorptivity, transmissivity and reflectivity factors.

The optimum value of insolation with respect to the efficiency, outlet temperature, and mass flow rate is close to 761.063 W/m^2.

5.2 Optimization Result for Packed Bed:

As discussed in the previous section, mass flow rate per unit area, outlet temperature, inlet temperature, insolation and thickness of bed have been considered as the factors and efficiency as the response in solar air heater.

A total number of 26 investigations were performed with various permutation and combinations of the factor s as indicated by the test matrix generated from the design experiment software. The results so obtained in the investigations were fed to the software again and the analysis of variance (ANOVA) table are generated.

Table 5.3: Analysis of Variance for Efficiency (Packed Bed)

ANOVA for Response Surface Reduced Quadratic model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		**Mean**	**F**	**p-value**	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	1579.16	12	131.60	11.03	< 0.0001	significant
A-mass flow rate per unit area	*9.67*	*1*	*9.67*	*0.81*	*0.3842*	
B-outlet temperature	*1.08*	*1*	*1.08*	*0.090*	*0.7683*	
C-inlet temperature	*13.36*	*1*	*13.36*	*1.12*	*0.3091*	
D-insolation	*27.51*	*1*	*27.51*	*2.31*	*0.1527*	
E-thickness	*87.83*	*1*	*87.83*	*7.36*	*0.0177*	
AB	*70.18*	*1*	*70.18*	*5.88*	*0.0306*	
BC	*359.09*	*1*	*359.09*	*30.11*	*0.0001*	
BD	*168.20*	*1*	*168.20*	*14.10*	*0.0024*	
CD	*36.08*	*1*	*36.08*	*3.03*	*0.1056*	
DE	*107.77*	*1*	*107.77*	*9.04*	*0.0101*	
B^2	*371.05*	*1*	*371.05*	*31.11*	*< 0.0001*	
D^2	*489.41*	*1*	*489.41*	*41.04*	*< 0.0001*	
Residual	155.03	13	11.93			
Lack of Fit	*127.84*	*9*	*14.20*	*2.09*	*0.2487*	*not significant*
Pure Error	*27.19*	*4*	*6.80*			
Cor Total	1734.19	25				

The Model F-value of 11.03 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case E, AB, BC, BD, DE, B^2, D^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 2.09 implies the Lack of Fit is not significant relative to the pure error. There is a 24.87% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Table 5.4: Statistical values of the Efficiency of solar air heater (Packed bed)

Std. Dev.	**3.45**		**R-Squared**	**0.9106**
Mean	55.43		Adj R-Squared	0.8281
C.V. %	6.23		Pred R-Squared	0.3138
PRESS	1189.98		Adeq Precision	13.838
-2 Log Likelihood	120.21		BIC	162.56
			AICc	176.54

The "Pred R-Squared" of 0.3138 is not as close to the "Adj R-Squared" of 0.8281 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 13.838 indicates an adequate signal. This model can be used to navigate the design space.

5.2.1 Final Equation in Terms of Coded Factors:

Efficiency = +54.67 + 0.91 * A –0.28*B –0.97*C –1.43*D –2.73*E –3.39*AB –7.19*BC –4.64*BD –2.28*CD +4.20 *DE –4.21*B^2 +4.84* D^2 (5.3)

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels of the factors are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

5.2.2 Final Equation in Terms of Actual Factors:

Efficiency = -246.46713 +1654.64966 * A +13.19409 * B +7.46700 * C –0.10579 * E –43.38924 * AB –0.16348 * BC –3.23242E-003 * AD –2.31028E-003*CD+1.56167E-003 * DE –0.065783 * B^2 **+**1.50172E-004 * D^2 (5.4)

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor Because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space.

Proceed to Diagnostic Plots (the next icon in progression). Be sure to look at the:

1) Normal probability plot of the studentized residuals to check for normality of residuals.

2) Studentized residuals versus predicted values to check for constant error.

3) Externally Studentized Residuals to look for outliers, i.e., influential values.

4) Box-Cox plot for power transformations.

If all the model statistics and diagnostic plots are OK, finish up with the Model Graphs icon.

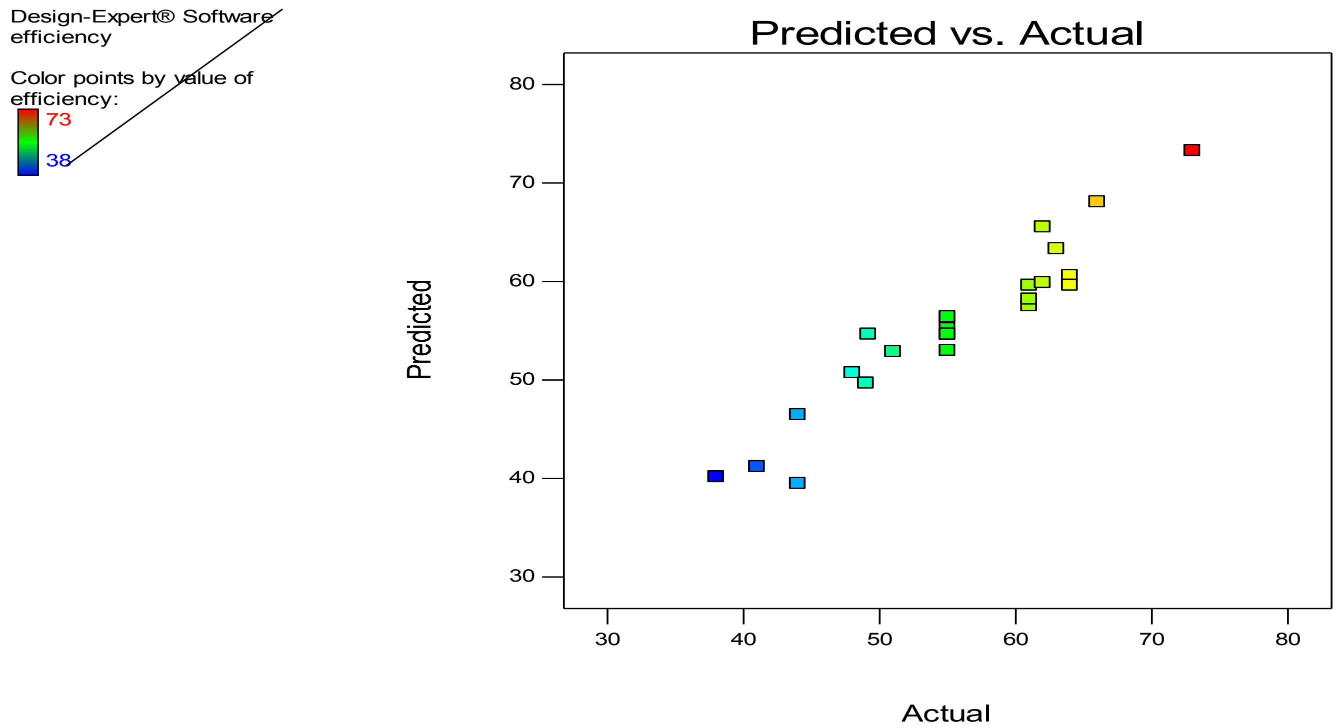

Figure 5.4: Predicted and observed Values for Efficiency of Solar air Heater for Packed Bed

5.2.3 Comparison between Actual and Predicted Responses:

Figure shows 5.4, the actual experimental values obtained and the predicted values from the a surface response method for the plane bed solar air heater. From the figure, the percentage of error for all data is in the range of 10 %. Hence it is concluded that the experimental values ranges from each response. The advantageous range leads close to zero (because the zero value mean the predicted equals to the actual value obtained).The focus was for maximizing the efficiency for the plane bed solar air heater. Taken the journey from the actual condition, I reached to diminish the losses against the system and I finally reach close to the range of 10% desirability.

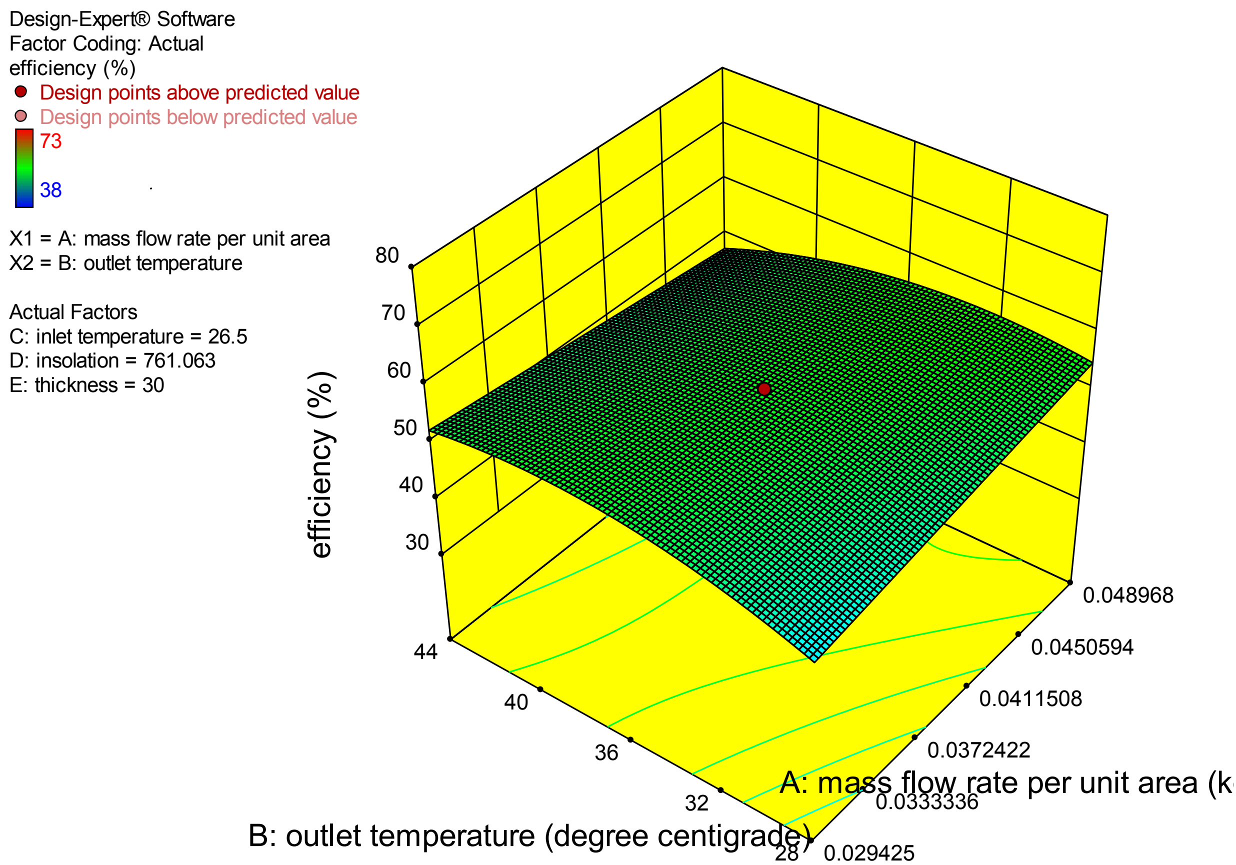

Figure 5.5: Response Plot for Effect of outlet Temperature and Mass Flow Rate on Efficiency

5.2.4 Effect of Mass Flow Rate on Efficiency:

The Result of mass flow rate per unit area per unit time in the packed bed solar air heater on efficiency as shown in figure 5.5. It is apparent that as the mass flow rate increases, the efficiency of the solar air heater of packed bed increases as same as conventional plane bed solar air heater. This is due to the fact that concomitant increases in pressure drop, proportional to the velocity which in turn increases the mass flow rate but the change is that the system has the packed bed using stone pebbles that will leads to the outlet temperature to be more due to enhancement of the addition of heat to the flowing air by means of convection heat transfer through stone pebbles.

The optimum value obtained for the mass flow rate corresponding to the efficiency and outlet temperature is in between 0.0391965 kg/m^2-s.

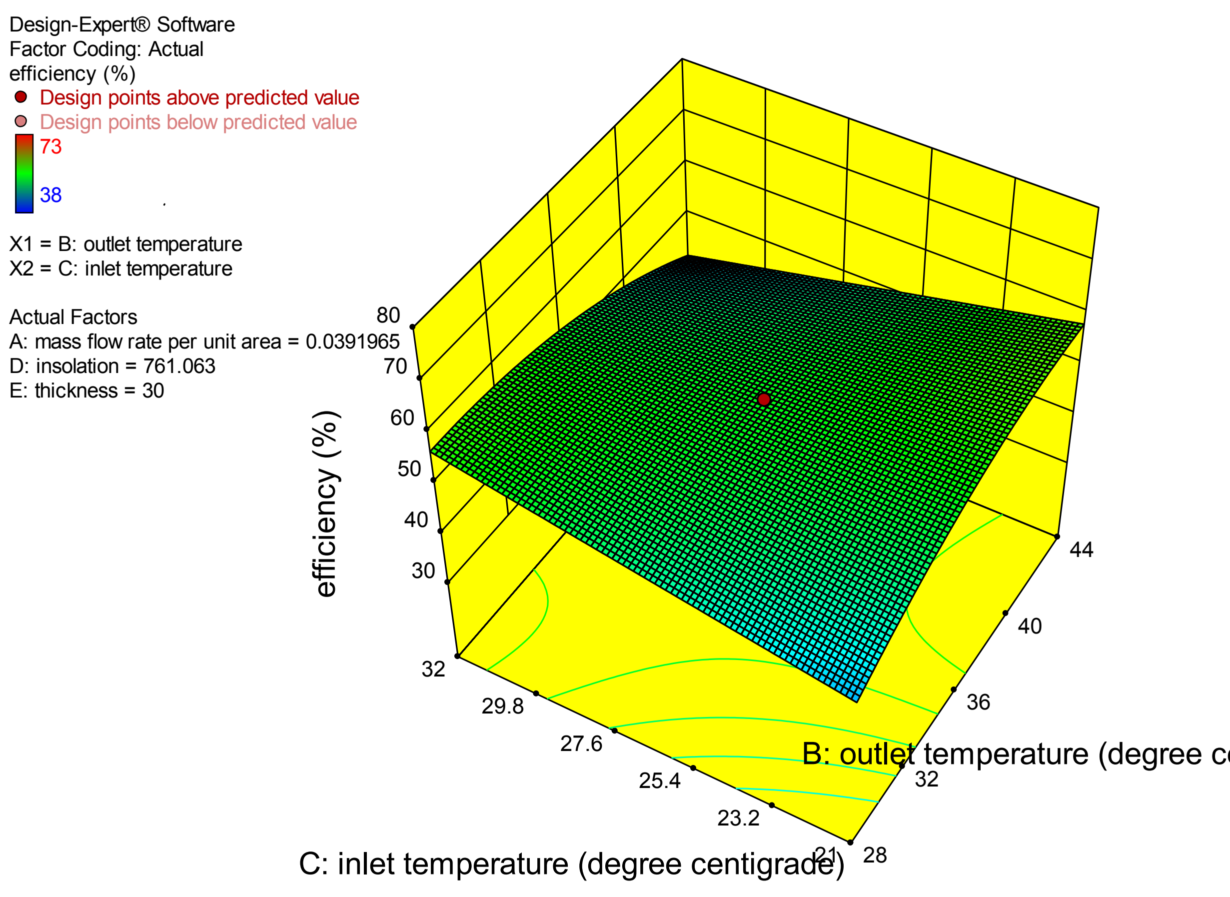

Figure 5.6: Response Plot for Effect Inlet and outlet Temperature on Efficiency

5.2.5 Effect of outlet Temperature on Efficiency :

The Effect of outlet temperature on efficiency in the packed bed solar air heater a shown in figure 5.6. It is apparent that as the outlet temperature increases, the efficiency of the system increases. This is due to the fact that as the outlet temperature increases kept the inlet temperature constant, the temperature difference in the efficiency term increases which in turn increases the heat gain by the flowing air or we can say that the increase in in the available energy of the flowing air, This leads to the increase in efficiency of the plane bed solar air heater. As compare to the outlet temperature obtained in the plane bed , we have gain the outlet temperature in packed bed due to the addition heat transfer between air and the stone pebbles.

The optimum value obtained for the outlet temperature with respect to the efficiency, mass flow rate per unit area per unit time and insolation is around 38.5°C.

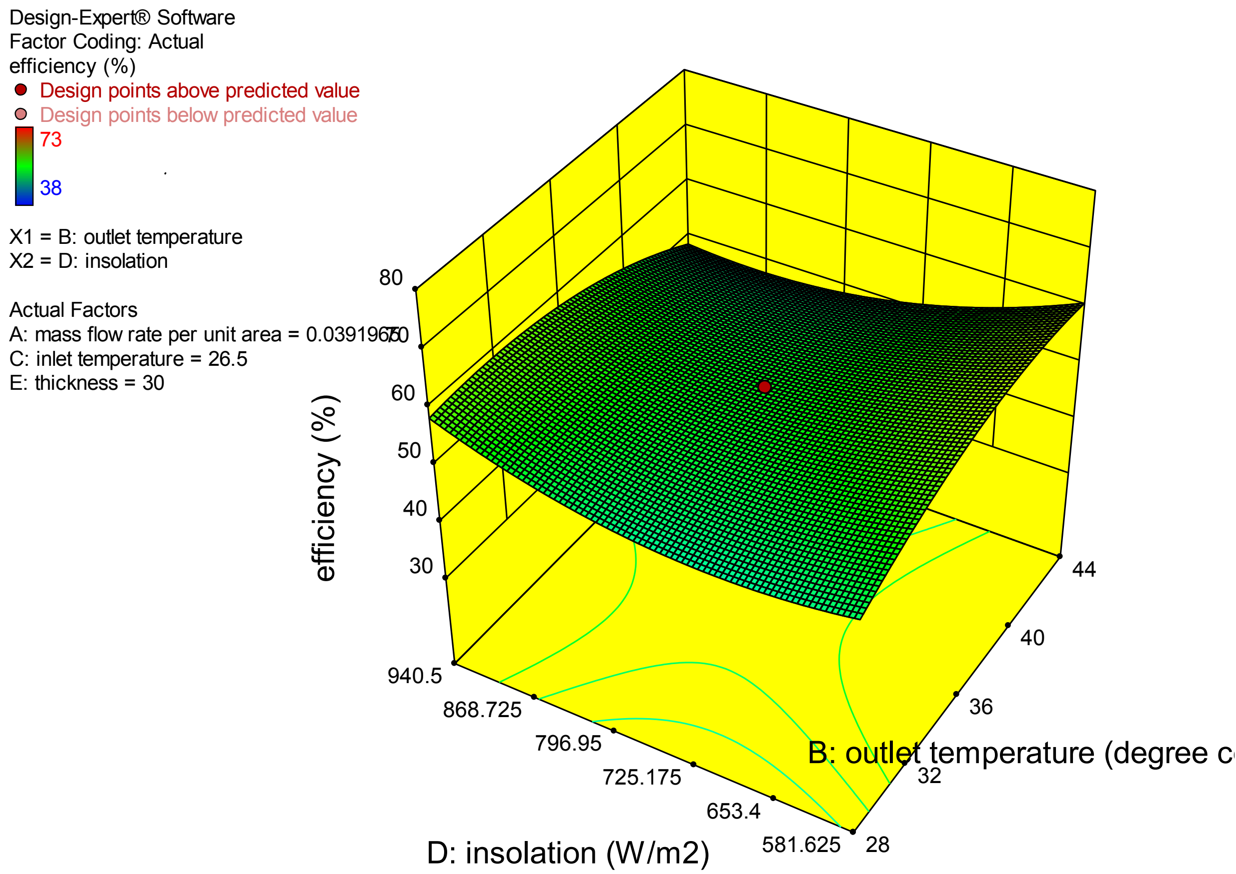

Figure 5.7: Response Plot for Effect of Insolation and outlet Temperature on Efficiency

5.2.6 Effect Of Insolation On Efficiency:

The effect of insolation on efficiency as shown in figure 5.7. Insolation is the amount of the solar radiation reaches on given surface area. As the insolation , the efficiency of the system decreases , this is due to the fact that , the insolation has the inverse relationship with respect to the efficiency , here we put the input source in the form of insolation to transfer the energy into flowing medium. Insolation is lost due to various factors such as absorptivity, transmissivity and reflectivity factors. As compare to the plane bed , packed bed has the high utilization factor for insolation because of the fact that the insolation is used to heat the air directly by radiation mode but also by means of the convection through the stone pebbles thickness which is in contact due to the temperature difference created between them.

The optimum value of insolation with respect to the efficiency, outlet temperature, and mass flow rate is close to 761.063 W/m².

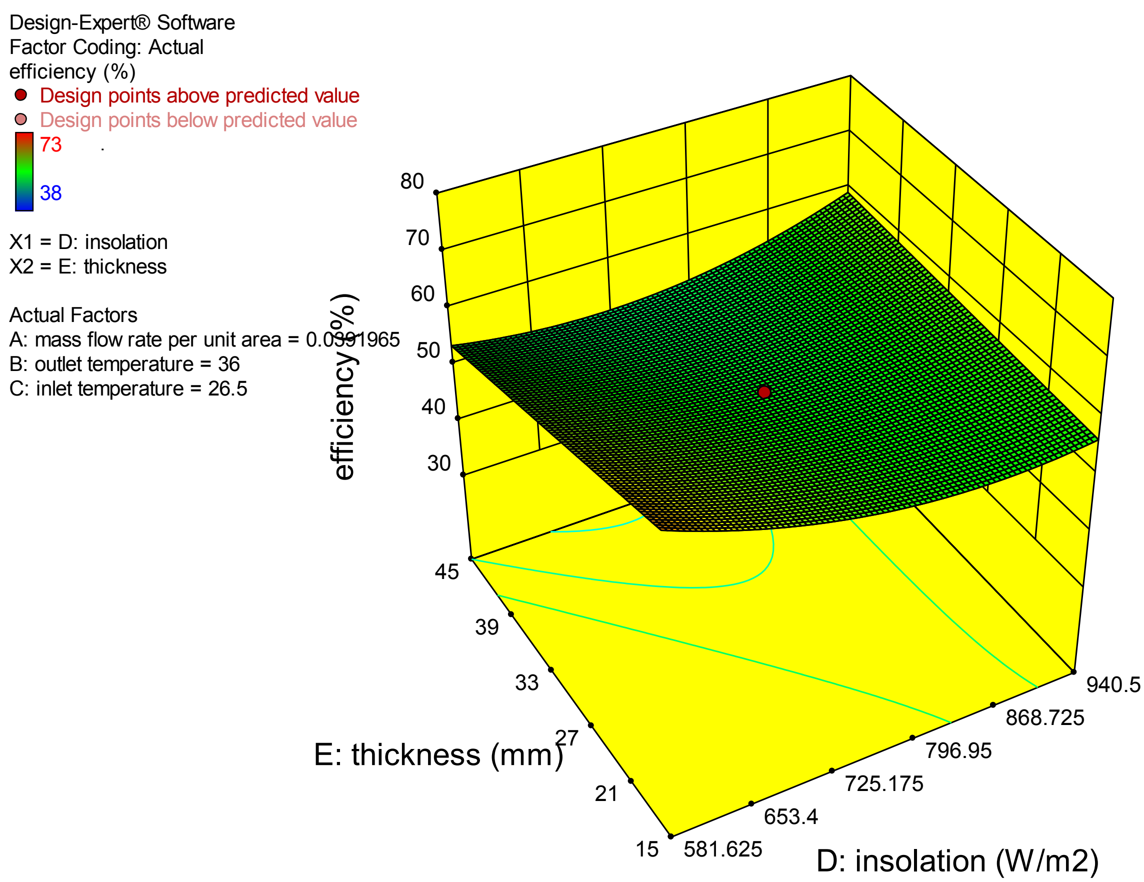

Figure 5.8: Response Plot for Effect of Thickness and Insolation on Efficiency

5.2.7 Effect of the Thickness of Stone Pebbles on Efficiency:

The effect of insolation on efficiency as shown in figure 5.8. The experiment was performed taking different iterations of thickness of the bed for. The efficiency was found highest at 30mm thickness of the bed. This will be optimized thickness of the bed. The reason for getting maximum efficiency at 30mm is that the solar flux is absorbed by the bed homogeneously due to which the upper temperature of the bed will be lower and the efficiency is higher. But at 15mm thickness of the bed the absorption of the solar flux will be by the bed material and the back plate of the bed and the upper temperature will be higher and in effect the upper loss will be higher and the efficiency will be low. Similarly when the thickness of bed is 45mm, the solar flux will be absorbed by the packing material and it will not reach the back plate so the heating will not be homogeneous throughout the bed and thereby surface temperature is higher and consequently the upper losses is higher and again the efficiency will be low.

5.3 Sample Calculation:

The calculation procedure employed for the data reduction and the results of the table correspond to set of observations record at 12:30pm

(i) Length of the bed (L) = 1.5m

(ii) Breadth of the bed (b) = 0.49m

(iii) Area of the Bed (A_c) = L*B = .735 m^2

(a) Mass Flow Rate:

For the observed pressure drop of 90mm of water across orifice meter, the throat air velocity (V_2) can be calculated from equation.

$$V_2 = [2g\rho_w(P_1-P_2) / \{\rho_a(1-\beta_o^4)\}]^{1/2}$$

Where

β_o = the ratio of diameter of orifice meter to diameter of pipe = 0.5

$\Delta P = P_1 - P_2$ = difference of pressure in mm of the water column.

Mass Flow Rate (m) = $C_d \rho_a A_2 V_2$

The value of C_d for this case has been obtained which is given as 0.61.

Mass flow Rate per unit area (G) = m/A_c

G_{pb} = 0.0391965 kg/m^2-s

G_p = 0.0391965 kg/m^2-s

(b) Temperature Rise of Air :

The difference between the outlet and inlet temperature of air across packed and plane bed can be expressed as:

$\Delta t_{pb} = (t_o - t_i) = 38.5 - 26 = 12.5\ ^oC$ (for packed bed collector)

$\Delta t_p = (t_o - t_i) = 36 - 26 = 10\ ^oC$ (for plane bed collector)

(c)Efficiency of the collector:

The collector Efficiency

$$\eta = (GC_p \Delta t)/I$$

Where,

I = Intensity of Solar Radiation

C_p = 1005 J/kg-K

For Plane Bed

$$\eta_p = (GC_p \Delta t)/I = 0.51759818$$

For Packed Bed

$$\eta_{pb} = (GC_p\Delta t)/I = 0.64463745$$

(d) Enhancement Factor (E.F.) :

The ratio of thermal efficiency of packed bed to that of plane bed collector can be expressed in terms of enhancement factor.

$$E.F. = \eta_{pb} / \eta_p = 1.2583$$

Conclusions:

The following conclusions can be drawn on the basis of the investigations carried out in connection with the performance of packed bed solar air heater:

(i) It has been found that enhancement of efficiency is a strong function of mass flow rate and the porosity of the bed.The bed with lowest value of porosity, viz. 0.652 has the best therma l performance with efficiency lying between 51% to 65%.

(ii) Thermal performance of solar air heater considerably enhanced by packing its duct with bed of blackened absorber stone pebbles and this enhanced is a strong function of system and operating parameters. Packed bed solar air heater gave enhancement factor in thermal efficiency in the range of 1.25 the maximum value of this ratio being for 30mm thickness of the bed.

(iii) It has been found that the efficiency of packed bed solar air heater is strong function of geometrical parameters viz. Bed depth to element size ratio, porosity and the friction coefficient of the absorber matrix.

(iv) The analysis was performed taking different iterations of thickness of the bed. The efficiency was found highest at 30mm thickness of the bed. This is the optimized thickness of the bed. The reason for getting maximum efficiency at 30mm is that the solar flux is absorbed by the bed homogeneously due to which the upper temperature of the bed will be lower and the efficiency is higher. But at 15mm thickness of the bed the absorption of the solar flux will be by the bed material and the back plate of the bed and the upper temperature will be higher and in effect the upper loss will be higher and the efficiency will be low. Similarly when the thickness of bed is 45mm, the solar flux will be absorbed by the packing material and it will not reach the back plate so the heating will not be homogeneous throughout the bed and thereby surface temperature is higher and consequently the upper losses is higher and again the efficiency will be low.

(v) It has been found that the efficiency of the solar air heater increases with the increase in mass flow rate per unit area. This is due to the fact that as the mass flow rate increases, the velocity of air increases and hence turbulence increases and the heat transfer coefficient increases. Thus more energy is transferred to the air, leading to lower absorber plate temperature and hence less energy loss from the heater surface to the atmosphere.

(vi) It has been found that the air temperature rise parameter ($\Delta t/I$) decreases with increase in mass flow rate. This is because of relatively higher rate of energy collection as a result of higher heat transfer rates and relatively lesser thermal losses.

It can therefore be summarized that the thermal performance of solar air heater can be substantially enhanced by using packed bed solar air heater and that this enhancement is a strong function of geometrical parameters.

Future Scope:

(i) The present work was carried on thickness of stone pebbles as absorber material of packed bed solar heater. However there is need to consider other factors that are also responsible to the enhance the efficiency beyond this limit such as heat transfer coefficient, Absorber material properties, variability of heat transfer area, Shape of the solar air heater.

(ii) In the present work, we focus on the radiation mode of heat transfer. However, in future we have to focus on enhance the rate of heat transfer through mode of convection and conduction by optimizing the various parameters.

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