Optimization of Solar Coupled Heat Pump System for Space Heating Application using Taguchi Method

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Abstract. In the recent couple of decades the demands for energy in India growing at a very high rate such a way that the conventional energy sources are not sufficient to meet the demand. At present most of the energy demand is met by fossil fuels, however, renewable energy sources such as solar energy, wind energy, biomass energy etc. have also been harnessed to some extent. The energy usage can be broadly classified to different purpose such as, building sector, industries, transport and household purpose. Among these one third of the total energy consumed in the world is spent for heating/cooling applications. It is to be noted that most of the heating/cooling demand are met by conventional system. This research work proposes a methodology for energy efficient space heating technique using solar coupled heat pump (SCHP) system under Indian climatic conditions by optimizing the COP of SCHP system and efficiency of solar collector using Taguchi technique. For the five influencing operating parameters of the system with three levels, an orthogonal array of L27 (3^5) has been selected using higher the better concept for 1 ton heating load capacity of the system during the winter season. Based on the 27 experimental trial runs it is found that the efficiency of solar collector and COP of the SCHP system varies from 38.8% to 61.87% and 1.9 to 3.01, respectively. The implementation of Taguchi method has resulted in 5.7% and 4.3% increase in solar collector efficiency and COP of SCHP system respectively.

Keywords: Solar collector, Heat pump, Taguchi method, Efficiency, COP

1. Introduction

In recent years, there is a renewed interest on solar energy utilization for domestic and industrial applications due to the impact of environmental challenges posed by other conventional sources of energy. Though solar energy is green energy and environment friendly, it is a lean form of energy, which needs to be intensified for certain applications such as space heating etc. At the present energy scenario in India most of space heating demand is fulfilled by electric heating devices, which consume high grade energy and indirectly contributes for higher CO₂ emission as two-third electricity generation in India comes from coal fired power plants. Combination of a solar collector and heat pump called, solar coupled heat pump (SCHP) is one of the promising alternative techniques to meet the heating demand at reduced electricity consumption. Bakirci and Bedri [1] investigated the thermal performance of a solar source heat pump system using 19.68 m² flat plate solar collector for heating application. Based on the experimental results they found that the solar collector efficiency varied from 33 to 47% while the COP...
of heat pump and the whole system were found to be 3.8 and 2.9 respectively. Yumrutas and Kaska [2] reported annual heat pump COP values between 2.5 and 3 based on experimental investigation of a solar assisted heat pump system with energy storage. Wang and Qi [3] found that the efficiency of solar collector and absorbed solar energy were 40% and 70% through underground thermal storage. Lund and Ostamann [4] introduced the seasonal energy storage concept during non-heating periods and extract heat during heating period using three dimensional duct storage model. This method also ensured the protection of thermal imbalance problem. Sevik et al. [5] carried out an experimental study on mushroom drying with solar assisted heat pump system and obtained the average COP and collector efficiency varying from 2.1 to 3.1 and 46 – 51% respectively. Liu et al. [6] simulated the performance of a solar assisted heat pump system using TRNSYS simulation and found that collector efficiency reached around 51% using 814 m² area of evacuated tube. Zhao et al. [7] performed an experimental analysis on dual source solar and air source heat pump system using phase change material and reported system COP of 2.93 and 3.22 during night time and day time period respectively. Islam et al. [8] reported numerical analysis of a CO₂ transcritical cycle on solar assisted heat pump system. They predicted the system COP and collector efficiency varying from 1.5 – 2.8 and 50 – 55% respectively. Gunasekar et al. [9] demonstrated the modelling on solar assisted heat pump system with 1.92 m² area of solar collector and obtained the COP as 2.45, 2.6 and 2.5 for refrigerant mass charges of 700 g, 750 g and 800 g respectively.

Based on the literature survey it is found that there is not much research work available on the optimization of SCHP for day time space heating during winter season. Hence in the present paper a methodology to achieve energy efficient space heating technique using SCHP is proposed by optimizing the operating parameters using Taguchi method to obtain maximum collector efficiency and maximum COP.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| A_{SC} | Area of solar collector (m²) |
| CR     | Concentration ratio |
| d      | Diameter of collector pipe (mm) |
| F_R    | Heat removal factor |
| I      | Solar intensity (W/m²) |
| J      | Level |
| L_C    | Parabola length |
| m      | Mass flow rate (Kg/m²) |
| NV     | Parameters |
| Q      | Energy gain (KW) |
| S      | Absorbed flux (W/m²) |
| T      | Temperature (°C) |
| U      | Overall loss coefficient (W/m²K) |
| \( Y_i \) | Performance value |
| IHX    | Intermediate heat exchanger |
| in     | Inlet |
| a      | Ambient |

![Figure 1. Schematic diagram of SCHP system](image)
2. System Description

Figure 1 above shows the SCHP system considered in the present research work. In SCHP system parabolic trough solar collector is connected to the heat pump unit through an intermediate heat exchanger. The heat pump device consists of a compressor, condenser, fan coil, expansion valve and evaporator unit. In the SCHP system heat is extracted from solar collector using water as a working fluid and this heat is transmitted to the heat pump through R-22 refrigerant with the help of an intermediate heat exchanger. The refrigerant in the heat pump absorbs this heat for its evaporation and heat is rejected in the condenser after compression in the compressor. The rejected heat in the condenser is used for space heating application through fan coil unit. Then the refrigerant completes the cycle by expanding in an expansion valve before entering into the evaporator. The heat rejected in the condenser is circulated into the room to be heated using a fan-coil unit. In this research work Taguchi method has been employed to optimize the influence factors of the collector and COP of the SCHP system using thermodynamic analysis and heat transfer equations.

3. Thermodynamic and heat transfer equations

3.1. Parabolic Trough Collector

In the present research a parabolic trough solar collector is assumed to be used with the heat pump. In parabolic trough collector useful energy gain QSC and efficiency can be calculated using the following expressions [10, 11]:

\[ \eta_{SC} = \frac{Q_{SC}}{A_{SC} L} \]  
\[ Q_{SC} = F_{h} (W_{f} - d) L_{c} \left[ S - \frac{U_{i}}{CR} (T_{a} - T_{i}) \right] \]

3.2. COP of SCHP system for space heating

The COP of SCHP system is defined as follows:

\[ \text{COP}_{SCHP} \text{ of system} = \frac{Q_{\text{condenser}}}{W} \]  
\[ Q_{\text{condenser}} = m (h_{2} - h_{3}) \]

where, \( W \) represents the total amount of work input in SCHP system. Whereas \( h_{2} \) and \( h_{3} \) are represents the condenser inlet and outlet enthalpy.

4. Results and Discussion

For the purpose of optimization five parameters at three levels as shown in Table 1 are selected. Parameters A, B, C and D influence the efficiency of solar collector whereas parameters A, D and E are important for the COP of SCHP system. The minimum number of experimental trial runs are computed using the relation: \( N_{Taguchi} = 1 + NV(J-1) \).

| Table 1. Parameters and their levels |
|-------------------------------------|
| Label | Parameters | Level |
|       |            | 1     | 2     | 3     |
| A     | Mass Flow rate of liquid (kg/s) | 0.25  | 0.3   | 0.35  |
| B     | Area of solar collector (m²)   | 6.5   | 7     | 7.5   |
| C     | Solar Intensity (W/m²)         | 495   | 525   | 558   |
| D     | Specific heat capacity of liquid (J/kg K) | 3995 | 4191 | 4267 |
| E     | Work input (KW)                | 1.456 | 1.469 | 1.497 |

4.1. Taguchi method – Signal to Noise ratio for efficiency of solar collector and COP of SCHP

The main objective in the optimization procedure is to achieve maximum solar collector efficiency and maximum COP for the SCHP system and hence the signal to noise ratios (S/N) for all the experimental trial runs are computed using higher the better concept using the following relation [12]. Table 2 shows the S/N ratios of collector efficiency and COP of the SCHP system.
Higher the better $S/N = -10 \log \left( \frac{1}{\sum_{i=1}^{r} Z_i} \right)$ \hspace{1cm} (5)

Table 2. Efficiency of solar collector and COP of SCHP system

| Ex. trials run | Solar collector | SCHP | Solar collector | SCHP |
|----------------|-----------------|------|-----------------|------|
|                | Efficiency      | SN ratio | COP SN ratio | Efficiency | SN ratio | COP SN ratio |
| 1              | 38.80           | 33.5326 | 1.69          | 4.54461   | 15       | 43.26      | 32.7225     | 1.97        | 5.88703    |
| 2              | 43.77           | 33.5326 | 1.86          | 5.40371   | 16       | 51.82      | 32.5336     | 2.37        | 7.48056    |
| 3              | 47.49           | 33.5326 | 2.04          | 6.19913   | 17       | 42.33      | 32.5336     | 2.62        | 8.36277    |
| 4              | 35.64           | 32.0844 | 1.77          | 4.96063   | 18       | 47.75      | 32.5336     | 2.07        | 6.30304    |
| 5              | 40.20           | 32.0844 | 1.95          | 5.81973   | 19       | 57.02      | 35.8306     | 3.08        | 9.77892    |
| 6              | 43.62           | 32.0844 | 2.14          | 6.16151   | 20       | 61.82      | 35.8306     | 2.46        | 7.80598    |
| 7              | 31.86           | 30.0655 | 1.80          | 5.11673   | 21       | 50.55      | 35.8306     | 2.68        | 8.57829    |
| 8              | 35.94           | 30.0655 | 1.99          | 5.97583   | 22       | 60.77      | 35.6741     | 3.01        | 9.93501    |
| 9              | 39.00           | 30.0655 | 2.18          | 6.77125   | 23       | 61.87      | 35.6741     | 2.50        | 7.96208    |
| 10             | 57.39           | 35.1773 | 2.41          | 7.63666   | 24       | 53.88      | 35.6741     | 2.73        | 8.73439    |
| 11             | 46.89           | 35.1773 | 2.67          | 8.51887   | 25       | 50.07      | 32.9455     | 2.94        | 9.3629     |
| 12             | 52.89           | 35.1773 | 2.10          | 6.45914   | 26       | 54.33      | 32.9455     | 2.34        | 7.38996    |
| 13             | 46.95           | 32.7225 | 2.26          | 7.06454   | 27       | 44.39      | 32.9455     | 2.56        | 8.16227    |

Figure 2. $S/N$ ratio for efficiency of solar collector and COP of SCHP system

The term signal illustrates the preferable effect for the output, in the present case, solar collector efficiency and COP of SCHP system and the term noise represents the undesirable effects on the outputs for the real application before designing. Figure 2 highlights the final optimum influencing parameters. The levels of optimum parameters are A3B1C1D3E2 and A3B1C2D3E1 for collector efficiency and...
COP of SCHP system, respectively based on higher the better concept. It is noticed that parameters A, B, C and D only influence the collector efficiency, whereas factors A, D and E are the most influencing parameters for the COP of SCHP system.

4.2. Taguchi method – ANOVA analysis for efficiency of solar collector and COP of SCHP

ANOVA is used to calculate the percentage contribution of each parameter for collector efficiency and COP of SCHP system through different control factors such as degree of freedom (DF), sum of squares (SS) and mean of squares (MS) in SCHP system [12] as shown in Table 3.

| Source | DF | Sum of Square (SS) | Mean of Square (MS) | % of contribution |
|--------|----|--------------------|---------------------|-----------------|
|        |    | COP | Efficiency | COP | Efficiency |
| A      | 2  | 48.5259 | 49.5259 | 24.2629 | 24.7629 | 71.84 | 60.91 |
| B      | 2  | 0.00 | 18.9285 | 0.00 | 9.4642 | 0.00 | 23.28 |
| C      | 2  | 0.00 | 6.965 | 0.00 | 3.4825 | 0.00 | 8.56 |
| D      | 2  | 12.5743 | 4.877 | 6.2871 | 2.4385 | 18.61 | 6.00 |
| E      | 2  | 5.2731 | 0.00 | 2.6365 | 0.00 | 8.00 | 0.00 |
| Error  | 2  | 1.1728 | 1.0025 | 0.5864 | 0.152 | 100 | 100 |
| Total  | 12 | 67.5461 | 81.2989 | 100 | 100 |

From Table 3 it can be noticed that mass flow rate contributes highest contribution, around 60.91% and 71.84% for collector efficiency and COP of the SCHP system respectively. From this table the contributing parameters ranking can be found as ABCDE. Taguchi analysis also predicts the insignificant parameters for deciding the parabolic collector area, collector efficiency and COP of the SCHP system for real application.

4.3. Taguchi method – Confirmation test

Taguchi conformation test has been carried out using the results computed for 27 experimental trial runs. Based on these calculations the computed values of solar collector efficiency and COP of SCHP system are shown in Table 2. Thus implementation of Taguchi method has made it possible to determine the optimum collector efficiency and COP of SCHP system using the control factors at different levels listed in 27 experimental trial runs. From these results it is observed that the efficiency of solar collector and COP of SCHP system varies from 35.63% to 61.87% and 1.69 to 3.01 respectively. The optimum collector efficiency and COP of SCHP system are found to be 65.44% and 3.14 respectively after applying the optimum set of operating parameters among the all $L_{27}$ orthogonal array.

5. Conclusion

Solar coupled heat pump is an important alternate technology for utilization of renewable energy for space heating applications. In this study, an attempt is made to find optimum efficiency of solar collector and maximum COP of SCHP system for space heating application using Taguchi method. The important conclusions are:

- Based on $L_{27}$ orthogonal array it is found that the collector efficiency and COP of SCHP system varies from 31.86% to 61.87 and 1.69 and 3.01, respectively.
- By using Taguchi concept it is observed that the optimum value of collector efficiency and COP are 65.44% and 3.14 respectively.
- The optimum collector efficiency and COP of SCHP system are 5.7% and 4.3% higher than the maximum values computed based on $L_{27}$ orthogonal array.
- Based on the Taguchi method, it is noticed that mass flow rate is the most influencing parameter, which contributes around 60.91% and 71.84% to achieve the optimum collector efficiency and COP of SCHP system respectively.
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