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Experimental Investigation & Performance Analysis of Flat Plate Collector by Response Surface Method

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ABSTRACT

The optimization of flat plate collector performance by using L_{27} Orthogonal array and Response surface method in experimental investigation and performance analysis respectively is presented. The parameters such as the position of collector surface with respect to sun i.e. Tilting angle(AR), Processing time(TM) measured in 24 hr clock and the Water quality (WT) are considered as independent parameters and the O/P parameters related with FPC performance are the efficiency of FPC, Water outlet temperature (WT) and the Total heat energy(gain). The experiments conducted are based on three parameters, three level, central composite faced centered design with mathematical model and sensitivity analysis is carried out to identify the critical parameters

***Keywords*— Flat plate collector, Performance analysis, Response surface method, Taguchi Approach.**

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I. INTRODUCTION

Solar energy is the most readily available source of energy. If the means to make efficient use of solar energy could be found, it would reduce our dependence on non-renewable sources of energy and make our environment cleaner. Harnessing this abundance of sunshine would make a noticeable impact. Owing to its abundant quantity, solar energy is promising as energy to replace fossil fuel. However, it is a weak source and its maximum energy density is merely about 1000 watts/m^2 even when the sun is at the zenith. Therefore, for the utilization of solar energy, its efficient concentration is required. Solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert and distribute solar energy. Active solar techniques include the use of photovoltaic panels and solar thermal collectors to harness the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air.

With the increasing population and industrialization, there is need to cut down the load of fossil fuels and to reduce environmental pollution. Unlike conventional energy utilization, solar energy is free of connections, unlimited supply of source and also decease gas emission. Solar energy investments in developing countries are imperative to avoid an energy crisis arising from over-dependence on fossil fuels. The situation is critical because fossil fuels are finite and fast depleting. Various industrial surveys show that up to 24 percent of all industrial heat, directly used in the processes, is at temperatures from ambient to 180 °C. In several industries, 100 percent process heat requirement is below 180 °C which can be supplied economically by evacuated tube collectors and solar concentrators. From a number of studies on industrial heat demand, several industrial sectors have been identified with favorable conditions for the application of solar energy. The most important industrial processes using heat at mean temperature level are: sterilizing, extraction, pasteurizing, drying, solar cooling and air conditioning, hydrolyzing, distillation and evaporation, washing and cleaning, and polymerization.

Many methods are suggested to keep water temperature at a satisfactory level. Among them, the use of a selective absorber that reduces radiation thermal losses and double glazing, transparent insulation, and inverted or evacuated absorber to suppress convection thermal losses are suggested methods that preserve water storage heat. A flat plate surface solar collector of dimension, hinged on a horizontal support for quick adjustment of inclination from 0 to 90^o is fabricated, marked out at 10 intervals on a telescopic leg graduated in degrees. Measurement of the solar radiation, varying degrees of inclination will taken between 10:00 Morning to 5:00 pm for 40 days at clear sky hours, within the week of nth day of the year. The measurements will made for Dec. to March of the year in Indian scenario. At each degree of inclination, the solar radiation intensity will value will be taken.

The flat plate will set truly facing south with an engineering prismatic compass. Use of Solar panel is one of the various methods of harvesting the solar energy. These works will focused about having scope for field data based modeling to establish relationship in different variables of solar panel. Solar panel is studied with a typical experimental plan of simultaneous variation of independent variables. The Solar panel can be used for the supply of hot water for domestic purposes. These systems have one water storage tank which performs dual function of absorbing solar radiation and preserving heat of water. The Solar panel used is having an area that sunlight that falls onto this Solar panel. The focus is located on the axis of rotation to prevent it from moving when the Solar panel rotates. During the day concentrated light rotated around its own centre but does not move sideways in any direction and by this way the focus stays fixed. At the focus it has a container to hold some liter water. The Solar panel is brought to its normal position every morning by operator.

II. THEORY

Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate. These collectors heat liquid or air at temperatures less than 80°C.

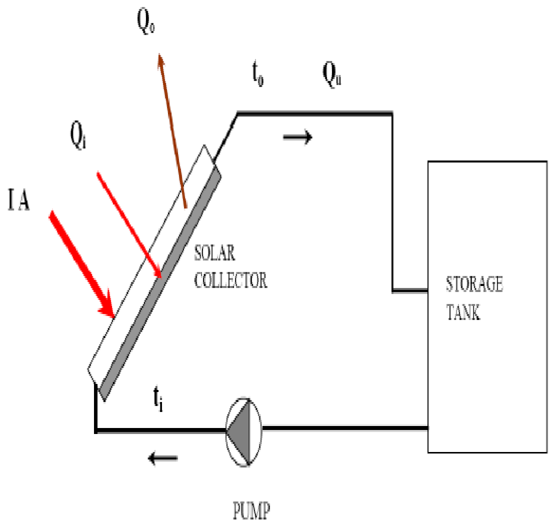

Fig.1: Flat Plate Collector

As seen in Fig. 1, a flat-plate collector consists basically of an insulated metal box with a glass or plastic cover (the glazing) and a dark-colored absorber plate. Solar radiation is absorbed by the absorber plate and transferred to a fluid that circulates through the collector in tubes.

Several researches are concerned with developing and/or analyzing existing solar thermal systems [3–11]. For example a comparison of performance and cost effectiveness of solar water heaters at deferent collector tracking modes in has been performed [3]. The thermal performance of differently designed solar heating systems including three solar combi systems, four marketed flat plate solar collectors and one marketed evacuated tubular solar collector is calculated with weather data. Experimental investigation of the overall performance of solar collectors under local weather conditions of Lebanon as encountered along the eastern coast of the Mediterranean Sea is carried out for two kinds of evacuated tube solar collectors, namely, the water-in-glass tubes and the heat-pipe designs [5]. In Turkey four solar air collectors: a finned collector with an angle of 75˚, a finned collector with an angle of70˚, a collector with tubes, and a base collector were tested. After that a comparison is made among them on the basis of first and second law efficiencies [6]. Most common types of solar collectors are presented in Ref. [7].The performance of a solar flat-plate thermal collector wholly manufactured in a copolymer material in low flow conditions [8]; solar collectors that are able to provide both hot water and hot air to increase annual thermal conversion ration of solar energy [9]; steady-state and quasidynamic test methods both for flat plate and evacuated tube collectors [10] and Neural network approach to determine the efficiency of flat-plate solar collectors [11].

Solar water heating for domestic purposes is at present the most attractive way of utilizing solar energy in Jordan [12]. Economical investigations of an integrated boiler-solar system in Jordan showed that using solar water heaters to heat space and for domestic water is cost-effective. Payback can be as low as 3 years, and utility bills are much lower than they would be using a conventional heating system [13]. Locally manufactured solar water heating systems were tested under the Jordanian climate conditions [14]. In a recent paper [15], Mohsen and Akash conducted an experiment on the performance of compact SWH under local climatic conditions. The tested collector in this experiment was of a box type with single glazing. It was found that a temperature rise of 30 C can be achieved by the system for a particular sunny day during the month of November. Researchers focused also on the demand on water heating systems and their energy saving potential in Jordan [16]. Furthermore fuzzy sets programming to perform evaluation of solar systems in Jordan was presented in [17].

The amount of direct light gathered by combination of reflector and flat-plate collector has been analyzed by McDaniels et al. more than 35 years ago [4]. The calculations were done allowing variable reflector and collector orientation angles, variable latitude and arbitrary sun hour angle away from solar noon. At the same time, Seitel explored the use of diffuse and specular flat reflectors to enhance the performance of flat-plate solar collectors by means of Fortran routines, which optimize the size, shape and placement of reflector and collector [5]. Also, the mathematical model to simulate the performance of flat-plate collector–reflector systems was analyzed by Grassie and Sheridan [6]. The model was used to predict the annual performance of a water heating system with several values of the reflector angle. The problems of energy performance of flat-plate collector–reflector systems were also investigated in works of Dang [7] and Arata and Geddes [8]. A model for the calculation of incident solar radiation from flat- and CPC-shaped external reflectors onto the flat plate solar collector arrays was developed by Perers and Karlsson [9]. Also, Perers et al. [10] studied intensity distribution in the collector plane from structured booster reflectors with rolling grooves and corrugations.

Another analytical model has been developed and used to determine solar irradiation on flat collectors augmented with planar reflectors by Bollentin and Wilk [11]. The use of corrugated booster reflectors for solar collector fields was considered by Ronnelid and Karlsson [12]. They have shown that by using the corrugated instead of flat booster reflectors it was possible to increase the annual irradiation onto the collector plane, thereby maximizing the annual output from the collector–reflector arrangement. Hussein et al. [13] gave a theoretical analysis of the instantaneous, daily and yearly enhancement in solar energy collection of a tilted flatplate solar collector augmented by a plane reflector. The shadow effect due to the reflector on the collector was considered in the analysis. Tripanagnostopoulos et al. [14] constructed and tested the flat plate solar collectors with colored absorbers for water heating applications. The theoretical analysis of a solar thermal collector with flat plate top reflector was presented by Tanaka [18]. He predicted the daily solar radiation absorbed on an absorbing plate of the collector throughout the year, which varied considerably with the inclination of both the collector and reflector, and was slightly affected by the ratio of the reflector and collector length.

The investigations described in this paper were performed on thermal collectors with and without flat plate solar radiation reflectors, and the goal was to determine optimal position of reflector plate for the given position of collector. First, we will present an analytical model for determination of the optimal position of aluminium sheet made flat plate solar reflector for inclination (tilt angle) of thermal collector of 45◦, during the day time over the whole year period. The theoretical results obtained by analytical model will be then shown to be in good agreement with experimental data. The thermal efficiencies of solar thermal collectors without reflectors and with reflectors in optimal position have been determined as well.

In 1942, Hottel and Wertz [22] conducted analyses and theoretical researches on the flat-plate collector based on the energy balance equation. Garg and Agarwal [22] studied the relationship between the flow rate of the working medium within the collector tube and thermal collection efficiency of the flat-plate collector by simulation. Results showed that given a high flow rate of the working medium within the collector tube, the efficiency is higher. Nahar and Gupta [6] conducted an experimental comparison on the influence of changes of the distance between endothermic plate and glass surface cover of the flat-plate collector on thermal collection efficiency, in order to determine the optimal distance. Yeh et al. discussed the solar flat-plate collector efficiency through experimental and theoretical research, and discussed the influence of the increasing number of collector tubes on the flatplate collector efficiency, where the area of the flat-plate collector is fixed. Eisenmann et al. [23] performed an experiment based on the relationship between the endothermic plate efficiency and various processing parameters, and estimated the relationship between the endothermic plate material and economic surface. Farahat et al. further discussed the relationship between the performance and processing parameters of the solar flat-plate collector upon the hypothesis that parameters, such as the endothermic plate area, flat-plate collector size, collector tube diameter, mass flow rate, inlet liquid temperature, and outlet liquid temperature, are variable parameters of the solar flat-plate collector. Most of the above studies only concerned the relationship between the performance and processing parameters of the flatplate collector, while did not discuss the parameter combination for the optimized overall performance of the flat-plate collector.

Therefore, this study discussed further optimization of the relationship between the performance and processing parameters of the flat-plate collector. This study conducted an experiment through parameter allocation to optimize the processing parameters. Generally, experimental parameters are set by empirical rules or trial and error method, which is time-consuming and not economical. Liu et al. [10] designed an experiment according to the Taguchi method and the L18 orthogonal array in order to obtain the processing parameter
optimization for synthesis of the CIGS (copper indium gallium (di)selenide) thin film solar cell. Jun et al. [11] designed an experiment based on the Taguchi method to optimize the electrical and optical properties of the ITO (Indium tin oxide) thin film solar cell, and finally obtained the optimized processing parameters. However, the Taguchi experimental design method can only process the optimization of a single quality characteristic. For more than one quality characteristic, the multiple quality analysis method is required. Chen et al. [12] converted multiple quality characteristics into GRG (grey relational grade) based on the grey relational analysis and the Taguchi method, and organized various quality characteristics according to their responses for selecting the optimal combination of the processing parameters. Tarng et al. [13] analyzed multiple quality characteristic problems of arc welding based on the Taguchi method and grey relational analysis. The GRG based on the SN ratio (signal-to-noise ratio) of the experimental data obtained through the Taguchi method was calculated in order to obtain the optimal combination of processing parameters of multiple quality characteristics. Chiang and Hsieh [14] conducted an experiment on the color filter process based on the Taguchi method and grey relational analysis to determine the optimal multiple quality parameters and improve the output of the thin Cr (chromium) film.

Taguchi technique is normally used in linear interactions only. This is due to the fact that in Taguchi design, interactions between controls factors are aliased with their main effects. 3D surfaces generated by RSM can help in visualizing the effect of parameters on response in the entire range specified whereas Taguchi technique gives the average value of response at given level of parameters . Thus[24]RSM is a promising analytical tool to predict the response which suits the range of parameters studies.

Based on the above literature references, we can concluded that

- The modeling and analysis of solar flat plate collector is not done by using tilting angle (AR),the processing timing (TM) measured in 24 Hr clock and the water quantity (WT) as a main parameters and response surface method as a methodology.
- The effects of tilting angle (AR), the processing timing (TM) measured in 24 Hr clock and the water quantity (WT) on efficiency and the water temp is not mentioned.
- Optimization and the sensitivity analysis by using response surface method (RSM) are not mentioned

There are various parameters which affects the performance of flat plate collector. The variables such as tilting angle (AR), the processing timing (TM) measured in 24 Hr clock and the water quantity (WT) are some examples of the controllable variables which affects the performance of flat plate collector. Choosing best set of these parameters for getting the best of parameters which maximized the performance. Response Surface Method (RSM) is the main priority in this research.

III.SPECIFIC OBJECTIVE

In the view of above the research goal can be defined as “Experimental Investigation and Performance Analysis of Flat Plate Collector by Response Surface Method” Following are Research Objectives:

1. Study and analyzing the performance of solar flat plate collector for the various combinations of process parameters.
2. Conducting the experiments according to the Taguchi’s L27 orthogonal array on FPC.
3. Measuring the various input parameters parameters such as tilting angle (AR), the processing timing (TM) measured in 24 Hr clock and the water quantity (WT).
4. Find out the best set of input parameters (Optimization) for optimizing the response parameters by using RSM method.
5. Find out the influence of various input parameters on the performance of flat plate collector.

INPUT PROCESS PARAMETERS

S. N	**Parameters**	**Symbol**	**Low Level**	**Medium Level**	**High Level**
1	Tilting Angle	AN	-1	0	1
2	Processing time	TM	-1	0	1
3	Water Quantity	WT	-1	0	1

Table 1 : List of Various Input Parameters

IDENTIFY OUTPUT PROCESS PARAMETERS

S. N	Parameters	Symbol
1	Water Temperature at Outlet	WT
2	Heat Gain	HG
3	Efficiency	EFF

Table 2 : List of Various Output Parameters

IV.EXPERIMENTAL SETUP

While working on the flat plate solar collector it is necessary to decide the parameters that affect on the temperature at focus point. This would be Possible when a quantitative relationship amongst various dependent and independent variables of the system is established by formulating the mathematical model of flat plate solar collector. It is well known that such mathematical model for flat plate solar collector cannot be formulated by applying only logic but formulation with an experimental data base is essential. In this experimental approach all the independent variables are varied over a widest possible range, While working on the flat plate solar collector it is necessary to decide the parameters that affect on the temperature at focus point. This would be Possible when a quantitative relationship amongst various dependent and independent variables of the system is established by formulating the mathematical model of flat plate solar collector. It is well known that such mathematical model for flat plate solar collector cannot be formulated by applying only logic but formulation with an experimental data base is essential. In this experimental approach all the independent variables are varied over a widest possible range, following figure 2 shows the experimental set up for the proposed work.

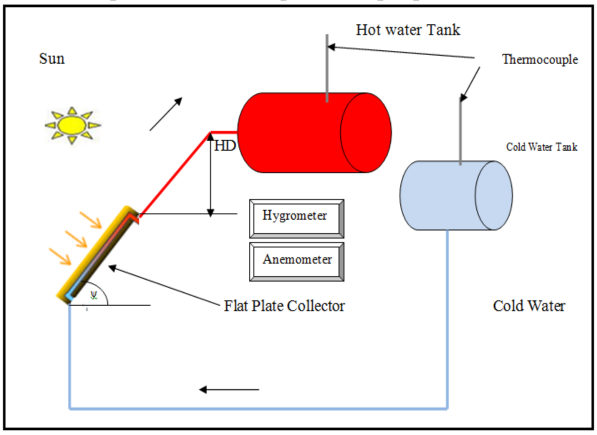

Fig 2 : Experimental set up for the proposed work

In the present work, thre levels, four factors and 27 experiments are identified. Appropriate selection of orthogonal array is the first step of Taguchi approach. The minimum number of experimental trails required in orthogonal array is given by

$$N_{min}= (L-1) F + 1;$$

Where,

- F= no. of factors= 3,
- L= no. of levels=3,
- Nmin= 7;

According to Taguchi approach L27 was selected.

Level	Tilting Angle	Processing Time	Water Quantity [Lit]
1	30	10:00 AM	10
2	60	1:00 PM	15
3	80	5:00PM	25

Table 3.Values considered

V.CONCLUSION

Based on the experiments carried out, the observed parameters, the considered I/P and O/P parameters were lined up in series of interdependent equations and the following RSM and Contour Plots were created using MINITAB Software.

Firstly the output parameter, Heat Gain is considered

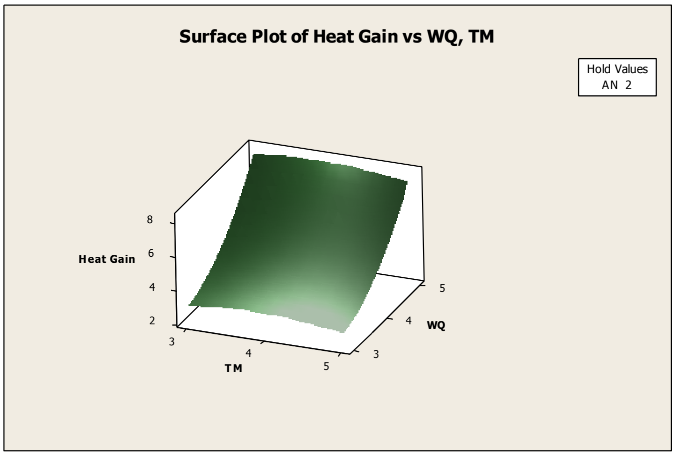

Figure 3 Surface Plot of Heat Gain vs. WQ, TM

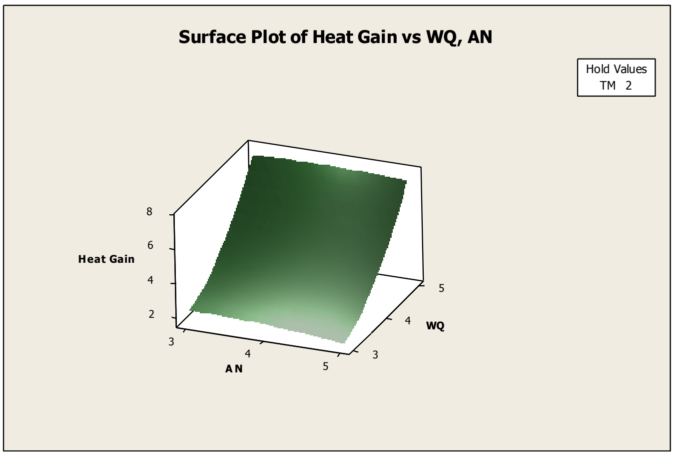

Figure 4 Surface Plot of Heat Gain vs. WQ, AN

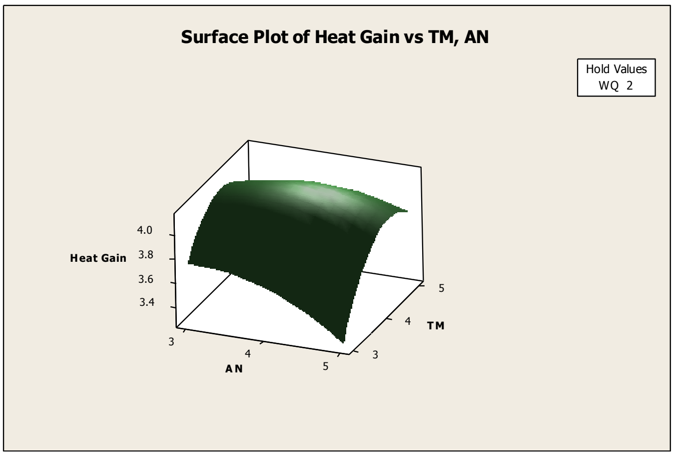

Figure 5 Surface Plot of Heat Gain vs. TM, AN

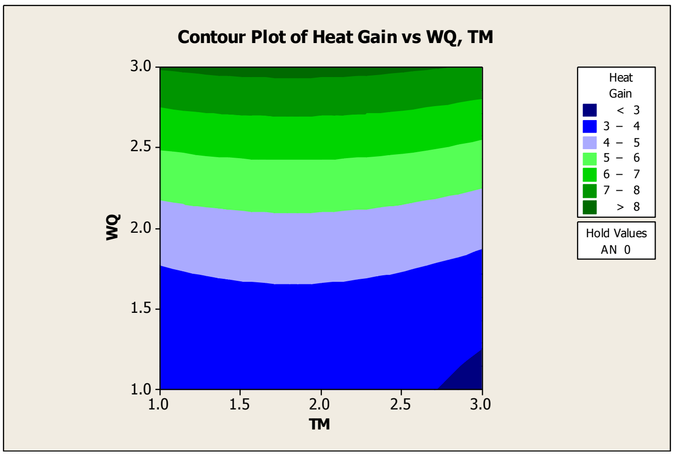

Figure 6 Contour Plot of Heat Gain vs. WQ, TM

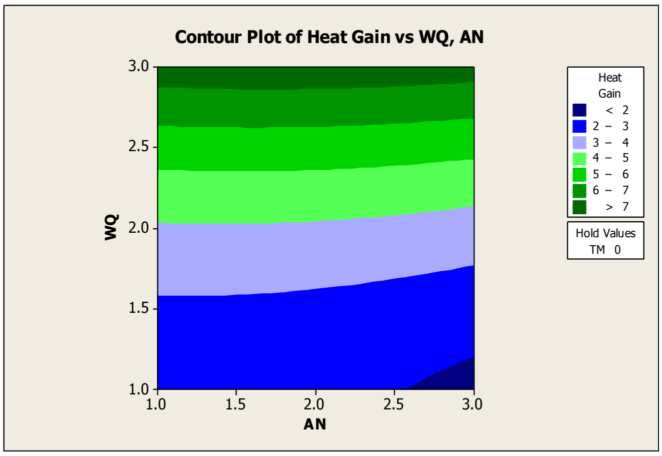

Figure 7 Contour Plot of Heat Gain vs. WQ, AN

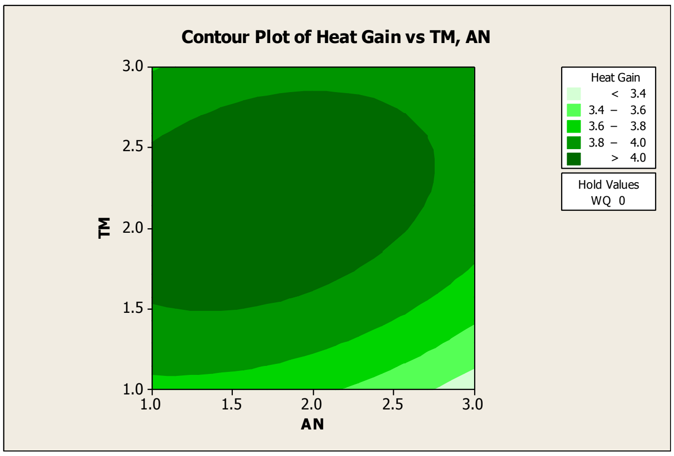

Figure 8 Contour Plot of Heat Gain vs. TM, AN

Secondly, efficiency is considered as the parameter to be considered.

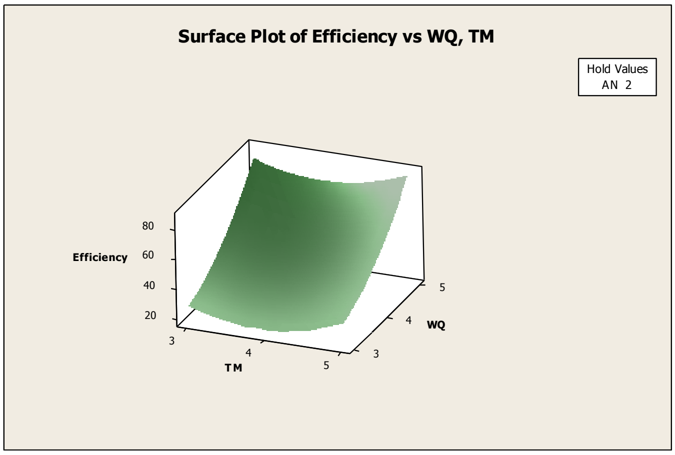

Figure 10 Surface Plot of Efficiency vs. WQ, TM

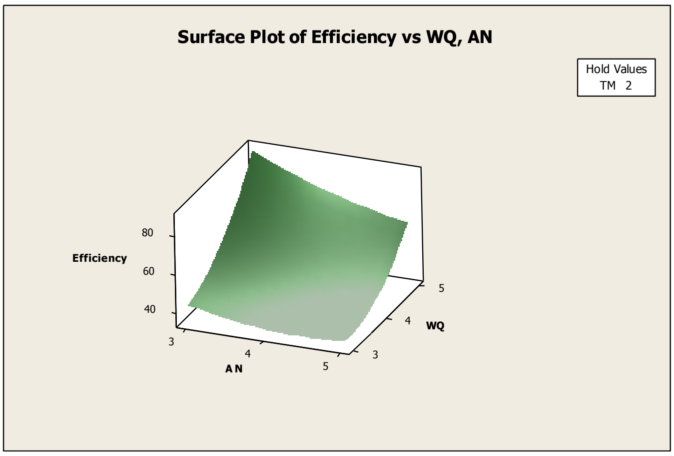

Figure 11 Surface Plot of Efficiency vs. WQ, AN

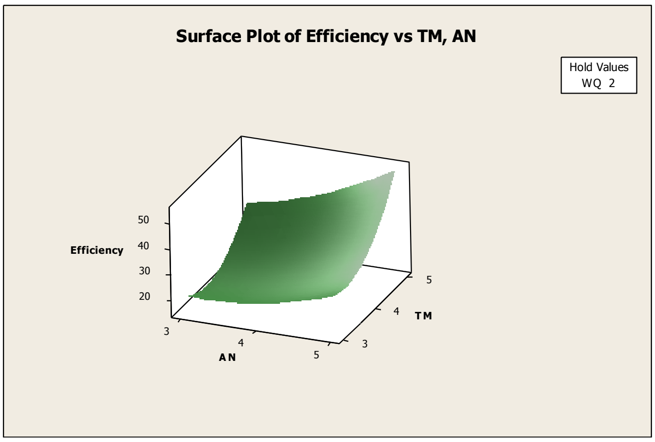

Figure 12 Surface Plot of Efficiency vs. TM, AN

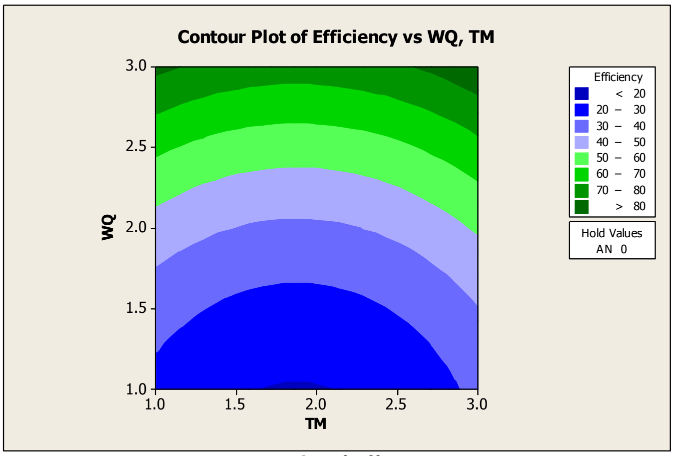

Figure 13 Contour Plot of Efficiency vs. WQ, TM

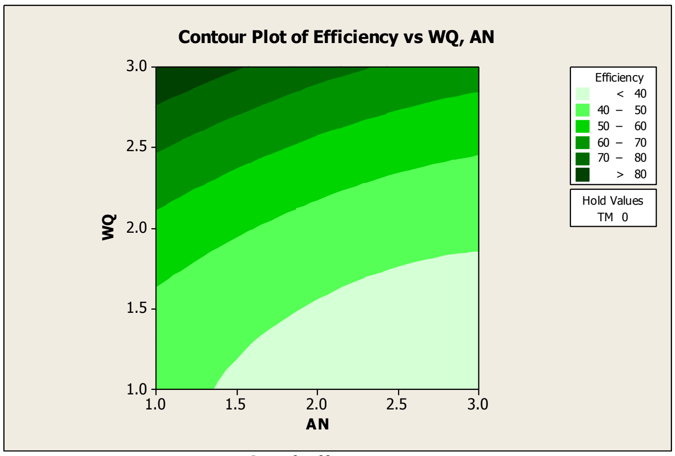

Figure 14 Contour Plot of Efficiency vs. WQ, AN

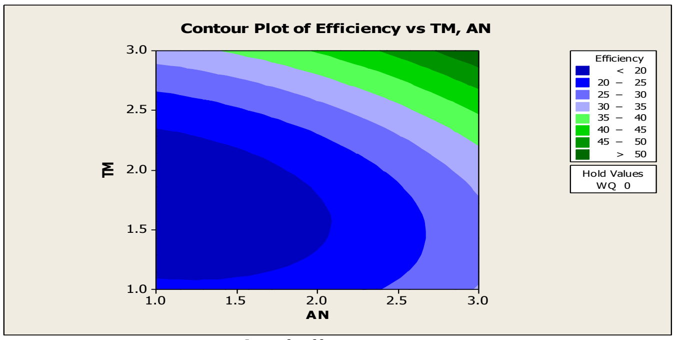

Figure 15 Contour Plot of Efficiency vs. TM, AN

VI. CONCLUSION

- A two degree response surface model for the various responses was formulated from the data obtained in L_{27} array.
- The model which correlates all the parameters under investigation was formulated
- Optimization of various input parameters and find out the best set of parameters to maximize the performance. To measure the influence of various parameters on the response variable can be done from the contour plots as shown in fig. 16 and 17.

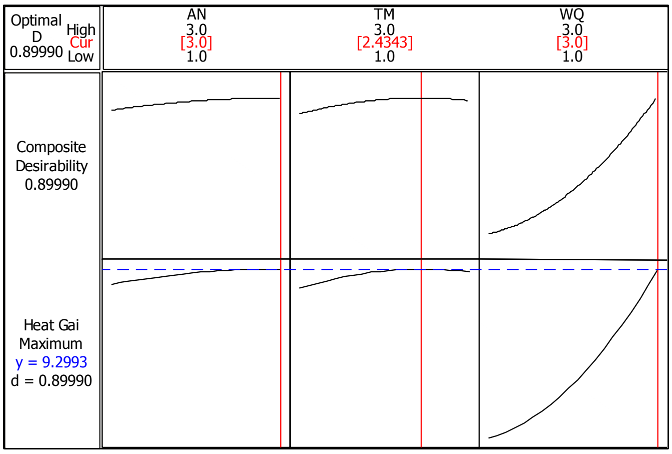

Figure 16 Response optimization for Heat Gain

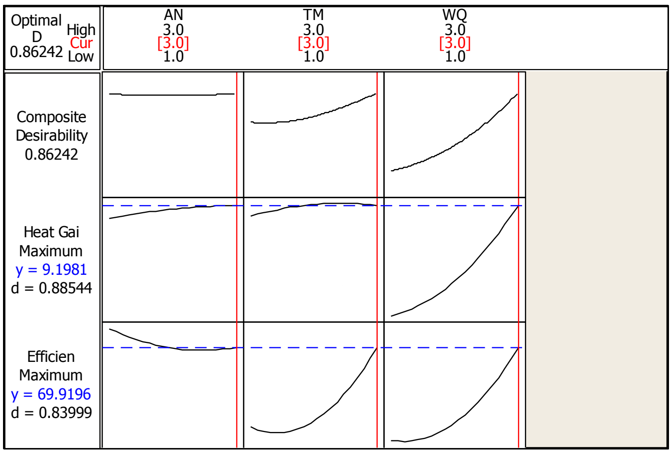

Figure 17 Response optimization for Efficiency

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