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A comprehensive review on energy and exergy analysis of solar air heaters

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Abstract For economic growth of nation, the energy plays an important role. The excessive use of fossil fuels results the increase in global warming and depleting the resources. Due to this reason, the renewable energy sources are creating more attraction for researchers. In renewable energy sector, solar energy is the most abundant and clean source of energy. In solar thermal systems, solar air heater (SAH) is the main system which is used for heating of air. As it is simple in construction and cheaper in cost, it is of main interest for the researchers. The concept of first law and second law of thermodynamics is used for the study of the energy and exergy analysis respectively. The energy analysis is of great importance for the study of process effectiveness while the exergetic analysis is another significant concept to examine the actual behavior of process involving various energy losses and internal irreversibility. For efficient utilization of solar energy, the exergy analysis is very important tool for optimal design of solar air heaters. The aim of the present work is to review the works related to energy and exergy analysis of various types of solar air heaters and to find out the research gap for future work.

Keywords: Solar energy; Energy; Exergy analysis; Solar air heater; Thermal performance

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Nomenclature

A_C	–	solar collector area, m^2
C_{pf}	–	specific heat, J/kg K
D_j/D_h	–	jet diameter ratio
E	–	energy rate, W
Ex	–	exergy rate, W
Ex_{dest}	–	irreversibility rate, W
h	–	enthalpy, J/kg
I	–	solar intensity, W/m^2
LM	–	Levenberg–Marquardt
$\dot{m}$	–	mass flow rate, kg/s
P	–	fluid pressure, Pa
$\dot{Q}_c$	–	solar energy incident on collector, W
$\dot{Q}_u$	–	useful heat gained by air, W
R_a	–	universal gas constant, J/kg K
Re	–	Reynolds number
S	–	entropy generation rate, W/kg K
SCG	–	scaled conjugate gradient
T	–	temperature, K
X/D_h	–	stream wise pitch ratio
Y/D_h	–	span wise pitch ratio

Greek symbols

η_{I} or η_{th}	–	energy efficiency
η_{II}	–	exergy efficiency
η_{eff}	–	effective efficiency
ψ	–	specific exergy, J/kg

Subscripts

a	–	air
c	–	collector
d	–	destruction
fi	–	inlet air
fo	–	outlet air
fm	–	mean air
gen	–	generation
s	–	sun

Abbreviations

ANN	–	artificial neural networks
DPSAC	–	duel pass solar air collector
ETC	–	evacuated tube collectors
FPC	–	flat plate collector
MPSACF	–	multipass solar air collector with fins
PCM	–	phase change material
PV/T	–	photovoltaic thermal
SAC	–	solar air collector
SAH	–	solar air heater

1 Introduction

Energy is the basic need for development of a nation. The requirement of energy is fulfilled by fossil fuels. The present world is facing two different types of problems such as energy crises and pollution. The fossil fuels are used in many sectors, such as transportation, industries and agriculture etc. and very limited. The best solution of this problem is utilization of renewable energy sources. Solar energy is one of the most promising and clean sources of energy of its kind. In solar energy utilization systems, solar air heaters (SAHs) play an important role for heating of air [1, 3]. For maximum use of solar energy is achieved by optimal designing of solar air heaters.

The absorber plate or solar collector is the major component of the SAH which converts the solar energy into thermal form and transmits to flowing air trough duct. The performance of conventional SAH is very poor due to low heat absorbing capacity of absorber surface and low thermal conductivity of flowing air. These problems are solved by increasing the heat transfer coefficient. There are many techniques used by various researches such as artificial roughness [4–7], porous/packed bed [8–11], extended surfaces [12–15], etc. for increasing the performance of SAHs.

Thermodynamics concept is very useful for analyzing the performances of thermal systems. The first and second law of thermodynamics are used for evaluating the energetic and exergetic performance of thermal systems [2]. The first law gives the quantity of matter but the second law provides the qualitative analyzing of the system. Various researchers were used this concept in residential [16], commercial [17, 18], industrial [19–21] and transportation sectors [22]. Ahamed *et al.* [23] and Dikmen *et al.* [24] evaluated the exergetic performance of refrigeration cycle. Sahu and Prasad used the thermodynamic concept on roughened solar air heaters [25, 26]. Fiuk and Dutkowski investigated the energetic efficiency of passive solar air collectors with wavelike baffles [27]. Wajs *et al.* [28] reported on investigation to increase the overall system efficiency of PV tiles by using heat recovery.

The energy and exergy analysis have used by many researchers in the various field such as thermal engineering [29], solar heat pumps [30], solar desalination system [31], solar air conditioning and refrigeration systems [32], hybrid photovoltaic/thermal (PV/T) solar systems [33], solar power plants [34], solar drying systems [35], solar collector systems [36], residential solar air conditioning [37], renewable energy systems [38], industrial fluidized bed drying of paddy [39], geothermal solar energy system [40], natural gas-fired boilers [41], food industries [42], solar stills [43], solar energy applications [44], air based photovoltaic thermal (PVT) collector [45], thermal power plants [46] and fuel cells [47].

From above literature, it has been observed that the energy and exergy analysis concept of thermodynamics are very important for thermal systems. The quantitative energy analysis of any system is based on the first law of thermodynamics, whereas the qualitative analysis is based on the second law of thermodynamics. These laws are very useful for solar thermal systems. It has been observed that no specific review is available on energy and exergy analysis of SAHs. For these reasons, the present study has focused on energetic and exergetic concepts of thermodynamics implemented for SAHs.

The main objective of the present paper is to review the experimental and analytical works of solar air heaters performances based on energy and exergy analysis. This analysis gives the researchers ideas to optimal utilization of the energy and provides the plan for designing and industrial operational processes. This paper also gives the research gap for future work and also helpful for those who are working with exergetic concept.

2 Details of solar air heaters and classifications

Figure 1 shows the detailed diagram of solar air heater (SAH). The working and construction details of conventional SAH has described by Garg and Prakash, which is given below [1]:

Frame – Metals and woods are used for construction of frame.

Matte black interior – For absorption of more solar radiations, the interior surfaces are painted with the black matte paint.

Absorber plate – absorber plate plays an important role in SAH unit which collects solar radiations and transmit the heat energy to the flowing air in the duct.

Inlet/outlet section – Inlet and outlet section is given for intake and discharge of air.

Glazing – Glazing is provided on the top surface of glass for absorbing more solar radiations. Generally acrylic, tempered glass, poly carbonate materials are used for glazing.

Insulation – The insulations are provided in the side and bottom walls of ducts to avoid the heat losses from the walls.

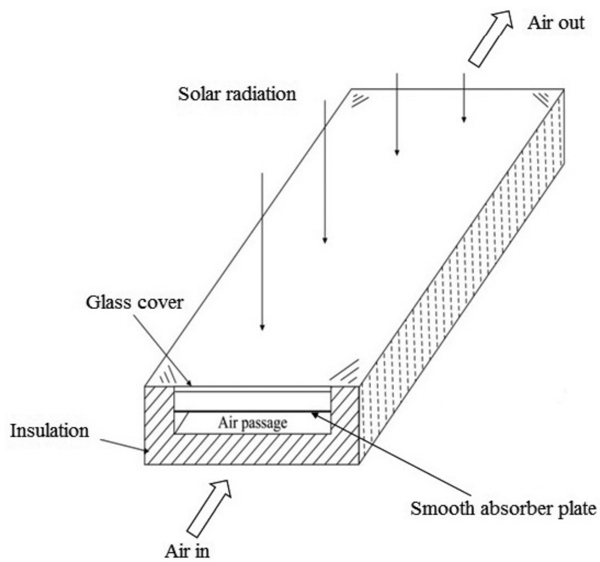

Figure 1: Convectional solar air heater.

2.1 Classification of solar air heaters

Solar air heaters are classified into many categories and types of classification are shown in Fig. 2. From this figure, it is noticed that SAHs are classified on the basis of glass covers, absorber materials, flow pattern, flow types, absorber surface shape, hybrid systems and their applications.

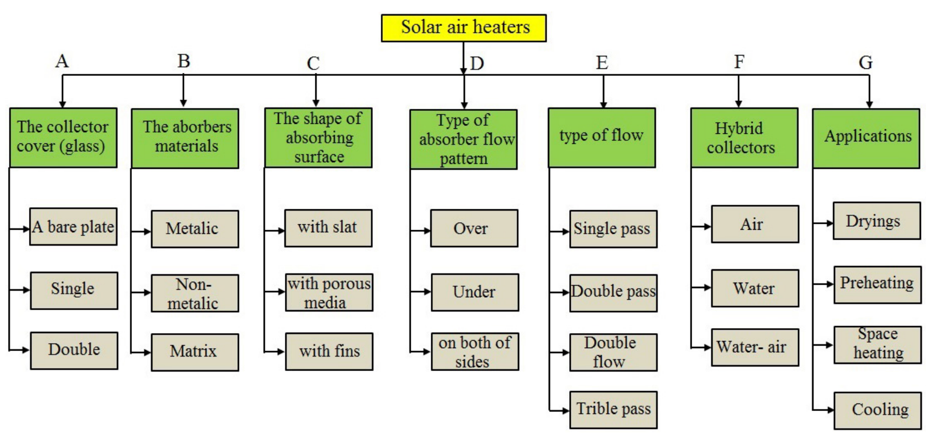

Figure 2: Classifications of solar air heaters [96].

3 Solar air heater performance study

3.1 Energy analysis

Solar air heater performance is evaluated by thermal efficiency which is the ratio of solar energy absorbed by the flowing air to solar energy received on the absorber area [1, 3]. This is represented by the following expression:

$$\eta_{th} = \frac{\dot{Q}_u}{\dot{Q}_A}\,. \tag{1}$$

The solar energy received by collector surface is given by

$$\dot{Q}_A = I A_c\,, \tag{2}$$

where I is the solar irradiance and A_c is the collector area, respectively.

The useful solar heat gained by flowing air is

$$\dot{Q}_u = \dot{m} C_{pf} \cdot \Delta T = \dot{m} C_{pf} \left(T_{fo} - T_{fi}\right), \tag{3}$$

where $\dot{m}$ is the mass flow rate of air, C_{pf} is the specific heat of air, and, T_{fo} and T_{fi} are the inlet and outlet air temperature, respectively.

Finally, the performance of SAH is written by the following equation [91,94,95]:

$$\eta_{th} = \frac{\dot{m} C_{pf} \left(T_{fo} - T_{fi}\right)}{I A_c}\,. \tag{4}$$

3.2 Exergy analysis

The concept of exergy analysis is very important for optimal utilization of energy in any system. Mostly this concept is used to plan for designing and industrial operations processes. The exergy efficiency is defined as the ratio of exergy gained by the flowing fluid to exergy gained by the system [3, 46–50].

For writing the exergetic equation in SAHs, following assumptions have been made:

(i) The experiments conducted at steady state condition.

(ii) Neglect the kinetic energy and potential energy.

(iii) Neglect the nuclear and chemical reactions.

(iv) Air is assumed as an ideal gas and its specific heat is constant.

(v) Work transfer direction from the system and heat transfer to the system are taken as positive.

Generally, energy and exergy balance equations can be expressed in rate form as [3, 36, 46–52]:

$$\sum \dot{E}_i = \sum \dot{E}_o \,, \tag{5}$$

$$\sum \dot{E}x_i - \sum \dot{E}x_o = \sum \dot{E}x_d \tag{6}$$

or

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,\,in} - \dot{E}x_{mass,\,out} = \dot{E}x_{dest} \,, \tag{7}$$

where, E is the energy rate and Ex is energy rate, and the subscript *in* stands for inlet, *out* for outlet, and *dest* for destruction.

Equation (7) can be written as in the general energy equation

$$\sum \left(1 - \frac{T_a}{T_s}\right) \dot{Q}_c - \dot{W} + \sum \dot{m}_i \psi_i - \sum \dot{m}_o \psi_o = \sum \dot{E}x_{dest} \,, \tag{8}$$

where, T_a and T_s are the temperatures of ambient and sun, respectively,

$$\dot{Q}_C = I A_C \,, \tag{9}$$

and the specific exergy is written as

$$\psi_i = (h_i - h_a) - T_a(s_i - s_a), \tag{10}$$

$$\psi_o = (h_o - h_a) - T_a(s_o - s_a) \,, \tag{11}$$

where h and s are the specific enthalpy and specific entropy, respectively.

From Eqs. (8) to (11) we get the expression

$$\left(1 - \frac{T_a}{T_s}\right) \dot{Q}_c - \dot{m} \left[(h_o - h_i) - T_a(s_o - s_i)\right] = \sum \dot{E}x_{dest} \,. \tag{12}$$

The enthalpy change and the entropy change of air are

$$\Delta h_{air} = h_o - h_i = C_{pf} \left(T_{fo} - T_{fi}\right) , \tag{13}$$

$$\Delta s_{air} = s_o - s_i = C_{pf} \ln \frac{T_{fo}}{T_{fi}} - R \ln \frac{P_o}{P_i} \,. \tag{14}$$

From Eqs. (12) to (14) the following expression can be obtained:

$$\left(1-\frac{T_a}{T_s}\right) IA_c - \dot{m}C_{pf}\left(T_{fo}-T_{fi}\right) + \dot{m}T_a\left(C_{pf}\ln\frac{T_{fo}}{T_{fi}} - R\ln\frac{P_o}{P_i}\right) = \sum \dot{E}x_{dest}. \tag{15}$$

The SAH exergetic efficiency is expressed by the ratio of net exergy output of the system to exergy input of the system [3]

$$\eta_{\mathrm{II}} = \frac{\dot{E}x_o}{\dot{E}x_i} = \frac{\dot{m}\left[(h_o-h_i) - T_a(s_o-s_i)\right]}{\left(1-\frac{T_a}{T_S}\right) IA_c}. \tag{16}$$

4 Case studies

Kurtbas and Durmus developed five various types of SAHs for analyzing the efficiency and exergetic analysis [53]. They conducted experiments with five different mass flow rates such as 0.012, 0.017, 0.022, 0.025, and 0.028 kg/s, and evaluated the experimental results with same radiations on the respective day. The radiation varies from 480–880 W/m^2. The maximum thermal efficiency observed for Type I: 29.25%, Type II: 44.3%, Type III: 60.4%, Type IV: 67%, and Type V: 16%. The effect of pressure loss on the exergy loss was found to be in the range of 12–15%. They concluded that the collector efficiency increases with $\dot{m}$ due to an enhancement in heat transfer to the flowing air. Also reported that the pressure loss, temperature difference $(T_{fo} - T_{fi})$, roughness geometry and collector efficiency, etc. are more important to examine the performances of SAH.

Ozturk and Demirel studied the energetic and exergetic performance of packed bed SAH using Raschig rings (Fig. 3) [54]. The experimental setup was designed with dimension 1.9 m × 0.9 m, and black painted absorber plate using aluminum material. They observed that the net $\eta_{\mathrm{I}} =$ 2.05−33.78% and $\eta_{\mathrm{II}} = 0.01-2.16\%$. Also obtained the average values of η_{I} and η_{II} as 17.51 and 0.91%, respectively. They reported that η_{I} and η_{II} increases with increase in T_{fo}.

Ozturk investigated the first and second law of thermodynamics of seasonal latent heat storage (LHS) system with 180 m^2 floor area [55]. For thermal storage, phase change material (PCM) – paraffin wax was used. The schematic diagram of LHS system for greenhouse heating is shown in

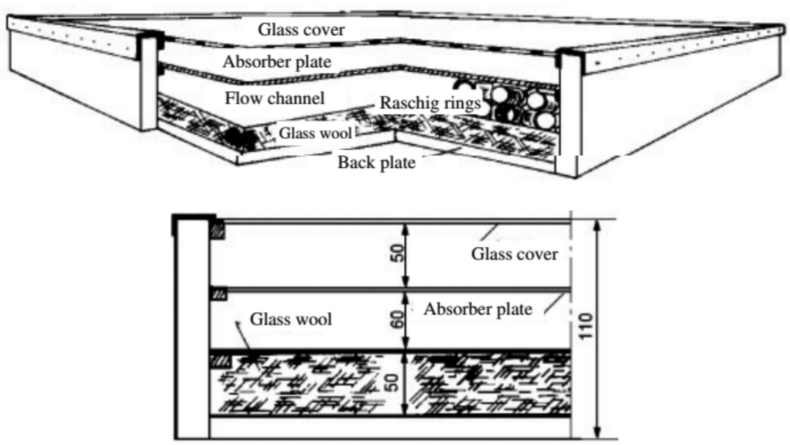

Figure 3: Packed-bed SAH.

Fig. 4. The experimental setup developed with five units, such as heat collection unit using SAC (solar air collector), heat transfer unit, LHS unit, data acquisition unit and greenhouse. They reported that the average values of storage in LHS unit and exergy transfer were 79.9 W and 111.2 W, respectively, and also found that the average values of $\eta_{\rm I}$ and $\eta_{\rm II}$ were 40.4% and 4.2%, respectively.

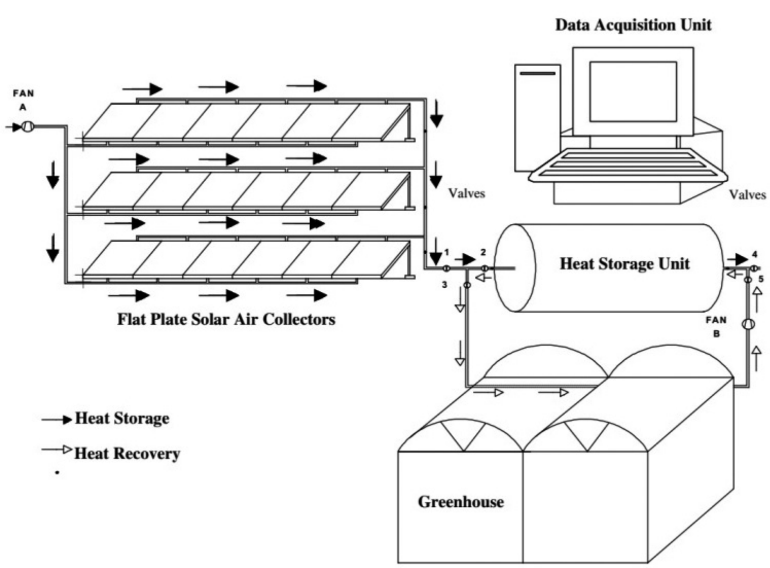

Figure 4: The schematic arrangements of LHS system for greenhouse heating.

Ajam *et al.* [56] worked on an exergetic optimization of SAH. For this objective, they developed the mathematical model of optical and thermal performance and programming is coded in Matlab software. They reported that the concept of exergetic is a superior technique to design, development and optimization for SAHs.

Kurtbas and Turgut studied the energy and exergy efficiency of SAH with fixed and free fins (Fig. 5) [57]. To achieve this aim, they conducted experiments with $\dot{m} = 0.03$–0.08 kg/s. They reported that the fixed fin SAC performs better than free fin collector, also found that the heat transfer and Ex_{loss}, both are increases with ΔP increases.

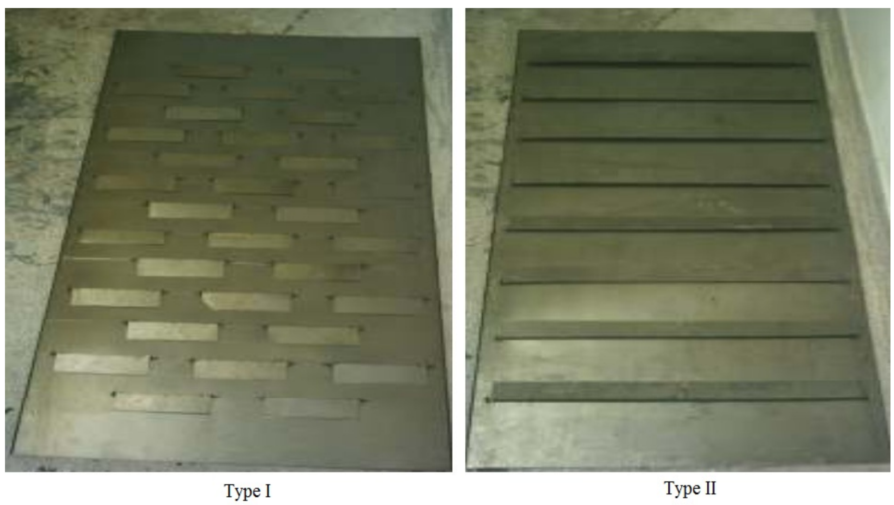

Figure 5: Pictorial view of fixed fins (Type II) and free fins (Type I) absorber plate.

Ucar and Inallı examined the thermal and exergetic performance of SACs with passive augmentation techniques [58]. For this aim they used five types of collectors (Fig. 6). They performed experiments and reported that the collector efficiency increases 10–30% using the passive techniques as compared to flat plate solar collector.

Karslı designed a novel type of SAC which is used for drying and evaluated the energetic and exergetic efficiencies [59]. For this aim, they developed experimental setup with four types of collectors (Fig. 7) and found that the η_{I} changed from 26%–80% for Type I, Type II: 26–42%, Type III: 60–70%, and Type IV: 26–64%. They obtained the η_{II} for all collectors as 0.27–0.64.

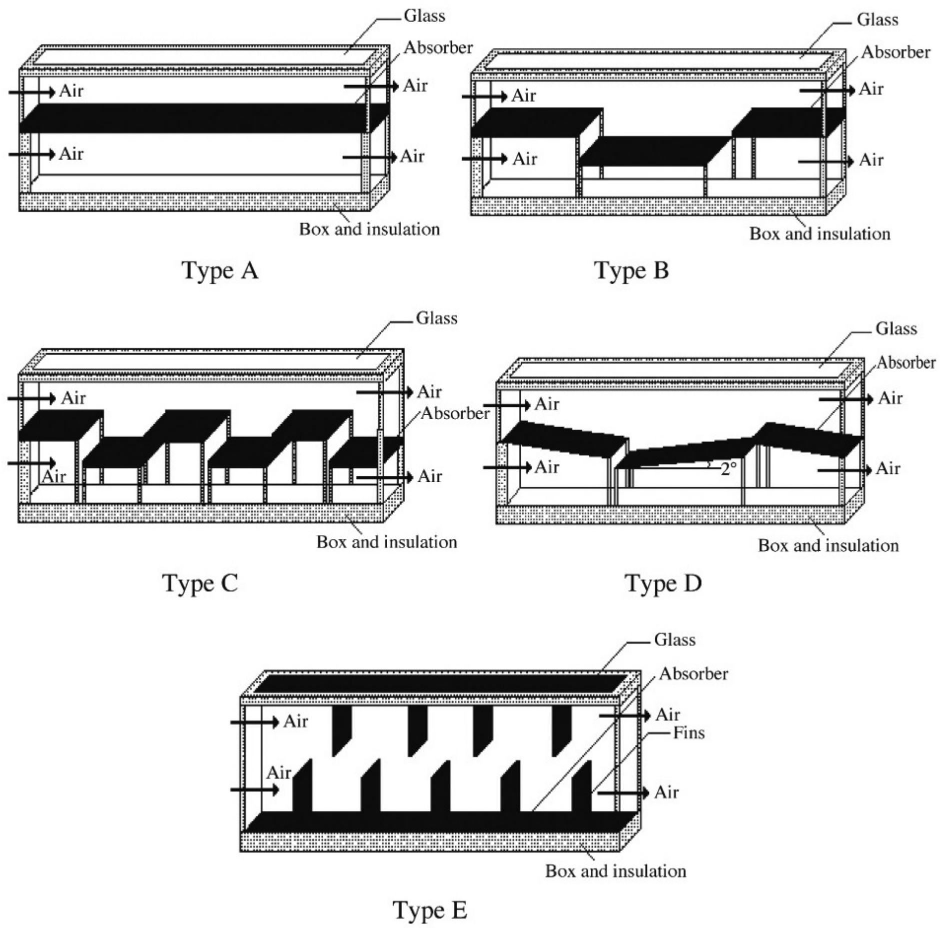

Figure 6: Solar air collectors.

Esen conducted an experiment with double flow SAH using with and without obstacles type absorber plates (Fig. 8) [60]. The experiments were conducted with $\dot{m}$ from 0.015 kg/s to 0.025 kg/s. By applying the concept of energetic and exergetic, it was found that the obstacles type SAHs performs better as compared to without obstacles type SAH at same operating conditions. From the experimental results it was found that highest efficiency for Type III SAC as compared to FPC (flat plate collector) and largest irreversibility occurred at FPC. Author obtained maximum $\eta_{\rm II}$ as 60.97% at $\dot{m} = 0.025$ kg/s for Type III at state II and lowest as 25.65% at $\dot{m} = 0.015$ kg/s for Type I at state I.

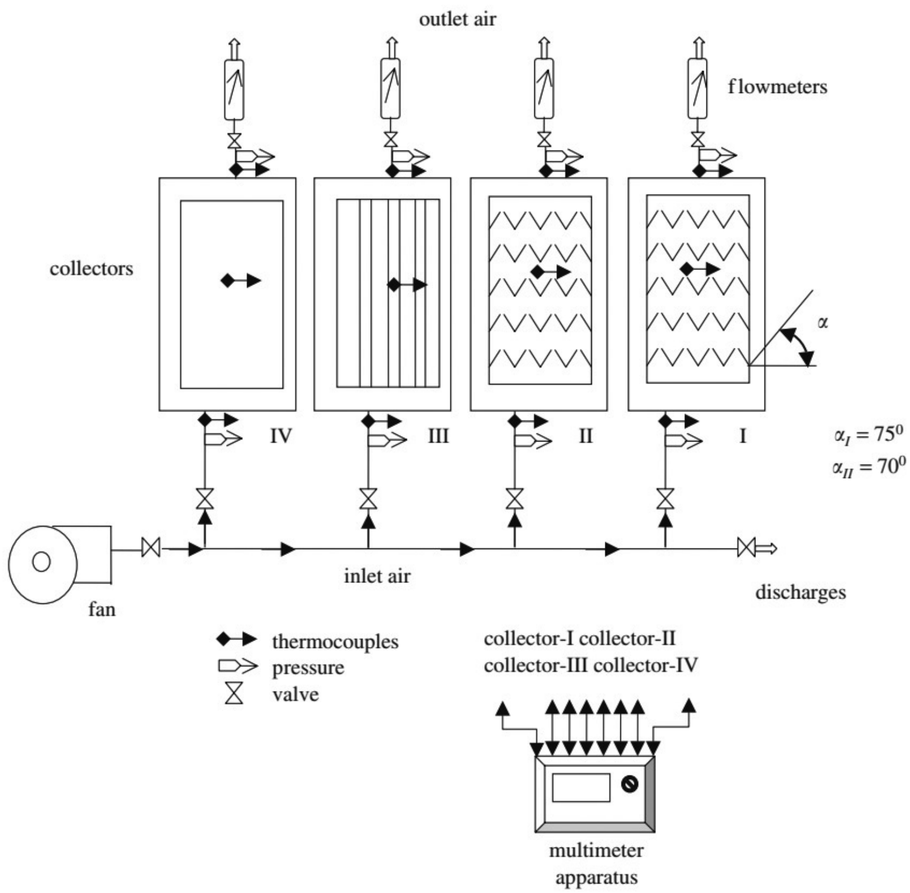

Figure 7: Experimental setup.

Gupta and Kaushik studied the exergetic performance of flat-plate SAH to achieve optimal performance [61]. They analytically evaluated the $\dot{E}_{out}$ and $\dot{E}x_{out}$ for various values of duct depth, $\dot{m}$ per unit area of the collector and aspect ratio. They found that maximum $\dot{E}x_{out}$ is observed at minimum value of $\dot{m}$ when the T_{fi} is low. Gupta and Kaushik analytically studied the energy, exergy and effective efficiencies of various types of roughness [62]. They selected six different types of roughness such as wedge shaped rib (Type I), circular ribs (Type II), V shaped ribs (Type III), chamfered rib-groove (Type IV), expanded metal mesh (Type V) and rib-grooved (Type VI). By the use of correlations they coded the program in Matlab software and calculated the η_{I}, η_{II}, and η_{eff}. They found that the efficien-

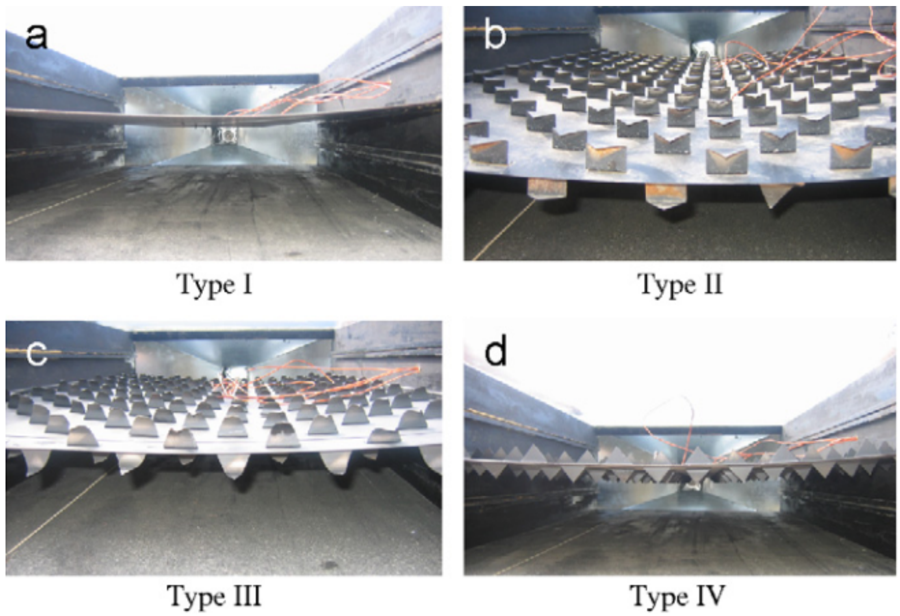

Figure 8: Photographic view of absorber plates.

cies are improved by using roughness as compared to the smooth surface (Type VII). Investigators reported that the energy efficiencies are generally increases in the following sequence of roughness types: smooth surface, circular ribs, V-shaped ribs, wedge shaped rib, expanded metal mesh, rib-grooved, and chamfered rib-groove (Fig. 9). It was also found that the exergy efficiency gets high for higher Re for circular ribs and V shaped ribs absorber surface, while at low Reynolds number chamfered rib-groove absorber surface gives high exergy efficiency.

Farahat *et al.* [63] performed analytical work for designing and optimization of flat plate solar collector using exergy concept. To achieve this aim, they programmed a computation code in Matlab software and evaluated η_{th} and η_{II}. They reported that the optical efficiency effects the exergy efficiency and in case of increasing the T_{fi}, the η_{II} increases but at maximum value of T_{fi}, the η_{II} decreases quickly.

Akpinar and Kocyigit developed a new design of SAH with and without obstacles and experimentally investigated the performances [64]. The four different absorber surfaces (Fig. 10) were used as: Type 1: the triangular obstacles of 5 cm × 5 cm dimension were manufactured and the obstacles were situated on the absorber plate at 10 cm intervals with 3.5 cm distance be-

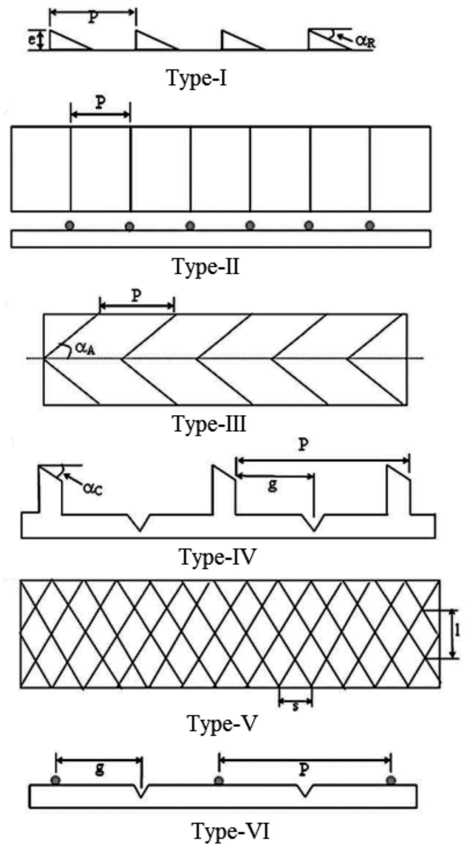

Figure 9: Roughness geometry of different investigators [62]: P – roughness pitch, e – roughness height, α_A – angle of attack for V-shaped rib, α_C – chamfer angle of rib, α_R – rib wedge angle, g – groove position, l – long way of mesh, s – short way of mesh.

tween successive lines. Type 2: the leaf shaped obstacles of 5 cm × 5 cm dimension were situated on the absorber plate at 10 cm intervals with 3.5 cm distance between successive lines. Type 3: the rectangular obstacles of 10 cm × 10 cm dimensions were situated at 2.5 cm intervals with at a 45° angle on the absorber plate. Type 4: there are no obstacles on the absorbent surface. The photographic view of absorber surface is shown in Fig. 11 which was used in the experiment. They conducted experiments using $\dot{m}$ at 0.0052 kg/s and 0.0074 kg/s. After the analyzing the energy and exergy analysis, it was found that the η_{th} varies from 20% to 82% while, the η_{II} varied from 8.32% to 44% at same operating condition. They also found that the solar intensity and geometry of absorber plate effects the efficiency of SAHs.

Alta *et al.* [65] fabricated new design of SAHs and investigated the energy and exergetic efficiency. They constructed the absorber plate using fins and

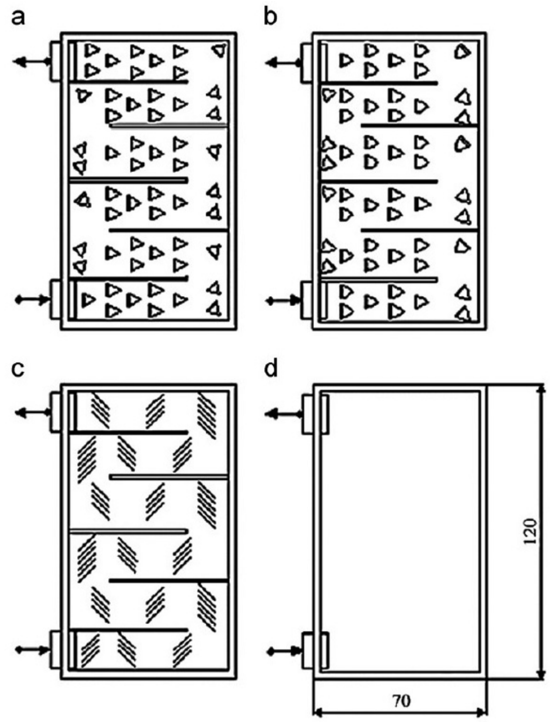

Figure 10: Schematic views of absorber plates: (a) with the triangular type obstacles, (b) with leaf type obstacles, (c) with rectangular type obstacles, and (d) without obstacles [64].

without fins as shown in Fig. 12. They evaluated the thermal and exergy efficiency for without fin, with fins using single glass cover and with fins using double glass cover at various air flow rates (25, 50, and 100 m^3/m^2h) with the tilt angle of 0°, 15°, and 30°. They found that the finned SAH with double glass cover was more effective due to the higher temperature difference as compared to without finned SAH. The maximum energy efficiency obtained as 39.05% for Type II, at tilt angle 30° and air flow rate 100 m^3/m^2h, on the other side the maximum exergy efficiency observed as 0.83% for Type II at tilt angle 0° and air flow rate 100 m^3/m^2h.

Tyagi *et al.* [66] applied the concept of I and II law of thermodynamics for evacuated tube collectors (ETC) type SACs. They developed ETC SACs using 12 numbers of tubes with thermal heat storage (THS) and without THS. Authors used two different materials for THS such as paraffin wax and hytherm oil. They found that the η_{th} and η_{II} of with THS SAHs performs

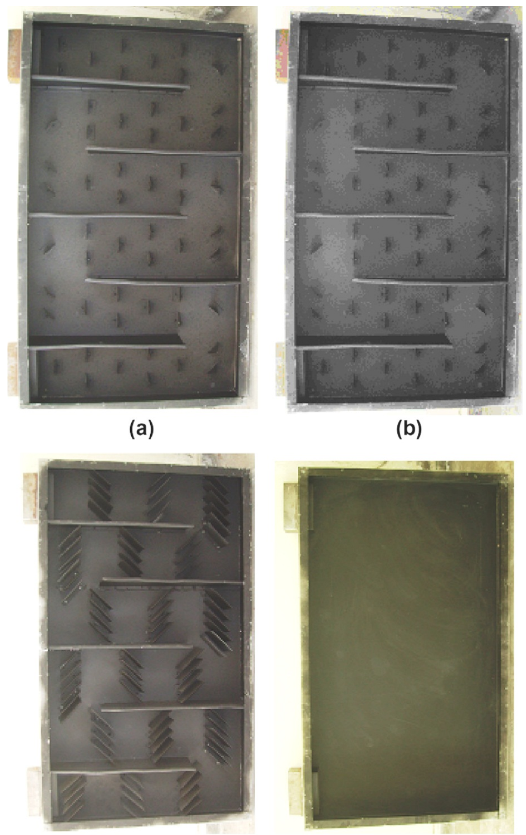

Figure 11: Photographic view of absorber plates with various obstacles.

better than the without THS solar collector also observed that the η_{th} and η_{II} of SAC using paraffinis greater then η_{th} and η_{II} of SAC using hytherm oil.

Bouadila *et al.* [67] designed a novel type of packed bed SAH using spherical capsules (Fig. 13) for analysis of energetic and exergetic performance. To achieve this object they conducted experiments and applied I law and II law of thermodynamics for calculating the η_{I} and η_{II}. They found that the net daily η_{I} from 32% to 45%, while the daily η_{II} from 13% to 25%. Then they developed a new packed bed SAH using PCM (phase change material) spherical capsules (Fig. 14) [70]. They conducted experiments and evaluated the energetic and exergetic performances using the first and second law of thermodynamics. They observed that the daily η_{th} = 32–45% and η_{II} = 13–25%, also found that the $\dot{m}$ of air effects the T_{fo} of SAH.

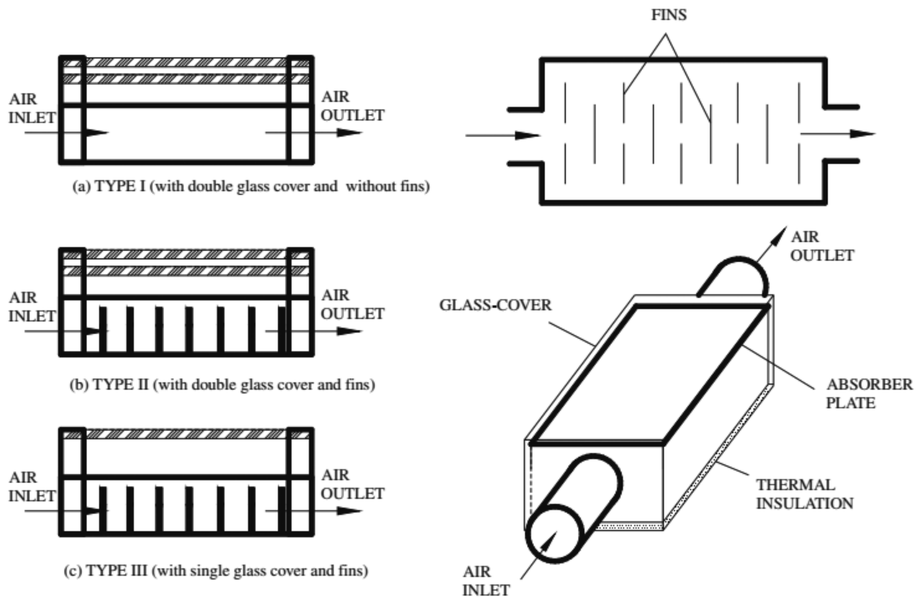

Figure 12: Construction details of different types of SAHs.

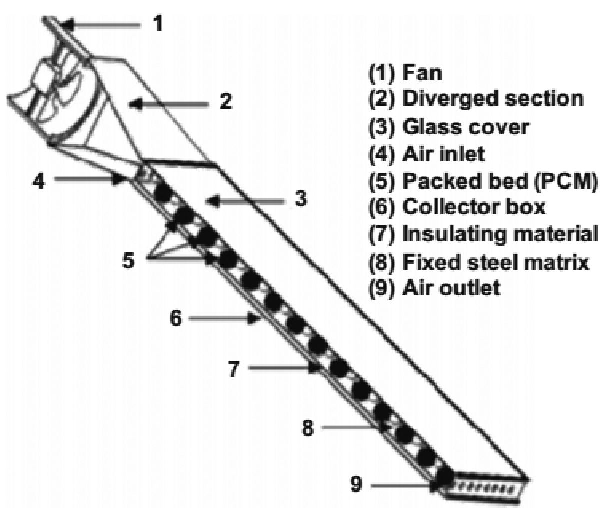

Figure 13: Schematic diagram of packed bed SAH.

Benli applied the concept of the first and second law of thermodynamics for evaluating the energetic and exergetic efficiency of new designed SAH

Figure 14: Photographic view of packed bed SAH using PCM spherical capsules.

with different absorber surface [68]. Author constructed four different types of absorber plate which is given in Fig. 15, also used the smooth absorber plate. The experiments were conducted with various $\dot{m}$ from 0.02 kg/s to 0.05 kg/s. Investigator obtained that the efficiency of solar collectors increases with increasing roughness of absorber plate and also observed that the heat transfer and pressure loss increases in the same time.

Bayrak *et al.* [69] designed new type of SAH using porous baffles inserted (Fig.16). They used energy and exergy analysis method for SAH performance. They conducted experiments with two different $\dot{m}$ such as 0.016 kg/s and 0.025 kg/s, and used five different cases. From the experimental result, it was found that the maximum η_{th} and η_{II}, and temperature difference obtained for 6 mm thickness of porous materials at $\dot{m}$ = 0.025 kg/s in case III, while the minimum values are obtained for the flat plate SAC at $\dot{m}$ = 0.016 kg/s in case I.

Velmurugan and Kalaivanan developed the energy balance equation for single, double, and triple pass SAHs to analyze the energetic and exergetic performances [71]. They programmed a simulation code in Matlab software

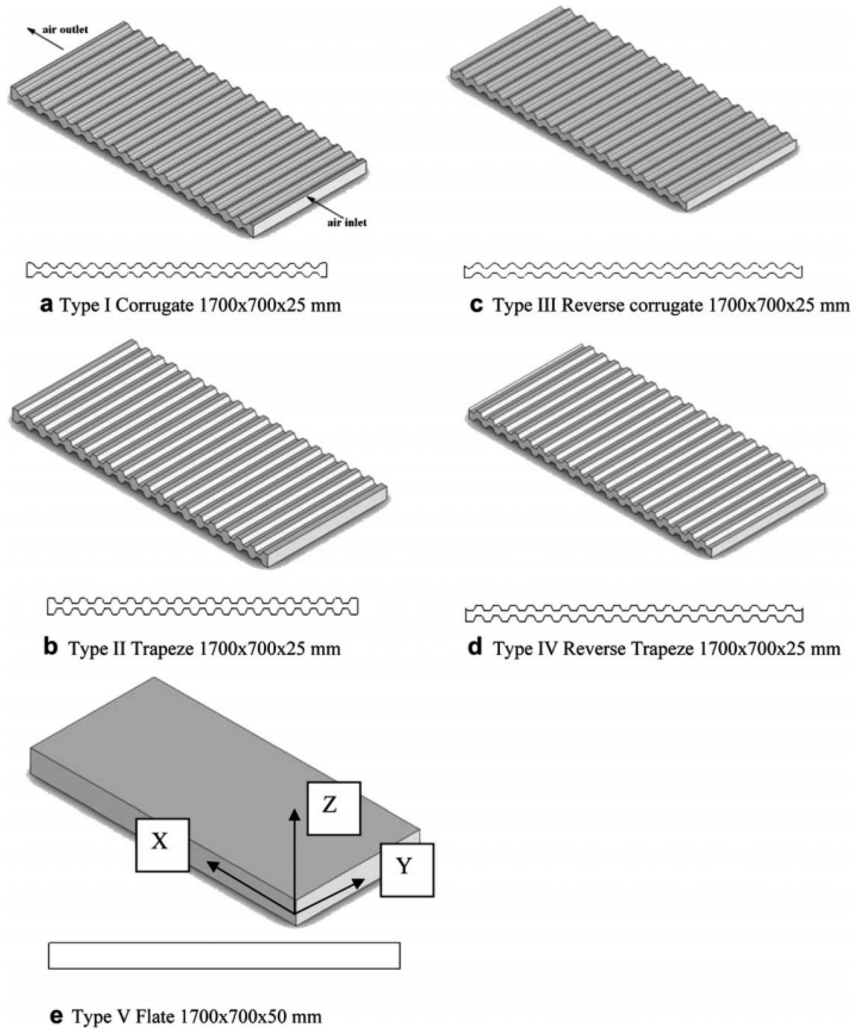

Figure 15: Different types of absorber plates.

for calculating the η_{th} and η_{II}. They studied the effect of $\dot{m}$ on energetic efficiency, exergetic efficiency, improvement efficiency, irreversibility and rise in temperature difference. It was found that triple pass SAH performed better than the single and double pass SAH. They experimentally studied the energetic and exergetic performance of SAHs having single pass smooth absorber plate, double pass roughened absorber plate, double pass finned absorber plate and double pass wire mesh absorber plate [73]. They carried out

Figure 16: Photographic view of SAHs.

experiments with the $\dot{m}$ from 0.01 kg/s to 0.04 kg/s and I from 500 W/m^2 to 600 W/m^2. They concluded that the double pass wire mesh SAH performed better as compared to duel pass finned and roughened SAH. Also found that a maximum efficiency 76.46% obtained at $\dot{m} = 0.04$ kg/s, and the maximum temperature rise of air obtained as 25.2 °C at $\dot{m} = 0.01$ kg/s for wire mesh SAH. They also studied analytically the performances of four different types of SAHs and found that the results of analytical and experimental studies are satisfactory. They also analyzed the energy and exergy the dual pass SAH [76]. In the first pass, they used longitudinal fins on the absorber plate and different absorber surface geometry such as v-corrugated, finned, roughened and finned, wire mesh were used in the second pass of experimental system. Both researchers studied that the effects of various $\dot{m}$ and I on temperature rise of air, η_{th}, $\dot{E}x_{gain}$, and ΔP at steady-state condition. They found that the temperature rise of air, η_{th} and $\dot{E}x_{gain}$ depend on $\dot{m}$, geometry of absorber surface and I, while the ΔP depends on $\dot{m}$ and geometries of absorber surface.

Bahrehmand *et al.* [72] evaluated the SAC performances with single and two glasses cover having fins with and without thin metal sheet at forced convection flow. They developed mathematical model and coded a program for numerical calculations of energetic and exergetic efficiencies.

They observed that the without fins collectors, having a two glass cover and thin metal sheet is more efficient among collectors at low Reynolds number, while the single glass cover and thin metal sheet is more efficient at higher Reynolds number. Bahrehmand and Ameri studied the performance of single and double glass cover SAC. To achieve this aim, authors implemented the energetic and exergetic concept of thermodynamics [74]. They performed analytical study and examined the effect of triangular and rectangular shapes longitudinal fins, length and depth of channel and tin metal sheet suspended in the middle of the air channel on η_{th} and η_{II} of SACs. They concluded that the double glass covers SAC performs better than single-glass cover SAC. In case of fins: the triangular fins collectors performed better than rectangular fins collectors.

Kalaiarasi *et al.* [75] investigated experimentally new type of SAHs having copper tubes with extended copper fins as absorber. The experiments were conducted with $\dot{m}$ at 0.018 kg/s, and 0.026 kg/s. They used the first law and second law of thermodynamics for energy and exergy analysis, and found that the maximum $\eta_{\mathrm{I}} = 49.4$–59.2% and $\eta_{\mathrm{II}} = 18.25$–$35.53\%$ at $\dot{m} = 0.026$ kg/s for sensible heat storage SAH. Authors also reported that the SAH having sensible heat storage performed better than the conventional SAH.

Edalatpour *et al.* [77] designed and fabricated a double-glazed SAH using the phase change material (Fig. 17). They conducted experiments under the climatic condition of Mashhad, Iran, and studied energy, exergy and cost analysis of SAH. From the energy and exergy analysis, authors observed

Figure 17: Photographic view of double-glazed SAH.

that the daily η_{th} from 58.33% to 68.77%, whereas the daily η_{II} varies from 14.45% to 26.34%. Also predicted that the cost of 1 kg of heated air was 0.0036 US dollar when utilizing the double-glazed SAH.

Acır *et al.* [78] developed a novel type of SAH having circular turbulators absorber plate and investigated the energetic and exergetic performance. They used four black painted copper tubes (Fig. 18) having various obstacle relief angles (45°, 90°, 135°, and plain tube) are inserted inside the tube. Experiments were conducted at various $\dot{m}$ which are 0.0023, 0.0033, 0.0044, and 0.0055 kg/s. They observed that the η_I = 28.6–79.5% and η_{II} = 8.1–42.4%. The highest η_I and η_{II} obtained at 0.0055 kg/s having 45° obstacle relief angle. Acır *et al.* [80] performed the energetic and exergetic analysis of a new type of SAH. They used grey relational analysis (GRA) to observe the optimum parameters also investigate the effect of different obstacle relief angles, obstacle distances and Reynolds number on η_I and η_{II}. They also used regression analysis for predicting the η_I and η_{II}, and compared with actual data of experiments. Acır *et al.* [85] evaluated the energy and exergy analysis of a new type SAH. They conducted experiments with plain tube having varying hole number (HN = 2, 4, and 6) inserted inside the tube of SAHs (Fig. 19). They calculated η_I and η_{II} at $\dot{m}$ = 0.0023; 0.0033; 0.0044, and 0.0055 kg/s. The maximum η_I and η_{II} as $58.3 \pm 0.63\%$ and $20.7 \pm 1\%$, respectively, for HN = 2 at $\dot{m}$ = 0.0055 kg/s were found at noon. Also observed that the efficiencies of SAHs improved with increases in $\dot{m}$ and decreasing hole number above circular turbulators.

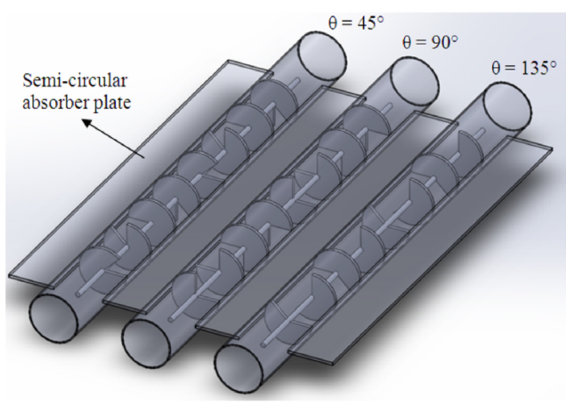

Figure 18: General view of semi-circular absorber plates.

Ghiami *et al.* [79] developed a novel type of a single-pass double-glazed solar air heater with the use of packed bed paraffin wax as a phase change

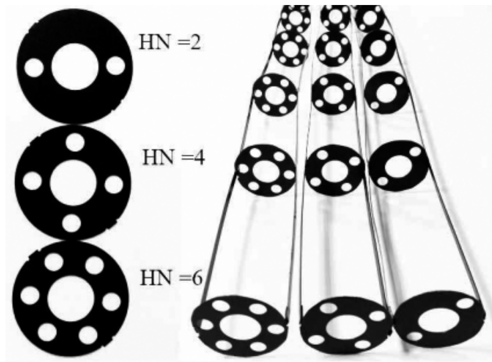

Figure 19: Schematic diagram of circular shaped turbulator having varying hole number.

material. They evaluated the performance on the basis of energy and exergy analysis. They reported that the daily energy efficiency varied between 20.7% and 26.8%, whereas the daily exergy efficiency varied between 10.7% and 19.5%. Ghiami and Ghiami [83] designed a novel type of SAH using PCM and studied of energy and exergy analysis. For this aim, they conducted experiments at three different $\dot{m}$ of 0.009, 0.014, and 0.017 kg/s and calculated the η_{I} and η_{II} using the concept of first law and second law of thermodynamics respectively. They found that the maximum η_{I} was attained for sequence-arranged baffle-equipped SAH (26.78%), while unequipped SAH had the least η_{I} (14.30%) at 0.017 kg/s, also observed that the η_{II} = 4.86–20.47% for all cases.

Ghritlahre and Prasad developed the neural model to predict the η_{I} and η_{II} of roughened SAH [81]. For this aim, first phase authors conducted experiments with $\dot{m}$ from 0.010 kg/s to 0.0175 kg/s using roughened collector surface as shown in Fig. 20 and calculated the η_{I} and η_{II}. Total 60 data sets were collected from the experiments and calculation. In second phase,

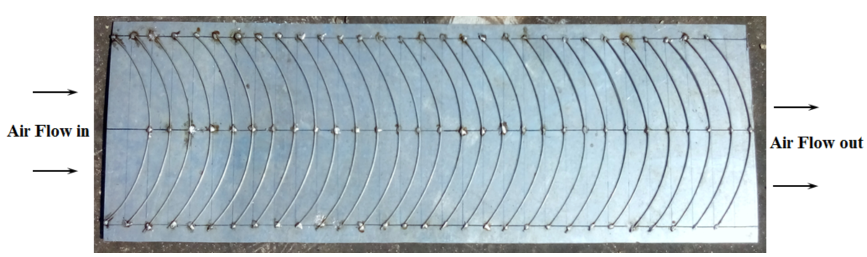

Figure 20: Photographic view of absorber plate.

they structured neural model with six input parameters and two output parameters as $\eta_{\rm I}$ and $\eta_{\rm II}$, and 4 to 7 number of neurons were selected in hidden layer. They trained the neural model using the Levenberg–Marquardt (L-M) training algorithm and found that the 6-6-2 neural model was optimal model for prediction. Ghritlahre [88] implemented neural model to predict the $\eta_{\rm I}$ and $\eta_{\rm II}$ of roughened SAH. For this object, author conducted experimentations using three different specifications of transverse wire rib roughened absorber plate and collected 50 sets of data. The neural model was structured with 6 input parameters and 2 output parameters and 4 to 7 numbers of neurons were selected in hidden layer. The training algorithms such as trainlm and trainscg were applied for training process. The author found that the L-M with 6-6-2 neural model (Fig. 21) was optimal model for prediction.

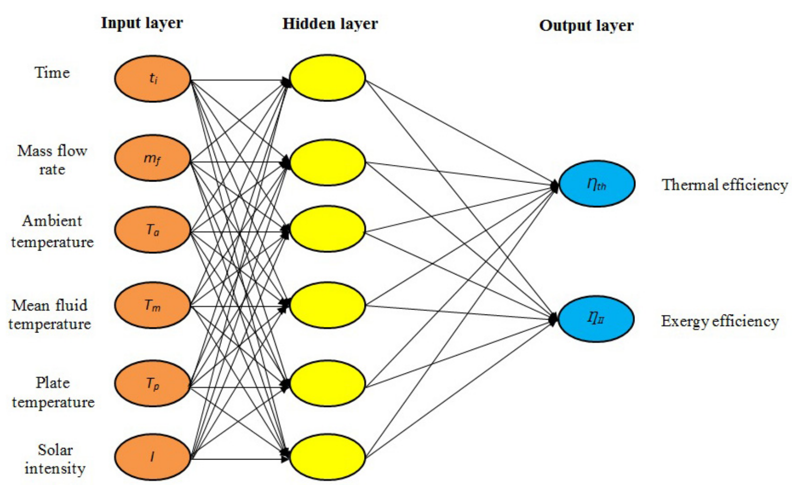

Figure 21: ANN model with neurons 6-6-2.

Saha and Sharma developed an analytical energy balance equations for study the energy and exergy analysis of double flow corrugated SAH [82]. They used three different types of corrugated surface (SA-1, SA-2, and SA-3) and for comparative investigation smooth absorber plate (SA-4) were also taken. A computation analytical program was developed in C^{++} software. Authors found that the maximum energy efficiency as 7.20% at $\dot{m}$ = 0.035 kg/s and also obtained that the $\eta_{\rm II}$ become negative at higher $\dot{m}$ ($\dot{m}$ > 0.072 kg/s) for all SAHs. They reported that the at specific $\dot{m}$: $\eta_{\rm I}$, $\eta_{\rm II}$, η_{eff} and ΔT increases with increase in solar intensity for all collectors.

Abuşka developed a new absorber plate with conical surface (Fig. 22) for SAH and conducted experiments with $\dot{m}$ from 0.04 kg/s to 0.10 kg/s [84]. Using the concept of energy and exergy analysis, it was found that the average η_{I} was obtained as 63.2–57.2% at 0.04 kg/s, 71.5–61.7% at 0.08 kg/s, and 74.6–64.0% at 0.10 kg/s in conical and smooth absorber plate, respectively. Similarly, on the other side, the average η_{II} was obtained as 19.3–16.1% at 0.04 kg/s, 15.1–11.5% at 0.08 kg/s, and 12.5–9.2% at 0.1 kg/s in conical and smooth absorber surface, respectively. Also found that 10% higher thermal efficiency of conical surface type SAH as compare to conventional SAH.

Figure 22: Photographic view of absorber plates with conical surface and smooth SAHs.

Debnath *et al.* [86] conducted experiments with SAH using flat plate absorber surface and evaluated the energetic and exergetic efficiencies at different tilt angle and spacing (Fig. 23). They measured parameters during experiments such as atmospheric temperature, absorber plate temperature, T_{fi}, T_{fo}, and I. They found that at tilt angle 24.83° and spacing 0.045 m observe best performance at $\dot{m} = 0.0118$ kg/s.

Devecioğlu *et al.* [87] designed and fabricated a novel SAH using absorber plate covered by wire mesh of copper material and conducted experiments at two mass flow rate using 0.030 kg/s and 0.055 kg/s, and collector tilt angles of 25° and 35°. They studied the energy and exergy analysis using the first and second law of thermodynamics respectively, and also the thermo-

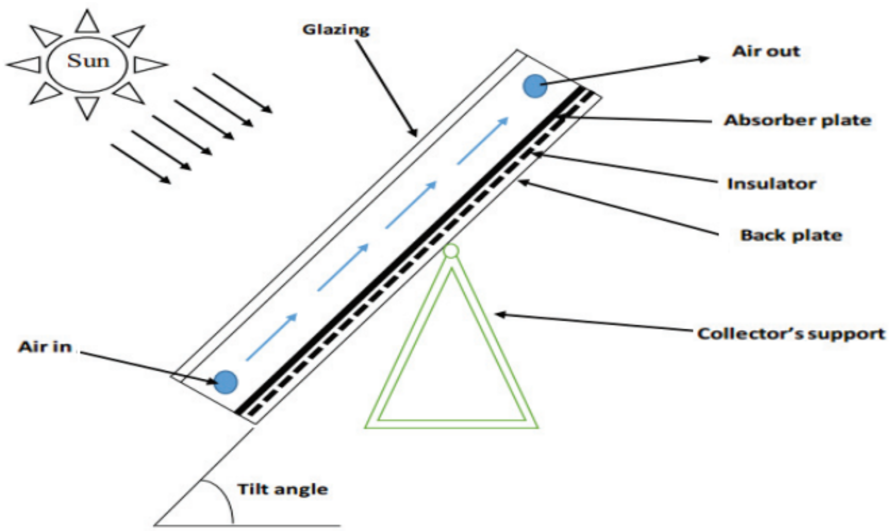

Figure 23: Schematic diagram of SAH [86].

hydraulic efficiency. From the results, it was found that $\eta_{\mathrm{I}} = 34$–82%, $\eta_{eff} = 25$–66% and $\eta_{\mathrm{II}} = 3.70$–$9.65\%$. They also suggested that at higher $\dot{m}$ and the lower tilt angle promotes improvements in η_{I} and η_{II} of SAH.

Matheswaran *et al.* [89] analytically studied η_{I} and η_{II} of the single pass double duct jet plate SAH. They coded a program in Matlab software for calculation of the energy and exergy efficiency. They developed a corrections for predicting η_{II} using the factors such as Reynolds number and design variables of jet plate. Matheswaran *et al.* [90] analytically studied the energetic, exergetic and enviro-economic performance analysis of parallel pass jet plate SAH using artificial roughness. They computed the energy, exergy and enviro-economic results by program coded in Matlab software. The authors reported that the single-pass double-duct jet plate SAH improves annual energy and exergy gain by 111.7% and 185.6%, respectively.

Aktaş *et al.* [92] developed a novel design of SAH using multipass collector with perforated fins (Fig. 24). They conducted experiments in two different conditions and examined the energetic and exergetic performances. The experiments were performed with $\dot{m}$ using 0.0069 kg/s and 0.0087 kg/s. They found that the η_{I} for dual pass solar air collector (DPSAC) varied from 30.37% to 69.03%, for multipass solar air collector (MPSACF) varied from 48.88% to 83.47%. Also reported η_{II} of DPSAC and MPSACF were 2.10–17.12% and 8.74–23.97%, respectively.

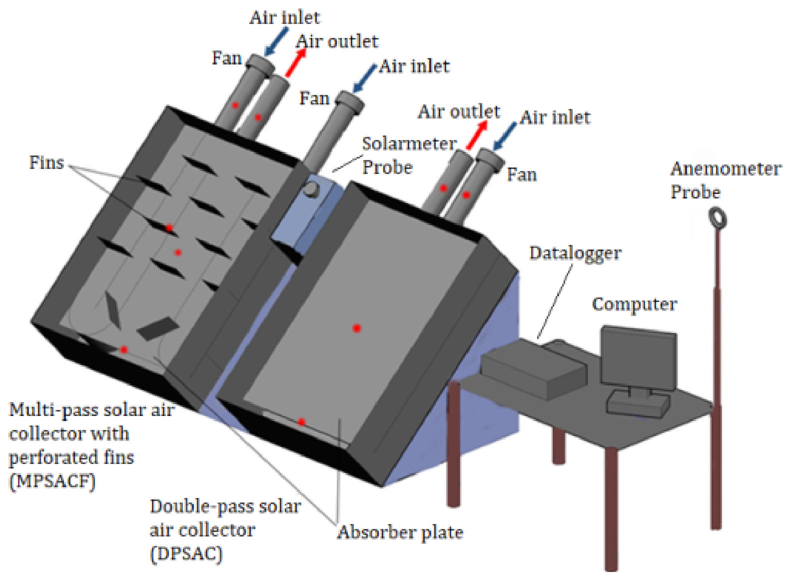

Figure 24: Schematic diagram of multi-pass SAC with perforated fins.

Kumar and Layak analytically examined the energy and exergy efficiency of SAH using twisted rib roughness (Fig. 25) on absorber plate [93]. They coded a program in Matlab software for calculation of the η_{th} and η_{II}. They found that the maximum enhancement in η_{th}, η_{eff}, and η_{exergy} as 1.81, 1.79, and 1.81 times, respectively, as compared to the smooth duct.

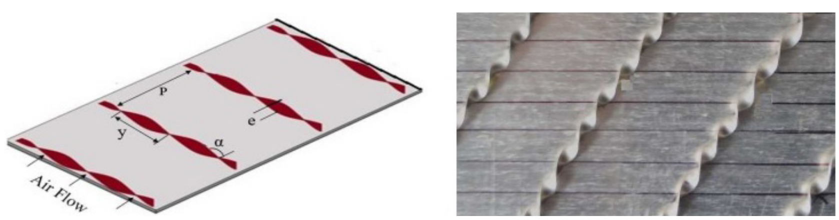

Figure 25: Schematic layout of the absorber plate.

4.1 Summary report on performance analysis of solar air heaters using the concept of energy and exergy

The concept of energy and exergy used by various researchers [53–93] on solar air heaters are shown in Tab. 1.

Table 1: Summary of reviewed papers of energy and exergy concept implemented in SAHs.

Author(s)	Year	Mass flow rate/ Air flow/ Reynolds number	Type of study	Results	References
Kurtbas and Durmus	2004	0.012, 0.017, 0.022, 0.025, 0.028 kg/s	Experimental	Heat transfer and pressure loss increases with increase in roughness of absorber plate. Also observed that ΔT of air, $\eta_{collector}$ and pressure loss are important parameters to decrease the Ex_{loss}. Maximum thermal efficiency observed for Type I: 29.25, Type II: 44.3%, Type III: 60.4%. Type IV: 67% and Type V: 16%. Effect of pressure loss on the exergy loss found to be in the range of 12–15%	[53]
Ozturk and Demirel	2004	600 m^3/h	Experimental	$\eta_{th} = 2.05$–33.78% and $\eta_{\mathrm{II}} = 0.01$–2.16%	[54]
Ajam *et al.*	2005	0.0736 kg/s	Analytical	Exergetic concept is a method to design, development and optimization of SAH	[55]
Ozturk	2005	600 m^3/h	Experimental	Average net $\eta_{th} = 40.2$ and $\eta_{\mathrm{II}} = 4.2\%$	[56]
Kurtbas and Turgut	2006	0.03–0.08 kg/s	Experimental	Fixed fin performed better as compared to free fin absorber. The maximum efficiency of Type II having free fins changed between 36% and 77% and fixed fins changed between 37% and 81% depending on mass flow rate of the air. Moreover, exergy loss ratio for Type I changed between 1.57 and 0.22 times and Type II changed between 1.55 and 0.17 times of heat gained	[57]
Ucar and Inalli	2006	0.008–0.026 kg/s	Experimental	The lower the efficiency of Type-I absorber plate (convention solar collector) the higher is irreversibility. Maximum η_{exergy} obtained as 56.09% of Type D, while the lowest η_{exergy} as 35.61% for Type A	[58]
Karsli	2007		Experimental	$\eta_{th} = 26 - 80\%$ and $\eta_{\mathrm{II}} = 0.27$–0.64 for all collectors	[59]

continued Tab. 1

Esen	2008	0.015–0.025 kg/s	Experimental	Obstacles type SAHs perform better as compared to without obstacles type SAH at all operating conditions. The mean η_{I} of Type III at states I–III is 46%, 58%, and 53%, respectively, at mass flow rate = 0.025 kg/s. For Type III, maximum $\eta_{\mathrm{II}} = 60.97\%$ at state-II and $\dot{m} = 0.025$ kg/s	[60]
Gupta and Kaushik	2008	$G = 0$–250 kg/hm^2	Analytical	Maximum Ex_{out} observed at lower $\dot{m}$, when T_{fi} is low	[61]
Gupta and Kaushik	2009	Re = 4000−21000	Analytical	Analytically studied the energy, exergy and effective efficiencies of various types of roughness	[62]
Farahat *et al.*	2009	0.001–0.009 kg/s	Analytical	Analytical work performed for designing and optimization of conventional solar collector by exergy concept. Reported that η_{II} increases from 0 to 5.4%	[63]
Akpinar and Kocyigit	2010	0.0052–0.0074 kg/s	Experimental	Concluded that $\eta_{\mathrm{I}} = 20$–82%, while $\eta_{\mathrm{II}} = 8.32$–$44\%$ at similar conditions	[64]
Alta *et al.*	2010	25, 50, 100 m^3/m^2 h	Experimental	The double glass cover with fins SAH (Type II) observed high efficient due to high ΔT. For air flow 100 m^3/m^{2}h, the maximum η_{I} obtained as 39.0525% at tilt angle 30°, while maximum η_{II} as 0.8340% at 0°	[65]
Tyagi *et al.*	2012	10, 20, 30, 40 l/min	Experimental	The performance of solar thermal heat storage collector was evaluated by the first and second law of thermodynamics	[66]
Bouadila *et al.*	2013	Blow air with fixed 1 m/s	Experimental	$\eta_{\mathrm{I}} = 32$–45%, while $\eta_{\mathrm{II}} = 13$–25%	[67]
Benli	2013	0.02–0.05 kg/s	Experimental	The solar collector efficiency increases with increase in roughness of absorber plate and also heat transfer and pressure loss increases in same time. At $\dot{m} = 0.036$ kg/s, the maximum energy efficiency obtained as: Type I: 39%, Type II: 33%, Type III: 27%, Type IV: 17%, while the lowest exergy loss obtained for Type I	[68]
Bayrak *et al.*	2013	0.016, 0.025 kg/s	Experimental	$\eta_{\mathrm{I}} = 39.35$–$77.57\%$ and $\eta_{\mathrm{II}} = 21.55$–$54.54\%$	[69]
Bouadila *et al.*	2014	Air velocity: 0.75, 1, 1.5, 1.75 m/s	Experimental	Performance of a packed bed SAH studied using PCM spherical capsules using the first and second law of thermodynamics. Reported that $\eta_{th} = 32$–45%, while $\eta_{\mathrm{II}} = 13$–25%	[70]

continued Tab. 1

Velmurugan and Kalaivanan	2014	0.01–0.06 kg/s	Analytical	Developed a mathematical model to evaluate the performance of single, double, and triple pass SAH using the first and second law of thermodynamics. Energy efficiency for triple pass conditions is higher than single pass and double pass air heater by 6–14% and 3–6%, respectively, and also exergy efficiency is higher for triple pass SAH	[71]
Bahrehmand *et al.*	2015	Re = 4000–24000	Analytical	Collectors without fins at low Re, double glass cover with thin metal sheet performed high energy and exergy efficiencies. Single glass cover performed higher efficiency at high Re	[72]
Velmurugan and Kalaivanan	2015	0.01, 0.02, 0.03, 0.04 kg/s	Experimental and Analytical	Examined experimentally and analytically energetic and exergetic performance. For wire mesh dual pass SAH, they found that the maximum energy efficiency as 76.46% at $\dot{m}$ =0.04 kg/s. Also reported the temperature rise of air and exergy output increases with the solar intensity (500–600 W/m^2)	[73]
Bahrehmand and Ameri	2015	Flow velocity 0.01541–0.1814 m/s	Analytical	Mathematical model developed for predicting the energetic and exergetic performance of SAC using single and double glass cover at natural convection	[74]
Kalaiarasi *et al.*	2016	0.018, 0.026 kg/s	Experimental	Observed the maximum η_{th} = 49.4-59.2%, η_{II} = 18.25–35.53% at $\dot{m}$ = 0.026 kg/s	[75]
Velmurugan and Kalaivanan	2016	0.01–0.04 kg/s	Experimental	They investigated I and II law of thermodynamics of dual pass SAH	[76]
Edalatpour *et al.*	2016		Experimental	η_{th} = 58.33–68.77% and η_{II} = 14.45–26.34%	[77]
Acır *et al.*	2016	0.0023, 0.0033, 0.0044, 0.0055 kg/s	Experimental	Studied the energy and exergy analysis of SAH with semi-circular absorber plate, and found that η_{th} = 28.6–79.5% and η_{II} = 8.1–42.4%	[78]
Ghiami *et al.*	2016	0.009, 0.014, 0.017 kg/s	Experimental	Reported that the daily energy efficiency varied between 20.7% and 26.8%, whereas the daily exergy efficiency varied between 10.7% and 19.5%	[79]

continued Tab. 1

Acır *et al.*	2017	Re = 4300, 5700, 7300	Experimental and Analytical	Examined the exergy and energy efficiencies of SAH using different obstacle relief angles (α), Re and obstacle distances (L), also used Grey relation analysis for parametric optimization. The optimum parameters for the highest energy and exergy efficiencies were obtained as A1B1C3 with $L = 100$ mm, $\alpha = 45°$ and Re = 7300	[80]
Ghritlahre and Prasad	2017	0.010–0.0175 kg/s	Artificial intelligence technique	Developed neural model to predict the energetic and exergetic efficiency of roughened SAH	[81]
Saha and Sharma	2017	0.035–0.083 kg/s	Analytical	Developed a computation analytical program in C++ software to estimate the energy and exergy analysis of double flow corrugated SAH. Maximum enhancement in energy efficiency of SA-1 solar air heater is 7.20% as compared to SA-4 for the mass flow rate of 0.035 kg/s. Also the exergy efficiency become negative at higher mass flow rate ($\dot{m} > 0.072$ kg/s) for all types of solar air heater	[82]
Ghiami and Ghiami	2017	0.017, 0.014, 0.009 kg/s	Experimental	Designed a novel type of SAH using PCM and studied its energy and exergy analysis. At the mass flow rate of 0.017 kg/s, the maximum energy efficiency was attained for sequence-arranged baffle-equipped SAH (26.78%), while unequipped SAH had the least energy efficiency (14.30%) at the same mass flow rate. Exergy efficiencies varied between 4.86–20.47% for all studied cases	[83]
Abuşka	2018	0.04, 0.08, 0.10 kg/s	Experimental	Developed a new design of SAH using absorber plate with conical surface and observed $\eta_{\mathrm{I}} = 57.2$-74.6% and $\eta_{\mathrm{II}} = 9.2$–19.3%	[84]
Acır *et al.*	2018	0.0023, 0.0033, 0.0044, 0.0055 kg/s	Experimental	At $\dot{m} = 0.0055$ kg/s: for HN= 2: $\eta_{\mathrm{I}} = 58.3 \pm 0.63\%$ and $\eta_{\mathrm{II}} = 20.7 \pm 1.00\%$; for HN= 6: $\eta_{\mathrm{I}} = 53.7 \pm 0.59\%$ and $\eta_{\mathrm{II}} = 18.4 \pm 0.73\%$	[85]
Debnath *et al.*	2018	0.0118 kg/s	Experimental	Experiments for analysis of energy and exergy for flat plate solar air collector with different tilt angle and spacing: $\eta_{th} = 34.51-59.38$ for double glass SAH, and $\eta_{th} = 30.87$–49.40% for single glass SAH, while the $\eta_{\mathrm{II}} = 0.73$–32.99% at tilt angle 24.83° and spacing 0.045 m	[86]

continued Tab. 1

Devecioğlu *et al.*	2018	0.030, 0.055 kg/s	Experimental	η_{th} = 34–82%, η_{eff} = 25–66% and η_{II} = 3.70–9.65%	[87]
Ghritlahre	2018	0.0235–0.0270 kg/s	Artificial intelligence technique	Neural structure developed to estimate the energetic and exergetic efficiency of roughened SAH. L-M and SCG algorithm used for training process and found that the L-M with 6-6-2 optimal model for prediction	[88]
Matheswaran *et al.*	2018	0.0035 kg/s	Analytical	Analytically studied the η_I and η_{II} of the single pass double duct jet plate SAH and also developed a correlation for predicting the exergetic efficiency using the factors such as Re and design variables of jet plate. Maximum η_{eff} = 72.3% and η_{II} = 4.36% at X/D_h 1.739, $Y/D_h = 0.869$, $D_j/D_h = 0.065$	[89]
Matheswaran *et al.*	2018	0.002–0.023 kg/s	Analytical	Mathematical model developed to study energy, exergy and enviro-economic analysis of parallel pass jet plate SAH with artificial roughness. Single-pass double-duct jet plate solar air heater improves annual usual energy and exergy gain by 111.7% and 185.6%, respectively	[90]
Aktaş *et al.*	2019	0.0069, 0.0087 kg/s	Experimental	η_{th} = 48.88–83.47% and η_{II} = 8.74–23.97% for MPSACF η_{th} = 30.37–69.03% and η_{II} = 2.10–17.12% for DPSAC	[92]
Kumar and Layak	2019	Re = 2000–40000	Analytical work	I and II law of thermodynamics of SAH studied using twisted rib roughness on absorber surface. Maximum enhancement in η_{th}, η_{eff}, and η_{II} as 1.81, 1.79, and 1.81 times as compared to smooth plate SAH at $P/e = 8$, twist ratio = 3, rib orientation angle = 60° and $\Delta T/I = 0.0125$ m^2K/W	[93]

5 Scope for further research

On the basis of the present literature review, it has been observed that the following research points can be used in the future work for solar air heaters:

1. Most of the research work presented only the magnitude of exergy destruction. They reported very few information regarding reduction or elimination of exergy losses.

2. Very few works related to exergy and energy analysis of glazing and Un-glazing type glass covers types of SAHs.

3. By using various soft computing techniques, prediction of the energy and exergy efficiencies of SAHs.

4. Very few works of analytical study of the first and second law of thermodynamics of different types of SAHs.

5. The experimental and analytical study of energetic and exergetic concept of three side roughened SAH.

6. Very limited work on porous and packed bed solar air heaters.

7. Limited studies on exergy analysis for flat plate SAH.

6 Conclusions

In present work, a comprehensive literature review has been done to study the first and second law of thermodynamics of various types of SAHs. The following results have been found from the present work:

1. The concept of the second law of thermodynamics very useful for optimal design, and identifying the actual and theoretical limits of performance of solar air heaters.

2. Studies revealed that energy efficiency is higher than the exergy efficiency, whereas the vice versa has also been found to be true in some studies, the reason being that the first law of thermodynamics is concerned with the quantity of energy while the second law of thermodynamics deals with the quality of energy and also the irreversibilities are taken into account.

3. Most of researchers compared the η_{th} and η_{II} of novel designs of SAHs with conventional SAH and found that the efficiencies of exergy and energy are better as compared to conventional SAH.

4. The effects of inlet temperature of air, time, solar intensity and mass flow rates on η_{I} and η_{II} has been studied and observed that they are highly influenced by the solar intensity.

5. It has been observed that the energetic and exergetic efficiencies of different types of SAHs varied from 2.05% to 82% and 0.01% to 60.97%, respectively.

6. A mass flow rate plays a vital role in energy efficiency. Due to this reason, maximum efficiency can be achieved at higher mass flow rates.

7. It has been observed that the maximum thermal efficiency 82% at mass flow rate 0.0074 kg/s for obstacles type solar air heater by Akpinar and Kocyigit [64]. On the other side, the maximum exergetic efficiency obtained as 60.97% at mass flow rate 0.025 kg/s for porous baffles inserted SAHs by Esen [60].

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References

[1] Garg H.P., Prakash J.: *Solar Energy Fundamentals and Applications*, Tata McGraw Hill publishing Co. Ltd, 2006.

[2] Cengel Y.A., Boles M.A.: *Thermodynamics: An Engineering Approach*. (5th Edn.) McGraw-Hill; New York 2006.

[3] Ghritlahre H.K.: *Performance evaluation of solar air heating systems using artificial neural network*. PhD Thesis, National Institute of Technology, Jamshedpur 2019.

[4] Kumar A., Saini R.P., Saini J.S.: *A review of thermohydraulic performance of artificially roughened solar air heaters*. Renew. Sustain. Energy Rev. **37**(2014), 100–122.

[5] Behura A.K., Prasad B.N., Prasad L.: *Heat transfer, friction factor and thermal performance of three sides artificially roughened solar air heaters*. Sol. Energy **130**(2016), 46–59.

[6] Ghritlahre H.K., Prasad R.K.: *Prediction of heat transfer of two different types of roughened solar air heater using Artificial Neural Network technique*. Thermal Sci. Eng. Progress **8**(2018), 145–153.

[7] Kumar V.: *Nusselt number and friction factor correlations of three sides concave dimple roughened solar air heater.* Renew. Energ. **135**(2019), 355–377.

[8] Sharma S.P., Saini J.S., Varma H.K.: *Thermal performance of packed bed solar air heaters.* Sol. Energy **47**(1991), 59–67.

[9] Varshney L., Saini J.S.: *Heat transfer and friction factor correlations for rectangular solar air heater duct packed with wire mesh screen matrices.* Sol. Energy **62**(1998), 4, 255–262.

[10] Ghritlahre H.K., Prasad R.K.: *Investigation of thermal performance of unidirectional flow porous bed solar air heater using MLP, GRNN, and RBF models of ANN technique.* Thermal Sci. Eng. Progress **6**(2018), 226–235.

[11] Ghritlahre H.K.: *Performance prediction of porous bed solar air heater using MLP and GRNN model- A comparative study.* CSVTU Res. J. Eng. Technol. **5**(2019), 1, 70–81.

[12] Choudhary C., Garg H.P.: *Design analysis of corrugated and flat plate solar air heaters.* Renew. Energ. **1**(1991), 5/6, 595–607.

[13] Mohammadi K., Sabzpooshani M.: *Comprehensive performanceevaluation and parametric studies of single pass solar air heater with fins and baffles attached over the absorber plate.* Energy **57**(2013), 1, 741–750.

[14] Priyam A., Chand P.: *Thermal and thermohydraulic performance of wavy finned absorber solar air heater.* Sol. Energy **130**(2016), 250–259.

[15] Sahu M.K., Sharma M., Matheswaran M.M., Maitra K.: *On the Use of Longitudinal Fins to Enhance the Performance in Rectangular Duct of Solar Air Heaters – A Review.* J. Sol. Energy Eng. **141**(2019), 3. DOI: 10.1115/1.4042827.

[16] Saidur R., Masjuki H.H., Jamaluddin M.Y.: *An application of energy and exergy analysis in residential sector of Malaysia.* Energ. Policy **35**(2007), 2, 1050–1063.

[17] Masjuki H.H., Kalam M.A., Syazly M., Mahlia T.M.I., Rahman A.H., Redzuan M. et al.: *Experimental evaluation of an unmodified diesel engine using biodiesel with fuel additive.* In: IFOST 2006: 1st Int. Forum on Strategic Technology, Proc. 2006, 96–99.

[18] Mohammadnejad M., Ghazvini M., Javadi F.S., Saidur R.: *Estimating the exergy efficiency of engine using nanolubricants.* Energy Education Science and Technology A: Energy Science and Research **27**(2011), 2, 447–454.

[19] Saidur R., Ahamed J.U., Masjuki H.H.: *Energy, exergy and economic analysis of industrial boilers.* Energ. Policy **38**(2010), 5, 2188–2197.

[20] Saidur R., Khaliq A.H.A., Masjuki H.H.: *Analysis of energy and exergy use for process heating in the industrial sector of Malaysia.* Int. J. Exergy **3**(2006), 2, 1119–1149.

[21] Hacihafizoglu O.: *Energy–exergy analysis of gas turbine cycle in a combined cycle power plant.* Energy Education Science and Technology – Part A **27**(2011), 1, 123–138.

[22] Saidur R., Sattar M.A., Masjuki H.H., Ahmed S., Hashim U.: *An estimation of the energy and exergy efficiencies for the energy resources consumption in the transportation sector in Malaysia.* Energ. Policy **35**(2007), 8, 4018–4026.

[23] Ahamed J.U., Saidur R. Masjuki H.H.: *A review on exergy analysis of vapor compression refrigeration system.* Renew. Sustain. Energy Rev. **15**(2011), 3, 1593–1600.

[24] Dikmen E., Sencan A., Selbas R.: *Energetic and exergetic approach to vapor compression refrigeration cycle with two-stage and intercooler for new refrigerants.* Energy Education Science and Technology – Part A **26**(2011), 2, 205–219.

[25] Sahu M.K., Prasad R.K.: *Entropy generation and thermodynamic analysis of solar air heaters with artificial roughness on absorber plate.* Arch. Thermodyn. **38**(2017), 3, 23–48. DOI: 10.1515/aoter-2017-0014.

[26] Sahu M.K., Prasad R.K.: *Second law optimization and parametric study of a solar air heater having artificially roughened absorber plate.* Arch. Thermodyn. **40**(2019), 2, 107–135. DOI: 10.24425/ather.2019.129544.

[27] Fiuk J.J., Dutkowski K.: *Experimental investigations on thermal efficiency of a prototype passive solar air collector with wavelike baffles.* Sol. Energy **188**(2019), 495–506.

[28] Wajs J., Golabek A., Bochniak R.: *Photovoltaic Roof Tiles: The Influence of Heat Recovery on Overall Performance.* Energies **12**(2019), 4097. DOI: 10.3390/en12214097.

[29] Dincer I., Congel Y.A.: *Energy, entropy and exergy concepts and their roles in thermal engineering.* Entropy **3**(2001), 3, 116–149.

[30] Ozgener O., Hepbasli A.: *A review on the energy and exergy analysis of solar assisted heat pump systems.* Renew. Sustain. Energy Rev. **11**(2007), 3, 482–496.

[31] Gomri R.: *Energy and exergy analyses of seawater desalination system integrated in a solar heat transformer.* Desalination **249**(2009), 1, 188–196.

[32] Koroneos C., Nanaki E., Xydis G.: *Solar air conditioning systems and their applicability – an exergy approach.* Resour. Conserv. Recy. **55**(2010), 1, 74–82.

[33] Joshi A.S., Dincer I., Reddy B.V.: *Analysis of energy and exergy efficiencies for hybrid PV/T systems.* Int. J. Low Carbon Technol. **6**(2011), 1, 64–69.

[34] Xu C., Wang Z., Li X., Sun F.: *Energy and exergy analysis of solar power plants.* Appl. Therm. Eng. **31**(2011), 17–18, 3904–3913.

[35] Panwar N.L., Kaushik S.C., Kothari S.: *A review on energy and exergy analysis of solar dying systems.* Renew. Sustain. Energy Rev. **16**(2012), 2812–2819.

[36] Oztop H.F., Bayrak F., Hepbasli A.: *Energetic and exergetic aspects of solar air heating (solar collector) systems.* Renew. Sustain. Energy Rev. **21**(2013), 59–83.

[37] Aman J., Ting D.S-K., Henshaw P.: *Residential solar air conditioning: energy and exergy analyses of an ammonia-water absorption cooling system.* Appl. Therm. Eng. **62**(2014), 2, 424–432.

[38] Park S.R, Pandey A.K, Tyagi V.V. Tyagi. S.K.: *Energy and exergy analysis of typical renewable energy systems.* Renew. Sustain. Energy Rev. **30**(2014), 105–123.

[39] Sarker M.S.H., Ibrahim M.N., Aziz N.A., Punan M.S.: *Energy and exergy analysis of industrial fluidized bed drying of paddy.* Energy **84**(2015), 131–138.

[40] Ezzat M.F., Dincer I.: *Energy and exergy analyses of a new geothermal–solar energy based system.* Sol. Energy **134**(2016), 95–106.

[41] Terhan M., Comakli K.: *Energy and exergy analyses of natural gas-fired boilers in a district heating system.* Appl. Therm. Eng. **121**(2017), 380–387.

[42] Zisopoulos F.K., Rossier-Miranda F.J., van der Goot A.J., Boom R.M.: *The use of exergetic indicators in the food industry – A review.* Crit Rev Food Sci Nutr. **57**(2017), 1, 197–211.

[43] Sharshira S.W., Elsheikhd A.H., Penga G., Yanga N. E-Samadonyf M.O.A., Kabeel A.E.: *Thermal performance and exergy analysis of solar stills – A review.* Renew. Sustain. Energy Rev. **73**(2017), 521–544.

[44] Sansaniwal S.K., Sharma V., Mathur J.: *Energy and exergy analyses of various typical solar energy applications: A comprehensive review.* Renew. Sustain. Energy Rev. **82**(2018), 1576–1601.

[45] Fudholi A., Musthafa M.F., Abrar Ridwan A., Yendra R., Desvina A.P., Rahmadeni, Suyono T., Sopian K.: *Energy and exergy analysis of air based photovoltaic thermal (PVT) collector: a review.* IJECE **9**(2019), 1, 109–117. DOI: 10.11591/ijece.v9i1.pp109-117.

[46] Ahmadi M.H., Nazari M.A., Sadeghzadeh M., Pourfayaz F., Ghazvini M., Ming T., Meyer J.P., Sharifpur M.: *Thermodynamic and economic analysis of performance evaluation of all the thermal power plants: A review.* Energy Science & Engineering, 2019. DOI: 10.1002/ese3.223.

[47] Arshad A., Ali H.M., Habib A., Bashir M.A., Jabbal M., Yana Y.: *Energy and exergy analysis of fuel cells: A review.* Thermal Science and Engineering Progress **9**(2019), 308–321. https://doi.org/10.1016/j.tsep.2018.12.008.

[48] Rabha D.K., Muthukumar P., Somayaji C.: *Energy and exergy analyses of the solar drying processes of ghost chilli pepper and ginger.* Renew. Energ. **105**(2017), 764–773.

[49] Ghritlahre H.K., Prasad R.K.: *Exergetic performance prediction of solar air heater using MLP, GRNN and RBF models of Artificial Neural Network technique.* J. Environ. Manage. **223**(2018), 566–575.

[50] Ghritlahre H.K., Prasad R.K.: *Exergetic Performance Prediction of a Roughened Solar Air Heater Using Artificial Neural Network.* Strojniški vestnik – J. Mech. Eng. **64**(2018), 3, 195–206.

[51] Ghritlahre H.K., Prasad R.K.: *Prediction of exergetic efficiency of artificial arc shape roughened solar air heater using ANN model.* Int. J. Heat Technol. **36**(2018), 3, 1107–1115.

[52] Fudholi A., Sopian K.: A review of solar air flat plate collector for drying application. Renew. Sustain. Energ. Rev. 2019; 102: 333–345.

[53] Kurtbas I., Durmus A.: *Efficiency and exergy analysis of a new solar air heater.* Renew. Energ. **29**(2004), 1489–1501.

[54] Ozturk H.H., Demirel Y.: *Exergy-based performance analysis of packed-bed solar air heaters.* Int. J. Energy Res. **28**(2004), 423–432. DOI: 10.1002/er.974.

[55] Ozturk H.H.: *Experimental evaluation of energy and exergy efficiency of a seasonal latent heat storage system for greenhouse heating.* Energ. Convers. Manage. **46**(2005), 1523–1542.

[56] Ajam H., Farahat S., Sarhaddi F.: *Exergetic optimization of solar air heaters and comparison with energy analysis*. Int. J. Therm. **8**(2005), 4, 183–190.

[57] Kurtbase I., Turgut E.: *Experimental investigation of solar air heater with free and fixed fins: efficiency and exergy loss*. IJSR **1**(2006), 1, 75–82.

[58] Ucar A., Inalli M.: *Thermal and exergy analysis of solar air collectors with passive augmentation techniques*. Int. Commun. Heat Mass **33**(2006), 1281–1290.

[59] Karsli S.: *Performance analysis of new-design solar air collectors for drying applications*. Renew. Energ. **32**(2007), 1645–1660.

[60] Esen H.: *Experimental energy and exergy analysis of a double-flow solar air heater having different obstacles on absorber plates*. Build. Environ. **43**(2008), 1046–1054.

[61] Gupta M.K., Kaushik S.C.: *Exergetic performance evaluation and parametric studies of solar air heater*. Energy **33**(2008), 11, 1691–1702.

[62] Gupta M.K., Kaushik S.C.: *Performance evaluation of solar air heater for various artificial roughness geometries based on energy, effective and exergy efficiencies*. Renew. Energ. **34**(2009), 465–476.

[63] Farahat S., Sarhaddi F., Ajam H.: *Exergetic optimization of flat plate solar collectors*. Renew. Energ. **34**(2009), 1169–1174.

[64] Akpinar E.K., Koçyiğit F.: *Energy and exergy analysis of a new flat-plate solar air heater having different obstacles on absorber plates*. Appl. Energ. **87**(2010), 3438–3450.

[65] Alta D., Bilgili E., Ertekin C., Yaldiz O.: *Experimental investigation of three different solar air heaters: energy and exergy analyses*. Appl. Energ. **87**(2010), 2953–2973.

[66] Tyagi V.V., Pandey A.K., Giridhar G., Bandhopdhayay B., Park S.R., Tyagi S.K.: *Comparative study based on exergy analysis of solar air dryer using temporary thermal energy storage*. IJSR **36**(2012), 724–736.

[67] Bouadila S., Kooli S., Lazaar M., Skouri S., Farhat A.: *Performance of a new solar air heater with packed-bed latent storage energy for nocturnal use*. Appl. Energ. **110**(2013), 267–275.

[68] Benli H.: *Experimentally derived efficiency and exergy analysis of a new solar air heater having different surface shapes*. Renew. Energ. **50**(2013), 58–67.

[69] Bayrak F., Oztop H.F., Hepbasli A.: *Energy and exergy analyses of porous baffles inserted solar air heaters for building applications*. Energy and Buildings **57**(2013), 338–345.

[70] Bouadila S., Lazaar M., Skouri S., Kooli S., Farhat A.: *Energy and exergy analysis of a new solar air heater with latent storage energy*. Int. J. Hydrogen Energ. **39**(2014), 27, 15266–15274.

[71] Velmurugana P., Kalaivanan R.: *Energy and Exergy Analysis of Multi-Pass Flat Plate Solar Air Heater—An Analytical Approach*. Int. J. Green Energy **12**(2015), 810–820.

[72] Bahrehmand D., Ameri M., Gholampour M.: *Energy and exergy analysis of different solar air collector systems with forced convection*. Renew. Energ. **83**(2015), 1119–1130.

[73] Velmurugana P., Kalaivanan R.: *Energy and Exergy Analysis of Solar Air Heaters with Varied Geometries*. Arabian Journal for Science and Engineering **40**(2015), 4, 1173–1186.

[74] Bahrehmand D., Ameri M.: *Energy and exergy analysis of different solar air collector systems with natural convection*. Renew. Energ. **74**(2015), 357–368.

[75] Kalaiarasi G., Velraj R., Swami M.V.: *Experimental energy and exergy analysis of a flat plate solar air heater with a new design of integrated sensible heat storage*. Energy **111**(2016), 609–619.

[76] Velmurugana P., Kalaivanan R.: *Energy and exergy analysis in double-pass solar air heater*. Sādhanā **41**(2016), 3, 369–376.

[77] Edalatpour M., Kianifar A., Aryana K., Tiwari G.N.: *Energy, exergy, and cost analyses of a double-glazed solar air heater using phase change material*. J. Renew. Sustain. Energy Rev. 2016; 8, 015101. DOI: 10.1063/1.4940433.

[78] Acir A., Ata I., Şahin I.: *Energy and exergy analyses of a new solar air heater with circular-type turbulators having different relief angles*. Int. J. Exergy **20**(2016), 1, 85–104. DOI: 10.1504/IJEX.2016.076680.

[79] Ghiami A, Kianifa A, Aryana K, Edalatpour M.: Energy and Exergy Analysis of a Single-Pass Sequenced Array Baffled Solar Air Heater with Packed Bed Latent Storage Unit for Nocturnal Use. Heat Transfer Asian Research 2016. DOI: 10.1002/htj.21230.

[80] Acir A., CanliM.E., Ata I., Çakiroğlu R.: *Parametric optimization of energy and exergy analyses of a novel solar air heater with grey relational analysis*. Appl. Therm. Eng. **122**(2017), 330–338.

[81] Ghritlahre H.K., Prasad R.K.: *Energetic and exergetic performance prediction of roughened solar air heater using artificial neural network*. Ciencia e Tecnica Vitivinicola **32**(2017), 11, 2–24.

[82] Saha S.N., Sharma S.P.: *Energy and exergy analysis of double flow corrugated absorber solar air heaters*. Int. Energy Journal **17**(2017), 171–184.

[83] Ghiami S., Ghiami A.: *Comparative study based on energy and exergy analyses of a baffled Solar Air Heater with Latent Storage Collector*. Appl. Therm. Eng. **133**(2018), 797–808.

[84] Abuşka M.: *Energy and exergy analysis of solar air heater having new design absorber plate with conical surface*. Appl. Therm. Eng. **131**(2018), 115–124.

[85] Acir A., CanliM.E, Ata I., Tanürün H.E.: *Effect of the circular shaped turbulator having varying hole number of energy and exergy efficiencies of solar air heater*. Int. J. Ambient Energy 2018. DOI: 10.1080/01430750.2017.1423385.

[86] Debnath S., Das B., Randive P.R.: *Experimental energy and exergy analysis of flat plate solar air collector having different spacing and tilt angle*. AIP Conf. Proc. 2018; 1998(1): 020014. DOI: 10.1063/1.5049110.

[87] Devecioğlu A.G., Oruç V., Tuncer Z.: *Energy and exergy analyses of a solar air heater with wire mesh-covered absorber plate*. Int. J. Exergy **26**(2018), 1/2, 3–20.

[88] Ghritlahre H.K.: *Development of feed-forward back-propagation neural model to predict the energy and exergy analysis of solar air heater*. Trends Renew. Energy **4**(2018), 213–235. DOI: 10.17737/tre.2018.4.2.0078.

[89] Matheswaran M.M., Arjunan T.V., Somasundaram D.: *Analytical investigation of solar air heater with jet impingement using energy and exergy analysis.* Sol. Energy **161**(2018), 25–37.

[90] Matheswaran M.M., Arjunan T.V., Somasundaram D.: *Energetic, exergetic and enviro-economic analysis of parallel pass jet plate solar air heater with artificial roughness.* J. Therm. Anal. Calorim. **136**(2019), 1, 5–19. DOI: 10.1007/ s10973-018-7727-4.

[91] Patel S.S., Lanjewar A.: *Exergy based analysis of solar air heater duct with W-shaped rib roughness on the absorber plate.* Arch. Thermodyn. **40**(2019), 4, 21–48, DOI: 10.24425/ather.2019.130006.

[92] Aktaş M., Sözen A., Tuncer A.D., Arslan E., Koşan M., Çürük O.: *Energy-exergy analysis of a novel multi-pass solar air collector with perforated fins.* IJRED **8**(2019), 1, 47–55.

[93] Kumar A., Layek A.: *Energetic and exergetic performance evaluation of solar air heater with twisted rib roughness on absorber plate.* J. Cleaner Production 2019. DOI: 10.1016/j.jclepro.2019.05.363.

[94] Ghritlahre H.K., Prasad R.K.: *Development of optimal ANN model to estimate the thermal performance of roughened solar air heater using two different learning algorithms.* Annals of Data Science **5**(2018), 3, 453–467.

[95] Ghritlahre H.K., Prasad R.K.: *Modelling of back propagation neural network to predict the thermal performance of porous bed solar air heater.* Arch. Thermodyn. **40**(2019), 4, 103–128.

[96] Ghritlahre H.K., Chandrakar P., Ahmad A.: *A Comprehensive review on performance prediction of solar air heaters using artificial neural network.* Annals of Data Science 2019, 1–45.