Performance studies of Solar Air Collector through Design of Experiment approach

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Abstract: Energy has made an immutable place in the human society as a driver to socio-economic engine that control each and every activity of existing biosphere on the planet Earth. The human activities during first Industrial Revolution (early part of 18th century to mid-19th century) were limited due small scale of production. However subsequent developments that followed as I-2.0, I-3.0 and Industry- 4.0 were in a totally different arena where energy demand grew at exponential rate and climatic restrictions to power generation became more stringent. The sustainability principles are today the order of the day owing to excessive environmental degradation due to alarming rate of fossil fuel usage. The carbon footprint has a marked impact on each and every process envisaged by engineering community under the concept termed as eco-friendly design. The promotion of renewable energy has been one of the promising strategies to mitigate the environmental impact due to the use of fossil fuels. The United Nations Development Programme (UNDP) has promulgated the 17 Sustainable Development Goals that aim to bring in improved overall living standards. The work presented deals with application of Design of Experiment concept in optimizing the suitable operating conditions for solar air heater. The approach has been reported to be a novel route in product realization and its optimization that ensures better resource utilization with least environmental and social impact. The study has resulted in appropriate choice of air flow rate in solar flat plate air heater useful for crop drying.

Keywords: Design of Experiments, sustainability, solar insolation

1. Introduction

In recent years, globalization made India witness speedy and wide-spread developments in industrial, economic and socio-cross cultural development sectors. It improved the living standards and per capita energy consumption of large part of rural as well as urban Indian population. The energy consumption of this large sector of population was solely depended on conventional fuel that resulted in alarming situation in society/environment on account of huge quantity of emanated pollutants. The government of India has designed programs and policies to resolve this fossil-fuel imposed environmental implications. Solar energy mission is one such program, which emerged promising to promote solar energy for both thermal and electrical energy generation and utilization. Solar energy, even though used over many centuries demands specialized skill sets for optimum and effective utilization. Research on solar
energy over a wide span of four decades or more has relied upon various tools and techniques to optimize performance that are strongly location specific. The generalized regression model to assess and optimize performance has become essential for subsequent improvement of system operation. The Response Surface Method (RSM) based regression model for solar air heater based on local climatic was used in statistical comparison against experimental results obtained as part of reported study.

The RSM is statistical tool that involves experimental design to establish, refine and optimize process/operational parameters in designed experiments. The past system observations evolve prediction model by optimizing system with respect to multiple inputs that influence output or yield response. The response measures system performance through series of test execution (termed as run) that modify input variables in relation to output to evolve computational framework that gets bound into empirical relationship. The quadratic models are usually in first and second order generalized as presented by equation (1 and 2) and (3 and 4) respectively.

\[
y_{ij} = \beta_0 + \beta_1x_{i1} + \beta_2x_{i2} + \ldots + \beta_mx_{mi} + \epsilon_{ij} \quad (1)
\]

\[
y_{ij} = \beta_0 + \sum_{k=1}^{m} \beta_k x_{ki} + \epsilon_{ij} \quad (2)
\]

\[
y_{ij} = \beta_0 + \beta_1x_{i1} + \beta_2x_{i2} + \ldots + \beta_{11}x_{i1}^2 + \beta_{22}x_{i2}^2 + \ldots + \beta_{(m-1)m} x_{(m-1)} + \epsilon_{ij} \quad (3)
\]

\[
y_{ij} = \beta_0 + \sum_{k=1}^{m} \beta_k x_{ki} + \sum_{k=1}^{m} \sum_{l=k+1}^{m} \beta_{kl} x_{ki} x_{li} + \epsilon_{ij} \quad (4)
\]

Where \( x_i = (x_{i1}, x_{i2}, \ldots, x_{im}) \) are input variables, \( \epsilon_{ij} \) are error terms and \( \beta = (\beta_1, \beta_2, \ldots, \beta_m) \) are regression coefficients for first-order multiple-regression model with design variables as predictors and \( \beta_k \) defining regression coefficients. The RSM results have deviations that include physical and computational errors due to incomplete convergence or round off. The RSM can also be applied in process or equipment design and optimization. The regression equation in RSM method gets initiated at identified level of input parameters (factors) and corresponding responses. The combination of identified factors (K) and levels (L) using full factorial method yielded number of trial runs equal to \( L^k \). It is used to determine regression coefficients of system variables in physical experiments and mathematical models [1].

2. Literature survey

The research findings reported on DoE tool for various engineering applications lay emphasis on applications such as solar crop drying system. This section has highlights on summary of implementation of DoE technique to solar thermal collector design.

M. Badache et al., (2012) experimented on an unglazed transpired solar collector to optimize thermal performance on basis of DoE approach. Their experiments were designed to optimize performance using full factorial method and developed matrix for four selected variable of air flow rate, inlet diameter, solar insolation and absorber coating, at three levels. The study identified absorber coating and performance of unglazed solar collector. The highest thermal efficiency was reached at 80 percent, for 0.7 coating level and 0.093kg/m²/s air flow rate [1].

Hannane et al., (2013) analyzed electrical performance of SPV system for indoor conditions adopting DoE for three levels of temperature and irradiation as input and short circuit current and open circuit voltage as responses. The results obtained were compared with simulation results of HIDE software for same operating conditions. The simulation results have good agreement with experimental results, and it was concluded that DoE appear to be good forecasting tool to predict SPV performance under any operating condition, and constitutes an excellent tool for assessing and comparing quality of different PV panels [2].

Dharmalingam et al., (2015) optimized parameters of solar water heating system using Taguchi method for performance. Nine set of experiments were designed for three selected variable at three levels for Reynolds number (5000, 15000, 25000), silver nano-particle concentration (0, 0.01%, 0.03%) and...
incident heat flux (800 W/m², 900 W/m² and 1000 W/m²) using L9 orthogonal array with support of Minitab 17. The optimum thermal performance was analyzed in terms water outlet temperature, thermal efficiency and overall heat gain. It was observed that maximum outlet temperature, and thermal efficiency were reported for combination of 800 W/m², 0.03% and 25000, and overall heat gain was recorded for set of combination of 1000 W/m², 0.03%, 25000 respectively [3].

Barone et al., (2019) explained historical developments of DoE and its applications in sectors of manufacturing and other allied sciences. The usage trend of DOE rapidly enhanced owing to advanced computing tools like Minitab, Statistica, SPSS, SAS, Design-Expert, Statgraphics, Prisma, Microsoft Excel, R-platform ANOVA, and regression models. The sectors like medicine (18%), engineering and biochemistry (20%), physics and computer science (13%) counted around 50% of its usage as compared to all other scientific and engineering areas in design, development and optimization process. The DoE tool featured as multipurpose tool for comparison, screening of variable, transfer function identification, optimization and robust design in various situations [4].

Kanimozhi et al., (2017) experimented on solar water heating system with thermal energy storage system for heat gain of honey wax and paraffin wax for three flow rate (6 kg/min, 4 kg/min and 2 kg/min) based on DOE approach. The results showed paraffin wax and honey wax absorb maximum up to 5840 kJ and 6408kJ of heat during charge and discharge processes at flow rate of 6 kg/min at 70 °C respectively. Based on experimental results the ANN model was developed for storage materials that were validated through experimental results in terms of selected statistical indicators viz: MAPE, chi-square and regression. The results of mathematical had good fit with experimental results with 95 % of confidence level [5].

Prakash and Rai (2018) optimized thermal performance of Parabolic Trough Collector (PTC) in terms of heat gain and water outlet temperature through set of experiments designed and developed using DoE. The experimentation trail runs were developed and test rig was set-up based on Taguchi L27 orthogonal array using MINITAB 17 software for combination of three group of water flow rate (0.001756 kg/s, 0.001578 kg/s and 0.001311 kg/s), receiver diameter (0.030 m, 0.026 m and 0.021 m) and Copper, Aluminum and Galvanized Iron as reflecting materials. The results showed that maximum heat gain and exit water temperature were observed for the combination of Copper as reflecting material and at flow rate of 0.001756 kg/s. However it was reported that receiver with diameters 0.0026 m and 0.0030 m produced maximum heat gain and highest exit water temperature respectively [6].

Barone et al., (2019) developed dynamic simulation model to assess thermal performance of hybrid turbo-expander system coupled with high-vacuum forced circulation solar water heater for climatic conditions at Messina (South-Italy) using MATLAB. The DoE model developed based on optimized 92 m² collector solar power plant, 4600 liter hot water storage capacity at nominal water flow rate of 0.3145 kg/s. The model dynamically estimates energy, exergy, CO₂ mitigation and economic analysis of solar power plant. It was observed that at optimum configuration exergy was reported as 1.36 TWh/year, eliminated 348 tonne of CO₂/year and payback period of 4.51 year payback period [8].

Donggen Peng et al, have applied the numerical concepts to self-preheated solar collector/ regenerator to overcome the limitations of traditional solar collector for 24 Chinese cities located in its northern and southern provinces. The optimization studies focused on air flow-rate and Collector unit area for different locations lying in the ranges 50–100 kg/(m²·h) and 3–6 kg/(m²·h), with height of Collector glass cover to be in the range of 0.04–0.06 m respectively to attain higher collection efficiency[9].

Yadav Kapil Dev et al., have investigated the absorber plate with arc shaped wires used as roughening elements to enhance heat gain in solar air heater. The theoretical analysis covered the fluid flow char-
acteristics of the solar collector using MATLAB codes for iterative solutions to fix the influence of collector parameters. The results were compared with published experimental results that showed roughened surface were not preferred for Reynolds number greater than $0.29 \times 10^5$ that was in early transition flow limits [10].

3. Computational Analysis

The studies presented in this section highlight use of MATLAB tool for implementation of DoE concept for optimization of solar air heater operating parameters identified as collector plate temperature, mass flow rate of air, solar insolation and thermal performance of collector. The detailed parameters of investigation of conventional solar air heater are based on climatic/ operational parameters listed in Table 1 along with constructional features discussed in the section on experimental studies. The step by step process adopted in computational work is presented in Table 2 that includes execution of DoE principles to develop simulation expressions for a solar air heater.

| Sl. No. | Climatic/ operational parameters | Level Low | Level Medium | Level High |
|--------|----------------------------------|-----------|--------------|-----------|
| 1      | Air flow rate (kg/s)             | 0.01      | 0.025        | 0.035     |
| 2      | Solar insolation (W/m$^2$)       | 50        | 550          | 1050      |
| 3      | Wind velocity (m/s)              | 1         | 3            | 5         |
| 4      | Ambient temperature (K)          | 293       | 303          | 313       |

The details of computational investigations to identify role of each individual parameter was performed on basis of DoE concept presented in subsequent section of article. The multi-variable objective function is evolved on basis of combined experimental and numerical studies as highlighted by equation 1 for six dependent variables as a function of four operating characteristics listed in Table 1 in terms of a polynomial function with defined constants. The studies were based on the use of MATLAB computational tool that offer distinct advantages in terms faster learn-ability and robustness through of efficient DoE algorithms. The entire process of simulation plays a vital role in minimizing use of constructional material coupled to better utilization of renewable energy resource. The investigations also lead to the fact that embodied carbon foot-print of renewable energy conversion devices can also be reduced through technical interventions originated through numerical studies combined with experimental results.

Table 2: Steps involved in RSM modeling of Conventional solar air heater

Step 1: MATLAB based response prediction solar air heaters and irradiation to cover entire range between minimum and maximum magnitude.
Step 2: MATLAB generated response connected to Minitab for execution of DoE
Step 3: Choose RSM from Minitab tool through stat-pull down menu of Minitab
Step 4: Define factors and their levels, desired responses and order for equation fit.
Step 5: Develop regression equations for responses conventional air collectors based on coefficients listed in Table 3 using Eq. 5

The operation of solar air heater is governed by climatic factors and the constructional parameters of air heater that are subjected to multi-variable optimization through suitable choice of these two group of parameters.
y = \alpha m + \beta I(t) + cW + dT_a + e m^2 + f I(t)^2 + g W^2 + hT_a^2 + imI(t) + jmW + kmT_a - \\
I(t)W + nI(t)T_a + oW T_a

(5)

Table 3: ANOVA coefficients for conventional air collector.

|   | y      | T_o | T_p   | Q      | \eta_{th} | h_1   | h_2   |
|---|--------|-----|-------|--------|-----------|-------|-------|
| C | 10.376805 | 3.94293498 | -257.804 | 40.14335 | 3.3818 | 14.0952 |
| A | -879.3217   | -577.98493 | 5402.871   | 756.5256 | 0.6179 | 1033.691 |
| B | 0.0748256 | 0.04739536 | 1.11934 | -0.00693 | -1.6×10^{-6} | -0.00276 |
| C | -0.091844 | -0.0388072 | 0.038777 | -0.03564 | -9.5×10^{-7} | -0.00164 |
| D | 1.0365515 | 1.04228006 | 1.211452 | 0.068199 | -6.6×10^{-5} | -0.11162 |
| E | 7769.2344 | 5602.69071 | -105834 | -8671.09 | 1.4173 | 1754.959 |
| F | -9.889×10^{-7} | -7.13×10^{-7} | -3.1×10^{-5} | 2.21×10^{-6} | 5.03×10^{-11} | 8.32×10^{-8} |
| G | -0.00646751 | -0.0048712 | -0.1339 | -0.00795 | -4.6×10^{-8} | -8.5×10^{-5} |
| H | -0.00011372 | -9.44×10^{-5} | -0.0026 | -0.0002 | 1.22×10^{-7} | 0.0002 |
| I | -0.71535699 | -0.5048497 | 8.87424 | 0.155056 | -8.9×10^{-6} | -0.01259 |
| J | 1.459509851 | 1.95283401 | 21.25865 | 0.526184 | 1.24×10^{-8} | -0.00431 |
| K | 0.79806208 | 0.38109133 | 9.175411 | 0.525024 | -0.00117 | -1.83981 |
| L | -7.4438×10^{-5} | -0.000116 | -0.0027 | -4.2×10^{-5} | 1.59×10^{-9} | 2.65×10^{-6} |
| N | -3.4967×10^{-5} | -9.369×10^{-6} | -0.00105 | -1.3×10^{-5} | 4.34×10^{-9} | 7.13×10^{-6} |
| O | 0.000259196 | -2.107×10^{-5} | 0.000119 | 2.24×10^{-5} | 4.4×10^{-9} | 8.31×10^{-6} |

The RSM based regression between factors and response for conventional solar collector indicated that the duct air flow rate significantly influenced exit air temperature (T_o) plate temperature (T_p) collector heat gain(Q), overall efficiencies (\eta_{th}) and convective heat transfer coefficient (h_1 and h_2). The higher air flow rate improved efficiency for conventional solar collector owing to high heat removal capability. The lower air flow rate owing to increased duration of air retention in collector lead to higher exit air temperature is proving beneficial for conventional solar air collector. The higher magnitudes of solar insolation and ambient temperature contribute to increased exit air temperature on account of better direct heating and improved greenhouse effect. The high ambient temperature however reduced temperature gradient between fluid and absorber plate thereby lowered net collector heat gain and its thermal efficiency.

The wind pattern strongly influenced collector heat loss coefficient at top, bottom and side collector surfaces being dominant on top loss factor that increased for higher wind speeds. The heat losses from cover plates lowered thermal performance of collectors.

The regression equation 1 analyzed in Minitab -ANOVA tool at 95 percent confidence level established that all factors except wind velocity significantly influenced all response parameters except thermal efficiency with lower p-value (less than 0.05). The influence of wind velocity and ambient temperature were less significant with value greater than 0.05 for p value. The obtained results exhibited better fit with lowest Adj R^2 of 98 percent for thermal efficiency of air heater and highest Adj R^2 of 100 percent for convective heat transfer coefficients. The regression coefficients for significant response parameters were within acceptable limits of 98 percent to 100 percent that established utility of regression.
4. Experimental Analysis

The experimental studies conducted as part of investigations include the characterization of solar air heater in terms of operating parameters that include ambient air, solar insolation and wind speed. The experimental investigations were conducted to assess the performance factors that include exit air temperature, collector plate temperature, convective heat transfer coefficient, overall heat gain and overall thermal efficiency. The service conditions of a solar air heater demands specific conditions of heat exchange medium. An optimum condition of heat transfer includes a temperature within the safe hygiene limits of crop dried and the desired drying rate of the crop.

The Fig. 1 indicates pictorial view of experimental test rig of SPV/T and conventional air collector developed at the test location, to analyze thermal, electrical and overall performance at varied climatic conditions. However reported work reports only on performance of conventional air collector (collector with plane glass cover plate). Hence the following section covers detailed discussion on conventional air collector. The air heating system had mild steel frame of 2 × 1 × 0.08 m with 5 mm galvanized iron (GI) bottom cover plate and the 5 mm thick GI absorber plate (aperture of 1.98m x 0.98m) with 300 micron selective black chrome coating to facilitate good absorption of short-wave solar irradiance and a poor emitter of long-wavelength radiant energy. The artificial wedge shaped (φ=8.53°), vertical ribs of 60 number with dimensions of 0.15 m length, 0.002 m thick and pitch of 0.15m were fabricated on top surface of absorber plate, in zig-zag manner. The glass wool of 0.04m thickness and 0.02 m with thermal conductivity 0.010 W/mK was sandwiched between bottom cover plate and absorber plate and absorber plate and aluminum foil respectively to reduce bottom and side heat losses of the collectors. The plain toughened glass covers plates in conventional air heating system.

![Figure 1: Experimental set-up for characterization of conventional air collector](image)

The K-type thermocouples were mounted evenly on absorber surface to capture directional temperature changes in air flow. The inlet and outlet air temperature were measured by two well insulated thermocouples while the top and bottom surface temperatures were measured using surface thermo-
couples. The thermocouples readings were recorded using temperature data logger. Solar insolation, wind velocity and ambient temperature were registered using pyranometer, anemometer and thermometer respectively.

The results indicated in Fig. 2 clearly highlight the diurnal variations of important climatic parameters that have a direct influence on the operation of conventional solar air heater. The identified parameters for the investigations include solar insolation, ambient air temperature and wind velocity measured during experimental investigations by using high precision pyranometer, thermo-couple and precision anemometer. The solar insolation shows a variation defined by the standard solar diurnal cycle with peak solar insolation during solar noon and lower magnitude during fore-noon and late-evening session of the day. The solar insolation has a direct influence on overall heat gain of system owing to the fact that input heat energy enhances with solar insolation. On the contrary the ambient air temperature and wind speed has a minimal influence in terms of useful heat gain of the system that gets prominence in the heat exchange process between absorber plate and working fluid.

![Figure 2: Diurnal variation of climatic parameters influencing solar collector](image-url)
Figure 3: Thermal performance of solar collector influenced by convective coefficient

Figure 4: Thermal performance of solar collector influenced by convective coefficient
The convective heat transfer coefficient ($h$) has a pronounced effect on the overall heat transfer rate of conventional solar air heater owing to the fact that heat gain is dependent on all three modes of heat transfer at different locations of the device. The heat collection by the absorber plate is a more radiation driven process termed as ‘green-house effect’ that facilitates transmission of short wave-length irradiance incident on glass cover, while it blocks re-radiated long-wavelength emitted by absorber surface. The conduction heat transfer is cited at the locations that includes absorber surface and insulation necessary for transfer of heat to working fluid and losses to ambient air. The experimental results indicated by Fig. 3 through Fig. 5 show the influence of convective heat transfer coefficient ($h$) on the exit air temperature and thermal efficiency of conventional solar air operated under varying climatic parameters listed in Table 1 continuously measured. The higher value of ‘$h$’ increases convective losses to ambient air and hence collector exit air temperature decreases as observed for all the flow rates. A comparative study for the three flow rates indicated that lower mass flow rate leads to higher exit air temperature owing to higher rise in temperature. The variation of overall efficiency exhibits a similar trend with respect to heat transfer coefficient for three mass flow rates listed in Fig. 3 through Fig. 5 that clearly relate thermal efficiency to higher amount of convective losses.

5. Conclusions

The investigations based on experimental and computational analysis of conventional solar air heater has lead to following conclusions.

The solar air-heater as a device for agricultural applications reduces substantial amount of carbon emissions owing to deferment of fossil fuel usage.

The influence of climatic parameters is pivotal to the operation of solar air-heater as they directly influence collector nett heat gain and drying process.

The DoE supports in selection of suitable operating parameters for solar air-heater with $R^2$ value and $p$-value as indicators of the correlation between participating variables in the design. The DoE analytics of 0.05 $p$-value and Adj $R^2$ showed variation from 98% to 100% when computed with respect to identified climatic parameters, thus strongly suggest that solar insolation had maximum influence on thermal performance of solar air heater against wind speed and ambient temperature.

The developed correlations for system performance can be generalized for wide range of low temperature solar thermal applications with prediction accuracy within permissible limits of 10%.
Abbreviations

**Adj R**^2^: Adjusted R^2^ refers to the goodness of correlation of model considered in the optimization. The value of Adj R^2^ plays a dominant role on influence of inclusion of new variable in the factorial analysis. Its higher value results, only when new identified variable improves the model performance, else any deterioration in its value is an indication of poor co-relation.

**p-value**: is statistical parameter that relates to participating variable’s coherence with the parameter optimized. The p-value with respect to null hypothesis indicates no effect (p-value= 0) while its magnitude lower than 0.05 makes rejection of null hypothesis. The p-values determine whether a particular variable influences the model to a substantial extent and if it has to be part of the regression analysis.

**DoE**: Design of experiment

**h**: convective heat transfer coefficient, W/m^2^K

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