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Thermal Performance Analysis and Prediction of Steam Production from Solar Paraboloid Concentrator using Multiple Linear Regression (MLR)

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A study on performance evaluation and development of a model to predict the daily steam produced from solar paraboloid concentrator has been carried out. Dual-axis point-focus solar paraboloid concentrators of four numbers with cavity receivers were installed for steam production and the steam produced was used for cooking applications in Tamil Nadu Agricultural University. Convection losses were the significant losses when compared conduction and convection losses resulting in 24.5% thermal efficiency of the system. Multiple linear regression (MLR) was used to predict the linear relationship between variables. MLR predicted the steam production with 0.63 R^2. Among the input variables used, solar radiation was the only parameter that had significant effect on daily steam production.

Key words: Solar paraboloid concentrator**,** Cavity receiver, MLR.

Energy requirement of world is increasing at faster rate. Depletion of conventional fuel reserves and pollution issues imply alarming situations. To address these issues, dependency on fossil fuels has to be reduced. Renewable energy sources are promising solution to this problem. One of the most important renewable energy resources is solar energy. The approximate quantity of solar radiation received by earth is 1000 W m^{-2}. It has broad variety of applications including water heating, drying, cooking, space heating, direct steam generation and electricity generation. Paraboloid solar dish concentrators used for steam production overcomes the disadvantages of box type and scheffler cookers (Thakkar, 2013).

A study on performance evaluation of point focus solar parabolic dish concentrator operating conditions in terms of receiver heat losses including conduction, convection and radiation was carried out and it was found that convective heat loss from receiver affected by changing wind speed or wind angle. Head on wind flow caused maximum heat loss in the receiver rather than side on wind flow (Gorijan *et al.,* 2013).

Due to advancements in technology, monitoring devices can be installed at any place of solar paraboloid dish concentrator system and real-time data can be collected. Information about the available steam is inevitable for cooking. Statistical models are one of the best models used for solar forecasting. Formulation of statistical models can be done by considering the nature of variables, system limitations and number of samples. The developed models can be validated by comparing the performance metrices. Multiple linear regression models are simpler to determine the linear relationship between multiple input variables and single output variable (Kicsiny, 2015). Based on the facts in view, multiple linear regression was used to forecast daily steam produced from solar paraboloid concentrators in this study.

Material and Methods

The experiments were carried out in TamilNadu Agricultural University, Coimbatore located at 11.0123 °N latitude and 76.9355 °E longitude during the months from August 2017 to February 2018.

System description

The solar paraboloid dish system with 25 m^2 aperture area and 0.35 m cavity diameter consists of a truss assembly mounted with a reflecting surface, cavity receiver and control system. Using feedback control system, the truss assembly is rotated on dual axis to track the sun's position continuously during the day. The receiver is located at a focal point where concentrated solar radiation is used for converting water into steam. The system is completely automated with several in-built safety features. The steam produced from the system is efficiently utilized for cooking purposes in TNAU hostels and the excess steam produced was stored in the steam accumulator which serves as a thermal energy storage system. Four paraboloid dish systems were installed in hostel premises and the steam produced from all dishes were combined and utilized for cooking application. Cocentration ratio of system was 204. Design wind speed of the system was up to 8 m s^{-1}. Solar grade mirrors were used to reflect the solar radiation to the cavity receiver. Absorptivity and reflectivity of the mirror was 95% and greater than 90% respectively.

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Thermal performance analysis

Thermal performance of receiver was calculated from the losses take place in the receiver. Conduction and radiation losses were calculated using the equations given by (Gholamalizadeh and Chung, 2017). Receiver convection losses were calculated using the equation given by (Sukhatme and Nayak, 2008). Thermal efficiency of the system was calculated by considering receiver efficiency and optical efficiency. The value of optical efficiency by considering all losses was taken as 0.84 as suggested

$$\eta_{thermal} = \eta_{receiver} \times \eta_{optical} \text{ ---------------------- } (1)$$

by Thakkar *et al.,* 2015.

Data collection

Seven months data of solar irradiation, wind speed, feed water temperature, ambient temperature, cavity temperature and steam temperatures of each dish were collected. Solar radiation was measured using SMP3 pyranometer, wind speed was measured using 014A-L: 3 cup anemometer and temperatures of ambient, feed water, cavity receiver and steam were measured using PT-100 (RTD) sensors. Due to cloudiness and other weather interruptions, system had worked 130 days in seven months. These 130 samples were used as input for three different models. The input layer consists of twelve parameters namely T_F - feed water temperature in °C; T_A - Ambient temperature in °C; R - Solar irradiation in W/m$^{2;}$ W - Wind speed in m/s; T_{C1}, T_{S1}- Cavity and steam temperatures of dish 1; T_{C2}, T_{S2} - Cavity and steam temperatures of dish 2; T_{C3}, T_{S3} - Cavity and steam temperatures of dish 3 and T_{C4}, T_{S4} - Cavity and steam temperatures of dish 4. The output layer was TSP - Total steam production in kg/day.

Multiple linear regression (MLR)

Regression tool available in Statistical Package for Social Science (SPSS 16.0) was employed to perform the forecasts and regression analysis on the collected data. MLR modeling establishes the linear relationship between the every independent variable x and dependent variable y in the form of equation.

General form of MLR model is,

$$Y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i \text{ ----------------------- } (2)$$

Where,

Yi is the dependent variable; x_1, x_2, xi are the independent variables and β_0, β_1, β_2, β_i are the co-efficient of respective independent variable.

Results and Discussion

Thermal performance was analyzed from determining the losses of the system. Multiple Linear Regression was used to forecast daily steam produced from dual-axis solar paraboloid concentrators with cavity receivers. Results obtained were discussed in this chapter.

Table 1. Thermal performance of solar paraboloid concentrator

Month	Conduction Loss (W)	Convection heat loss (W)	Radiation Loss (W)	Overall heat loss (W)	Receiver η (%)	Thermal η (%) =(η_R x η_o) (η_o = 0.84)
August	32.44	3087.16	542.26	3126.30	27.57	22.88
September	34.27	3089.80	571.67	3131.21	29.77	24.71
October	35.38	2832.24	576.23	2875.16	34.21	28.39
November	35.05	2999.23	497.27	3040.76	20.07	16.66
December	36.84	3294.24	523.54	3337.88	17.60	14.60
January	41.01	3509.64	600.43	3558.44	23.05	19.14
February	46.03	4725.39	798.95	4782.39	18.97	15.74

Thermal performance of solar paraboloid concentrator

Average quantity of conduction, convection, radiation heat loss, receiver efficiency and system efficiency were calculated and given in Table 1. Maximum conduction heat loss was in February month due to cloudiness and weather conditions. Minimum conduction loss occurred in august, September and December months. Conduction heat loss per day was increased gradually from August to February. In February, maximum convection heat loss (7014 W) occurred at 25th due to high wind speed of 2.73 m s^{-1}. In this month, wind speed of 1 to 3 m s^{-1} was retained in this month which in turn increased the convection heat loss. Most of the days in February had wind speed more than 2 m s^{-1}. Convective heat loss was in the range of 2200 to 7014 W for February. Radiation heat loss was mainly influenced by shape of cavity receiver, total surface area of aperture and Stefan-Boltzmann constant. Average heat losses were given in figure 2.From Table 1, it was inferred that the heat lost due to conduction was insignificant when compared to convection and radiation losses and difference in temperatures of cavity wall didn't affect the convective heat transfer co-efficient as reported by Gorijan, 2013. According to Ma 1993, convective heat losses occurred in receiver was moderately increased when the wind speed was in the limits of 2.5 to 3.5 m s^{-1}. The values of heat loss due to radiation were in accordance with a study presented by Jilte *et al.,* 2013.

Multiple linear regression (MLR)

MLR model was developed using the given input parameters.

The equation obtained in MLR was,

$$TSP = 0.329\, R^{*} + 8.301\, W - 1.711\, T_F + 0.448\, T_A - 0.354\, T_{C1} + 0.313\, T_{S1} + 0.423\, T_{C2} + 0.510\, T_{S2} + 4.741\, T_{C3} + 1.564\, T_{S3} + 0.141\, T_{C4} - 5.464\, T_{S4} - 152.869$$

The R^2 value was low (0.627) and the model result shows that other than radiation the effect of change in input parameters were insignificant on the change in total daily steam production. Radiation had the

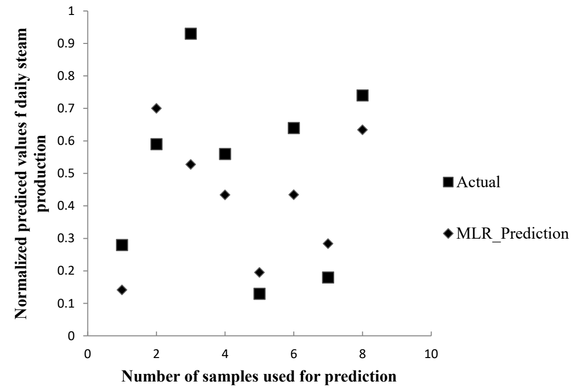

Fig. 1. Comparison between actual and calculated values of daily steam production

significant effect on total daily steam production with 99% confidence level. Combined effects of wind speed, feed water, steam, cavity and ambient temperatures were also insignificant.

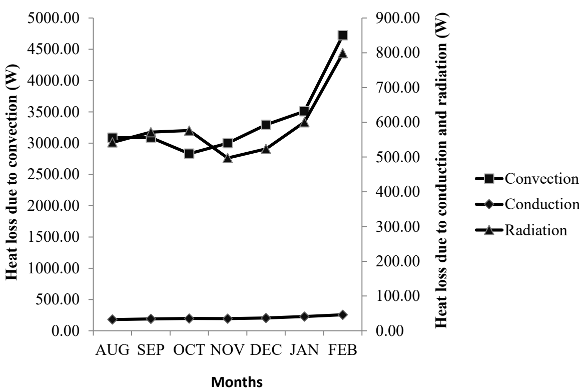

Fig. 2. Heat loss characteristics of solar paraboloid concentrator

Model validation

Sample values were taken and the quantity of steam produced per day was estimated from the equation developed using multiple linear regression. Developed models were validated by comparing the calculated values with actual values observed from the system. comparison between predicted and actual values are given in figure 1. By comparing the calculated and actual values, it was observed that multiple linear regression model was not sufficient enough predict the relationship between all input variables and total daily steam production.

Conclusion

A study on thermal performance analysis and prediction of daily steam production from solar dual-axis paraboloid concentrator was carried out. Convection losses were the major losses contributing to the reduction in thermal efficiency of the system. Resulted average thermal efficiency of the system was 24.5%. To predict the daily steam generation, multiple linear regression model was employed and the goodness of fit estimated. R^2 value of multiple linear regression (MLR) was 0.63. Change in solar radiation had the significant effect on change in daily steam production. Multiple linear regression model was only suitable for variables having linear relationship. It was observed from the results that, combined effects of change in wind speed, ambient temperature, feed water temperature, cavity and steam temperatures of each dish were insignificant and non-linear on prediction of daily steam generation.

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