Comparative study based on exergy analysis of solar air heater collector using thermal energy storage

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SUMMARY

This communication presents the comparative experimental study based on energy and exergy analyses of a typical solar air heater collector with and without temporary heat energy storage (THES) material, viz. paraffin wax and hytherm oil. Based on the experimental observations, the first law and the second law efficiencies have been calculated with respect to the available solar radiation for three different arrangements, viz. one arrangement without heat storage material and two arrangements with THES, viz. hytherm oil and paraffin wax, respectively. It is found that both the efficiencies in case of heat storage material/fluid are significantly higher than that of without THES, besides both the efficiencies in case of paraffin wax are slightly higher than that of hytherm oil case. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS

phase change material; temporary heat energy storage; hytherm oil; solar air heater collector; exergy analysis

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1. INTRODUCTION

Thermal comfort plays a very important role on the health, growth, working efficiency and feeling of human beings. All living beings including humans are very much concerned about the suitable climate and thermal comfort, especially, temperature and humidity. Owing to the increasing pressures of energy demand, the degradation of environment, global warming and depletion of ozone layer, etc., there is a need for efficient energy utilization and waste heat recovery. In the excessively hot climates it is necessary to reduce the temperature and humidity, whereas in the excessively cold climate there is a need to increase the temperature within the presence of suitable moisture content. If the temperature drops below thermal comfort level, especially, in the winter season, the heating devices such as burning of wood, coal, etc. are found to be traditional systems for heating and being used for decades, in the undeveloped and poor countries. With the advancement of technologies, the electric systems such as room heater, heat pipes, heat pump systems are employed to produce heating. In some countries, where the atmospheric temperature is very low, natural heating like solar energy is not sufficient. In such a case, refrigeration and fuel-fired systems are proven to be suitable heating devices [1].

Continuous efforts have been made by numerous researchers on different types of heat pumps in order to improve their performance and to make them cost effective. Some of the heat pumps developed so far still have not gained much importance. This may be due to various factors, such as low coefficient of performance, high investment and operational costs and/or their limited heat producing capacity. Owing to the limited resources of energy and the increasing demand, there is a concern in the scientific community to rethink and to develop the energy efficient system which is not only economical but also environment friendly. The energy consumption in buildings, commercial installations and space air conditioning constitutes a huge share of total energy consumption not only in the developed...
world but also in the developing countries. Facing ever the increasing pressure of energy demand, environmental degradation, global warming and depletion of ozone layer due to various reasons most commonly the industrialization [2].

The efficient use of energy is a hot topic of research, especially, after the Kyoto and the Montreal Protocols. It is well known that there is a huge potential of low-grade energy usage such as solar energy, and waste heat from the industry for hot water, space heating and crop & grain drying. This will not only helpful in the saving of high-grade energy resources but also can decrease the ozone depletion and release of greenhouse gases. This in turn can help in the long run for solving the huge environmental degradation and global warming problems. Owing to high pressure from the scientific community, some governments have decided to emphasize the use of solar and other renewable energy, besides, to restrict the wastage of energy in different form by means of penalty on the industries for the release of waste heat into the environment [1–3].

In such a case, the heat exchanger, solar air heater collector and heat pump systems can be used to extract the heat from low-grade energy sources and the waste from industries to utilize it for other low- and medium-temperature industrial applications, such as in dye industry, heating, cleaning and so on. This not only can utilize the freely and abundantly available renewable energy and waste heat for higher temperature applications but also can reduce a huge potential of the environment degradation. Solar energy is freely available, clean and can be utilized for different heating/cooling and space conditioning applications such as domestic, agricultural and industrial sectors with suitable design and modifications as per the requirements. But it is fluctuating in nature and also available only in the daytime and hence, there is a need for thermal heat storage so that the heat collected from the collector can be stored and used when there is no availability of sunlight [2,3].

The thermal energy storage is defined as the temporary storage of the thermal energy at high or low temperatures. Energy storage can reduce the gap between energy supply and energy demand, and it plays an important role in energy conservation, and hence, maximizes the use of available energy. Kovarik and Lesse [4] studied the optimal flow for low-temperature solar heat collector, whereas Farries et al. [5] studied the energy conservation by adaptive control for a solar-heated building. The optimal and semioptimal control strategies and sensitivity for the mass flow rate and other parameters for liquid solar collector system were carried out by Orbach et al. [6] and Winn et al. [7]. Bejan et al. [8,9] studied the second law analysis and exergy extraction from solar collector under time varying conditions.

Keeping this aspect in mind, Singh and Kaushik [10] and Misra [11] carried out a thorough study about exergy analysis of a 35-kW parabolic trough-based solar thermal power plant situated near the capital of India. They [10,11] observed that most of the exergy is lost in solar collector system followed by high-temperature heat exchanger, whereas the exergy loss in the low-temperature heat exchanger is found to be very less unlike the energy losses. Because exergy is the quality of energy, once it is lost, is lost forever and can not be recovered unlike energy. They also mentioned some techniques to decrease the loss in different components of a solar thermal power plant and how to increase the efficiency of solar thermal devices. Fath [12] studied the performance of the simple design solar air heater; the conventional flat plate absorber is presented by a set of tubes filled with a thermal energy storage material [13] predicted in the thermal performance of four common types of single pass solar air heater.

For commercial applications, ability of the drier to process continuously is very important to dry the products for its safe storage level and to maintain the quality of the product. Normally thermal storage systems are employed to store thermal energy, which includes sensible heat storage, chemical energy storage and latent heat storage. The solar drier is an energy efficient option in the drying processes [13]. The use of forced convection solar driers seems to be an advantage compared with traditional methods and improves the quality of the product considerably [14–16]. Normally thermal storage systems are employed to store heat for both short and long periods [17]. Common sensible heat storage materials used to store sensible heat are water, gravel bed, sand, clay, concrete, etc. [15–17]. Mohranj and Chandrasekar [18] analyzed heat storage material for copra drying of a flat plate solar air heater.

In recent years, few authors [19–25] have studied different features of solar collector system using various approaches. For example, Mohranj and Chandrasekar [18] and Kurthbas and Durmus [19] have studied the solar air heater for different heating purposes, whereas Luminosu and Fara [20] and Torres-Reyes et al., [21] have studied the optimal thermal energy conversion and design of a flat plate solar collector using exergy analysis. On the other hand, Bakos et al. [22], Kaushik et al. [23] and Tyagi et al. [24] have studied the optimum design of a parabolic trough collector (PTC) and have given some fruitful results, especially, the mass flow rate of the moving fluid and the concentration ratio of the PTC collector.

Ozturk and Demirel [25] experimentaly investigated the thermal performance of a solar air heater having its flow channel packed with Raschig rings based on the energy and exergy analyses. It was found that the average daily net energy and exergy efficiencies were 17.51 and 0.91%, respectively. In addition, the energy and exergy efficiencies of the packed-bed solar air
heater increased as the outlet temperature of the heat transfer fluid increased. Potdukhe and Thombre [26] designed, fabricated, simulated and also tested a solar dryer fitted with a novel design of absorber having inbuilt thermal storage capabilities. The length of operation of the solar air heater and the efficiency of the dryer were increased, and better quality of agricultural products in terms of colour value was obtained compared with open sun drying. MacPhee and Dincer [27] worked on thermodynamic analyses of the process of charging of an encapsulated ice thermal energy storage device through heat transfer. The energy efficiencies are found to be more than 99%, whereas the thermal exergy efficiencies are found to vary between 40 and 93% for viable charging times. The results confirm the fact that energy analyses, and even thermal exergy analyses, may lead to some unrealistic efficiency values.

In the present study, evacuated tube collector (ETC)-based solar air heater collector with and without thermal energy storage has been studied using the experimental data measured for typical days and time at Solar Energy Centre, Gurgaon, India. The measured data include solar radiation, temperature of the air/working fluid at different state points for different mass flow rates of air. Based on the measured data, different properties of air such as density, specific heat etc. have been calculated using online air calculator and with the help of above-mentioned parameters other properties such as enthalpy and entropy were calculated. Finally, energy, exergy, first and second law efficiencies were calculated. Based on findings, conclusions were made about the most probable time in a day at which the first law and second law efficiencies are found to be the maximum for all the three cases. In this analysis, it is observed that both the efficiencies are significantly higher in the case where thermal energy storage materials, viz. hytherm oil and paraffin wax have been used than that of without storage. However, both the efficiencies are slightly better in case of paraffin wax than that of hytherm oil, filled within the tubes of solar collector.

2. EXPERIMENTAL SET-UP AND DESCRIPTION

In the present experimental study, the solar air heater collector with and without temporary heat energy storage (THES) has been made of an ETC. A total of 12 ETC collector tubes (four for PCM, four for hytherm oil and four for without THES individually) have been arranged in the series. The copper tube of 12 mm diameter has been inserted inside the evacuated tubes for air circulation. Out of three arrangements, mentioned above, one is to fill Paraffin wax inside ETC tubes and outside the copper tube; in second arrangement ETC tubes are filled with hytherm oil, in a way that the THES material is coated around the copper tube and heat is stored in the material and transferred to the copper tube and finally to the blowing air inside it. It also overcomes the sudden drop in the outlet temperature to the hot air, due to fluctuation in the solar radiation arises due to cloud and/or other reasons. On the other hand, there is no temporary heat storage material in the third arrangement.

Asbestos cloth was used for covering the copper tubes exposed into the open air, viz. outside the ETC tubes for insulation purpose to reduce/minimize the heat loss to the ambient air. Calibrated J-type thermocouples made of copper-constantine with a temperature range of −200–1350°C were used to measure air temperature at different state points. A Total of 13 sensors have been used in the experimental set-up, the cross-sectional view of a tube along with THES in Figure 1(a) and the schematic of the experimental set-up in Figure 1(b) can be seen. In this arrangement, one thermocouple has been used for measuring the input air temperature and other four were used for measuring the outlet temperature of air at different state points. The outlet air temperature of the first tube is the inlet of the second tube and the outlet of the second tube is the inlet of the third tube and so on. In this arrangement where THES is used, one thermocouple was made of copper-constantine with a temperature range of −200–1350°C was used to measure air temperature at different state points. A Total of 13 sensors have been used in the experimental set-up, the cross-sectional view of a tube along with THES in Figure 1(a) and the schematic of the experimental set-up in Figure 1(b) can be seen. In this arrangement, one thermocouple has been used for measuring the input air temperature and other four were used for measuring the outlet temperature of air at different state points. The outlet air temperature of the first tube is the inlet of the second tube and the outlet of the second tube is the inlet of the third tube and so on. In this arrangement where THES is used, one thermocouple has been inserted inside the collector tube for measuring the temperature of storage material, besides, the same number of thermocouples has been used at different state points mentioned above. To measure air flow rate, a Rotameter of 200 LPM capacity is used, which has been placed between the compressor and inlet of ETC (Figure 1(b)). Air was forced circulated through the system using half HP air compressor. For measuring solar radiation Pyranometer with multiplication factor 8.52 × 10⁻⁶ V W⁻¹ m⁻² has been used in the experiment. The Pyranometer is kept on the horizontal surface nearby the experimental set-up in the open air, so that no shadow and/or reflection of solar radiation from any other surface/object falls on it. For collection of data, the HP data acquisition unit attached with a computer has been used in this study. The specifications of the ETC are given in Table I.

As shown in Figure 1(a), solar collector consists of a double-walled evacuated glass tubes. Forced air flow is used as a working fluid in the system and PCM/hytherm oil as a heat storage material/fluid so that this stored heat can be used for drying when solar radiation is not available and/or suddenly fluctuates due to any reason in the daytime and/or late evening hours. There are four vacuum tubes in each arrangement and a black-absorbing coating is done on the outer surface of the inner tube. The tubes are made of glass and the specification is given in Table I, while the length exposed to sunlight is 172 cm and inclined at 45°. The volume flow rate of the circulating fluid is measured by volume flow meter before it enters the first tube. There
is a vacuum between the annular spaces of double-walled glass tubes to reduce the heat loss by conduction and convection. Whenever fluid enter in the first tube its temperature rises, which can be identified by measuring temperature with the help of thermocouple provided at inlet and outlet of each tube. Data were collected from the system for few days in different months by varying the volume flow rate of air.

Energy and exergy analyses have been carried out to evaluate the first and second law efficiencies of solar air heater collector system with and without THES. Volume flow rate of the fluid in the system is specified and the schematic description is shown in Figure 1(b).

The energy analysis is based on the first law of thermodynamics viz. the law of conservation of energy, while the exergy analysis is based on the second law of thermodynamics, i.e. using the concept of entropy generation and/or the law of degradation of the quality of energy, as given in the next section.

3. ENERGY ANALYSIS

The energy analysis is based on the first law of thermodynamics and the corresponding first law efficiency has been calculated. The energy analysis is based on the fact that it is an upper limit of efficiency.
**Table I.** Details about the solar air heater collector and storage materials.

<table>
<thead>
<tr>
<th>Specification of collector tubes</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>179.5 cm</td>
</tr>
<tr>
<td>Inner length</td>
<td>176 cm</td>
</tr>
<tr>
<td>Coating length</td>
<td>172 cm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>44 mm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>57.5 mm</td>
</tr>
</tbody>
</table>

Properties of the Paraffin wax as a PCM

- Melting point: 53.04°C*
- Specific heat: 2.05 kJ kg⁻¹°C⁻¹
- Latent heat of fusion: 183.1 kJ kg⁻¹
- Thermal conductivity: 0.21 (solid) (W m⁻¹ K⁻¹)
- Density at 70°C: 0.769 kg m⁻³

Properties of HP Hytherm 500 Oil

- Kinematic viscosity @ 40 c, cst: 27–35
- Flash point coc, c, min: 194
- Viscosity index: 95
- Power point c max: 0.0
- Copper strip corrosion 3 h @ 100 c (astm), max: 1.0
- Neutralization number mg kohm⁻¹, max: 0.15
- 260°C: 0.731
- 280°C: 0.751
- 300°C: 0.772
- 260°C: 0.097
- 280°C: 0.096
- 300°C: 0.095

*Measured by Differential Scanning Calorimeter (DSC).

Exergy analysis of solar air heater collector

with which the solar radiation can be converted into heat and the heat can be transferred for useful applications at a given frequency spectrum and intensity. Energy incident on the evacuated tube is given by

\[ Q_c = A I_o \]  

(1)

where \( Q_c \) is the energy incident on the collector tube, \( A \) is the projected area of collector tube exposed to the sun light, and \( I_o \) is the intensity of solar radiation at any particular site. Useful energy gained from the collector can be written as

\[ Q_u = \varepsilon \tau I_o A \]  

(2)

where \( \varepsilon \) is the absorptance of inner surface of ETC, \( \tau \) is the transmittance of outer surface of the collector. Useful energy transmitted into the evacuated tubes is absorbed by fluid, and can be calculated using the first law of thermodynamics, viz. the law of conservation of energy:

\[ Q_u = Q_f = m C_p \Delta T \]  

(3)

where \( Q_f \) is the energy absorbed by air, \( C_p \) the specific heat of air and \( \Delta T \) is the temperature difference and \( m \) is the mass flow rate of air, the first law efficiency of the collector system is given by

\[ \eta = Q_f / Q_i = m C_p \Delta T / A I_o \]  

(4)

where \( \eta \) is the abbreviation used for first law efficiency of the system.

**4. EXERGY ANALYSIS**

The rate at which exergy is collected by the solar collector can be increased by increasing the mass flow rate of the working fluid. Since the collector tubes are the most expensive component of any solar thermal system which needs advanced material and associated technology to build, therefore, it requires large investment. In order to reduce the capital cost, we need to optimize the dryer area, as the fuel (sunlight) is free. Again, for large mass flow rates, the fluid outlet temperature is very low and requires more power to pump/blow air/liquid through it. On the other hand, low flow rate results in high outlet temperature of the working fluid with high specific work potential. But due to the nature of entropy generation, exergy losses increase due to the temperature differences and hence, the optimum mass flow rate is required. The exergy analysis has been performed based on the configuration of solar air heater collector shown in Figure 1(b). The exergy received by collector is given by [8–11,23,24,28]

\[ E_{x_c} = Q_u (1 - T_o / T_k) \]  

(5)

where \( T_o \) is the ambient temperature, and \( T_k \) is the temperature of the source while, the exergy received by fluid is written as [8–11,23,24,28]:

\[ E_{x_f} = m \left( E_{o} - E_{i} \right) = m \left[ (h_o - h_i) - T_o (s_o - s_i) \right] \]  

(6)

where \( h_o \) is the output specific enthalpy, \( h_i \) is the input specific enthalpy, \( s_o \) is the output entropy, \( s_i \) is the input entropy, and \( m \) is the mass flow rate of air blowing through the collector tubes. The output specific enthalpy of the fluid is given by [23,24,28]

\[ h_o = C_{p_o} T_o \]  

(7)

where \( T_o \) is outlet temperature, and \( C_{p_o} \) is the specific heat of air at outlet. The specific enthalpy of inlet air is given by [23,24,28]

\[ h_i = C_{p_i} T_i \]  

(8)

where \( C_{p_i} \) is the input specific heat, \( T_i \) is the inlet temperature. While the entropy difference has been calculated using the following set of equations [23,24,28]:

\[ C_{p_i} = a + k \times T_i \]  

(9)

\[ C_{p_o} = a + k \times T_o \]  

(10)

\[ ds = dq/T = C_p dT/T = (a + b T) (dT/T) = a dT/T + k dT \]  

(11)

Using Equations (9–10), the values of constants \( a \) and \( k \) can be calculated and hence, the entropy...
difference thereafter using Equation (11). The second law efficiency, i.e. exergy efficiency of the system can be written as [8–11,23,24,28]:

\[ \psi = \frac{E_x}{E_c} = \frac{n[(h_0 - h_1) - T_0(s_0 - s_1)]}{Q_c(1 - T_0/T_5)} \]  

and first law efficiency can be written as [28]

\[ \eta = \frac{n(h_0 - h_1)}{Q_c} \]  

\[ H_c (kJ/sec) = m \times h_0 \]  

\[ H_t (kJ/sec) = m \times h_t \]  

\[ Q_c = 4AL \cos \frac{45}{\tau \times \alpha} \]  

where \( E_x \) is the exergy received by collector, \( E_t \) is the exergy received by fluid, \( a \) and \( k \) are constants, \( \eta \) is the first law efficiency and \( \psi \) is the second law efficiency of the solar collector-dryer system. Based on the above-mentioned equations, a sample calculation has been made and the results are shown in Table II, for a typical set of operating conditions.

## 5. ERROR ANALYSIS

The data given on solar radiation, thermal energy storage materials, solar collector tubes, digital temperature displayer and sensors, air flow meter, air compressor, rotameter have been measured/calculated using different instruments. For example, solar radiation data have been compared with the weather monitoring systems available with the Ministry of New and Renewable Energy, Government of India and found to be in good agreement with those taken by the Pyranometer with an error of 0.1–0.2%. Properties of the thermal energy storage material such as latent heat, melting temperature, etc. have been measured with an error of 0.5–0.8% in the exergy analysis of solar air heater collector. As it is well known—wind speed also affects heat transfer rates to and from the solar collector and hence affects the energy and exergy efficiencies of the system. Besides, the deposited dust particles on the collector, moisture content in the ambient air, location, orientation and so on, only slightly affect the overall performance of the experimental system.

| Time (h) | \( T_{co} \) (K) | \( T_o \) (K) | \( T_s \) (K) | \( T_v \) (K) | \( T_{in} \) (K) | \( T_{out} \) (K) | \( T_{oc} \) (K) | \( T_2 \) (K) | \( T_3 \) (K) | \( T_4 \) (K) | \( T_5 \) (K) | \( T_{in} \) (K) | \( E_c \) (kJ) | \( E_t \) (kJ) | \( E_x \) (kJ) | \( \psi \) | \( \eta \) |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 10.00   | 308             | 395             | 333             | 395             | 395             | 380             | 321             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 10.30   | 300             | 410             | 321             | 371             | 380             | 380             | 333             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 11.00   | 300             | 395             | 333             | 395             | 395             | 380             | 321             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 11.30   | 300             | 410             | 321             | 371             | 380             | 380             | 333             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 12.00   | 300             | 395             | 333             | 395             | 395             | 380             | 321             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 12.30   | 300             | 410             | 321             | 371             | 380             | 380             | 333             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 13.00   | 300             | 395             | 333             | 395             | 395             | 380             | 321             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 13.30   | 300             | 410             | 321             | 371             | 380             | 380             | 333             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 14.00   | 300             | 395             | 333             | 395             | 395             | 380             | 321             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 14.30   | 300             | 410             | 321             | 371             | 380             | 380             | 333             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 15.00   | 300             | 395             | 333             | 395             | 395             | 380             | 321             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 15.30   | 300             | 410             | 321             | 371             | 380             | 380             | 333             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 16.00   | 300             | 395             | 333             | 395             | 395             | 380             | 321             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |
| 16.30   | 300             | 410             | 321             | 371             | 380             | 380             | 333             | 360             | 371             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             | 360             |

Table II. Sample calculation for different parameters for a typical set of operating conditions.
the performance accuracy of the instruments. But as mentioned above, wind speed and deposition of dust particle were not taken into account in the present experimental study. Therefore, the overall influences of these input errors on the total results can also be very small and hence, can be neglected in the present study. However, to make an error-free system, all the parameters mentioned above must be taken into account for the better accuracy and performance of such systems for real-life applications.

6. RESULTS AND DISCUSSION

A comparative study on first and second law analyses of a typical solar air heater collector system with and without thermal heat energy storage (viz. hytherm oil and paraffin wax) has been carried out at different mass flow rates using hourly solar radiation. The solar radiation first and second law efficiencies against time are shown in Figures 2–6. From the graphs it is found that both the efficiencies increase as the time increases in all the three cases (with and without THES). But there are some fluctuations in the efficiencies as can be seen from these graphs, which is obvious because of the fluctuation in solar radiation throughout the day. In case of temporary storage material, both the efficiencies have peaks at different times than those obtained without THES. We note that graphs with phase change material and hytherm oil, have their peaks at about 16:30, while it is in the first half, in general, for those without THES, besides, they are fluctuating in nature as can be seen from Figures 2–6. The peak with THES occurs at around 16:30 h, which is because solar radiation goes down sharply, while the circulating air gets heated by temporary storage material at almost constant temperature for some time. As a result, the output to energy input ratio with temporary storage increases sharply, and hence, the first and second law efficiencies attain their peaks during the late afternoon with some shifting due to different mass flow rates.

However, due to finite heat storage capacity and mass of the storing material, the stored energy of THES decreases afterwards and hence, both the efficiencies in most cases decrease in the same pattern, as can be seen from the graphs (Figures 2–6). As mentioned above, the temporary storage material has finite heat capacity and limited mass due to the space
available in the evacuated tubes; the instantaneous fluctuation in solar radiation is compensated by the storage material that supplies heat at almost constant temperature. However, if the solar radiation fluctuates more often and/or for a longer time due to weather constraints, the fluctuation is also found in the efficiencies of the collector with THES. But in the case where there is no temporary storage, the fluctuation in both the efficiencies is found to be more frequent and significant, as can be seen from Figures 2–6. It is also important to note that the solar radiation is given in kW m\(^{-2}\) in Figures 2–6, which is done to fit the efficiency and radiation curve on the same axis.

It is also noted that the fluctuation in the efficiencies is in a phase where there is no temporary storage material, whereas the fluctuation in both the efficiencies is in the opposite phase, where temporary storage is being used, as can be seen from Figures 2–6. It can be explained with the same physical significance that the THES material behaves as a temperature regulator by supplying additional heat during the fluctuation in solar radiation. From the observations, it is found that the first law efficiency is much higher than that of the second law efficiency, because exergy represents the quality of energy which is obviously enhanced with the increase in the temperature unlike the quantity of energy. In addition, as explained by several authors [20–24,28], exergy once lost is lost forever and cannot be recovered, unlike energy. Moreover, the exergy loss is more in the collector receiver-assembly and not in the low-temperature utility unlike energy. This results in more losses in exergy than in energy and hence, we find that the second law efficiency is much less than that of the first law efficiency. The curves for second law efficiency are found to be smoother than that of first law efficiency, which may be due to the fact that exergy losses are less sensitive to the input energy, viz. solar radiation, while it is the reverse in the case of energy losses.

However, as the mass flow rate of the working fluid increases, the efficiencies in all the three cases increase due to the heat gain by the moving fluid (viz. the air) in the receiver tube increase, as a result, we get higher output, resulting in higher efficiency for all the cases. In addition, whatever the mass flow rate, first law efficiency is always greater than second law

Figure 3. Solar radiation and efficiencies versus time for 20 LPM (a) with PCM; (b) with hytherm oil; and (c) without THES.
efficiency. In the case where temporary storage material has not been used, only one peak is observed and it shifts towards the origin for both the efficiencies as the mass flow rate of working fluid is increased. This is due to the fact that the role of temporary storage material is significant in this way. In other words, the peak observed is around 13:00 h (Figure 2c). In case of 10 LPM, it is found to be 11:05 and 12:40 h in case of medium mass flow rates. However, in cases where temporary storage has been used, both the efficiencies attain their highest peaks at approximately 4:30 h (Figures 2–6) for all mass flow rates because at this time solar radiation goes down sharply and heat is supplied by THES up to some reasonable duration.

Both the efficiencies of solar air heater collector using PCM are slightly better than in the case of hytherm oil. But in general, both the efficiencies with THES have been observed to be better than those without THES. Besides, as the temporary storage material regulates the supply of heat at almost constant temperature, both the efficiencies are found to be smoother than that without THES as can be seen from Figures 2–6. However, both the efficiencies increase slowly and attain peaks at nearly 16:30 h, and then decrease and again increase; this is because the heat stored in the PCM/hytherm is supplied by THES which does not happen in the case of without THES. In case of empty collector tubes the efficiencies attain their peaks in the first half once, and then go down further as time increases as solar radiation also decreases; this is found to be different in the case with THES.

As can be seen from the literature [17–24,28–30], some studies have been carried out in solar collector/dryer/heaters systems using energy and exergy analyses with and without phase change materials and/or thermal energy storages. For example, Ahmad et al. [17] studied the thermo-hydraulic (effective) efficiency of packed bed solar air heater without phase change material using energy analysis. Mohanraj and Chandrasekar [18] studied the energetic performance with and without thermal energy storage for copra drying. Kurtbas and Durmus [19] carried out energy and exergy analysis of a solar air heater without phase change material and gave some new results for the performance enhancement of such systems. The performance study of the flat plate collector has been carried out by some authors [20–21] using exergy analysis without thermal energy storage. The

Figure 4. Solar radiation and efficiencies versus time for 30 LPM (a) with PCM; (b) with hytherm oil; and (c) without THES.
performance analysis and parametric study of parabolic trough concentrating collector have been carried out by different authors [22–24] using energy and exergy analyses without thermal energy storage and some useful results were also obtained. For example, in Reference [23–24] the authors studied the effects of concentrating ratio and mass flow rate of the working fluid on the first and second law analyses of concentrating collector and observed that the mass flow rate is a critical parameter and should be chosen very carefully to obtain the best performance of these solar collectors. Tyagi et al. [28] carried out the performance of an evacuated tube solar collector without any phase change material-based thermal energy storage. Similar studies have been carried out by other authors on flat plate collectors and/or solar air heaters, such as Koca et al. [29], and Akbulut and Durmus [30] using energy and exergy analyses and some useful results were given. But none of the studies mentioned above is concentrated on the evacuated tube solar air heater collector using different thermal energy storage materials and hence, the work presented in this paper is new and unique of this kind.

7. CONCLUSIONS

The comparative study based on the first and second law analyses of a typical solar air heater collector system with and without temporary thermal energy storage has been carried out at different mass flow rates using hourly solar radiation. From the present experimental study, some interesting results are found and can be summarized as follows:

- It is found that there is fluctuation in both the efficiencies which is mainly due to the fact that solar radiation also fluctuates throughout the day as can be seen clearly from the figures given in this paper. In addition, as time increases, both the efficiencies first increase and then decrease in case without temporary storage material and the similar trend is found for solar radiation.
- In case of without THES material, the efficiency increases with time, attains its peak in the first half in general (Figures 2–6) and then decreases after that. However, in cases where temporary heat storage material is used, both the efficiencies
increase with time, attain their peaks at approximately 16:30 h with a small fluctuation with flow rate and then decrease smoothly. This is due to the fact that the solar radiation sharply decreases in the late afternoon and heat is supplied only by THES for some time. But due to the limited mass and capacity of the storage material, this supply also decreases slowly after a certain time. As a result, the stored heat energy decreases smoothly, and hence, both the efficiencies again decrease towards the late evening hours.

- As the mass flow rate increases, peaks of both efficiencies slightly shift towards the origin in case without storage material/fluid. However, in case with THES, there is a small shift in the peak due to different mass flow rates of the working fluid except in case of 40 LPM which is because of a shift in the peak of solar radiation during that particular day.

- It is also noted that the fluctuation in the efficiencies is in a phase where there is no temporary storage material, whereas the fluctuation in both the efficiencies is in the opposite phase where temporary storage is being used, as can be seen from the graphs. It can be explained with the same physical significance that the THES material behaves as a temperature regulator by supplying additional heat during the fluctuation of solar radiation.

- From the observations, it is also found that the first law efficiency is much higher than the second law efficiency, because exergy represents the quality of energy, which is obviously enhanced with the increase in the temperature unlike the quantity of energy, and also as explained by several authors mentioned in this paper. Thus exergy, which is the quality of energy, once lost is lost forever and cannot be recovered, unlike energy. Also exergy loss is more in the collector receiver-assembly and not in the low-temperature utility unlike energy. This results in more losses in exergy than that of the energy and hence, we found the second law efficiency much less than that of the first law efficiency.

- The curves of the second law efficiency are found to be smoother than that of the first law efficiency, which may be due to the fact that exergy losses are less sensitive to the input energy, viz. solar

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**Figure 6.** Solar radiation and efficiencies versus time for 50 LPM (a) with PCM; (b) with hytherm oil; and (c) without THES.
radiation, while it is the reverse in the case of energy losses.

Thus, the results obtained in this study will be very useful and informative for real-life applications using temporary storage in both the solar collector and in the thermal energy utilities for better performance. Most importantly, there is a need for thermal energy without much fluctuation in the outlet temperature and heat content out of the solar collector system for various applications of physical importance.

**NOMENCLATURE**

- \( A \) = projected area of collector tube exposed to the sun light (m²)
- \( C_{Po} \) = specific heat of air at the outlet (J kg⁻¹ K⁻¹)
- \( C_{Pi} \) = input specific heat (J kg⁻¹ K⁻¹)
- \( C_P \) = specific heat of air (J kg⁻¹ K⁻¹)
- \( E_{Xf} \) = exergy received by fluid (W)
- \( E_{Xc} \) = exergy received by collector (W)
- \( h_o \) = output specific enthalpy (kJ kg⁻¹)
- \( h_i \) = input specific enthalpy (kJ kg⁻¹)
- \( H_o \) = output enthalpy (kJ)
- \( H_i \) = input enthalpy (kJ)
- \( I_s \) = intensity of solar radiation at any particular site (W m⁻²)
- \( m \) = mass flow rate of air (gm s⁻¹)
- \( Q_e \) = energy incident on the dryer/evacuated tube (W)
- \( Q_f \) = energy absorbed by air (W)
- \( s_i \) = input entropy (J kg⁻¹ K⁻¹)
- \( s_o \) = output entropy (J kg⁻¹ K⁻¹)
- \( \Delta T \) = temperature difference (K)
- \( T_a \) = ambient temperature (K)
- \( T_i \) = inlet temperature (K)
- \( T_o \) = outlet temperature (K)
- \( T_s \) = temperature of source (K)

**Greek letters**

- \( \alpha \) = absorptance of inner surface of ETC
- \( \tau \) = transmittance of the collector tube
- \( \eta \) = first law efficiency of the collector system
- \( \psi \) = second law (exergy) efficiency of the system

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**REFERENCES**


