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Review of the thermal efficiency of a tube-type solar air heaters

Poonam S. Pardeshi [a,*], Mikael Boulic [a], Andries (Hennie) van Heerden [a], Robyn Phipps [b], Chris W. Cunningham [c]

[a] School of Built Environment, Massey University, Auckland, 0632, New Zealand
[b] Victoria University of Wellington, New Zealand
[c] Research Centre for Hauora & Health, Massey University, Wellington, 6021, New Zealand

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ABSTRACT

There is an urgent need to provide evidence that solar air heaters can be effective for heating and ventilating low-rise buildings. Solar air heaters are devices that can convert solar energy into thermal energy for moderate and low-temperature applications such as space heating, preheating, crop drying, and the food industry. However, its efficiency is low due to the low heat transfer coefficient between the absorber and the flowing air, but they are also simple to construct and operate as there is low-risk leakage of heat transfer liquids. The two main types of solar air heaters are flat plate and tube-type. To date, flat plate solar air heaters have received the most attention in the research literature, but evidence of the efficiency gains from using tube-type solar air heaters is growing.

The study aims to provide up-to-date information on tube-type solar air heaters, which will help advance the development and uptake of solar air heaters. The research showed that thermal efficiency gains could be achieved by altering the design of the solar air heater including different artificial roughness geometries inside the tubes, integrating solar thermal energy systems, application of coatings or reflectors inside the solar air heaters, or using evacuated tubes and micro heat pipe array systems. This literature study showed that evacuated tubes and micro heat pipe array systems have higher thermal efficiency than other techniques. Based on the detailed discussion of various techniques for improving the thermal efficiency of solar air heaters, a new roughness geometry was proposed.

1. Introduction

In 2019, renewable energy sources supplied only 11 % of global energy demand [1]. Around 80 % of the worldwide energy demand for heat, electricity, and transportation is still fulfilled by the combustion of fossil fuels namely coal, oil, or gas. Burning fossil fuels releases carbon dioxide and greenhouse gases leading to global warming and climate change. One hundred and ninety-three states and the European Union have committed to the 2015 Paris Agreement to reduce greenhouse gas emissions and adapt to the climate change impacts. Renewable, non-polluting heat sources are essential to meet this commitment [2]. Therefore, there is a need to both reduce greenhouse gas emissions [3] and find alternate renewable and affordable energy solutions [4].

The International Energy Agency reports that space heating in residential and commercial buildings uses around 46 % of global energy [5]. A New Zealand study reports similar results that about 34 % of New Zealand's energy is used in households for space heating [6]. The World Energy Outlook 2022 report shows that energy consumption for building space heating is eight times higher than for space cooling, despite increased cooling demand [7]. Indoor spaces that are under-heated or under-ventilated can cause poor health outcomes for the occupants and be damp and mouldy [8]. With 10 % of the world living in energy poverty [9], there is a dire need to identify heating solutions that are both renewable and low-cost. The question to be addressed by the researchers is what is the most affordable renewable energy source technology that could fulfil the heating demand for low-rise buildings?

Heating with solar energy could reduce the dependence on fossil fuels [10]. The amount of solar energy that reaches the earth in 1 h is 4.3 $\times 10^{20}$ J, which is slightly higher than the annual worldwide consumption of energy used for space heating of 4.1 $\times 10^{20}$ J [11]. Therefore, harvesting even a fraction of available solar energy can contribute to space heating and offset fossil fuel dependence. Solar energy the utilization could potentially reach an annual growth rate of about 34 % within the next decade, meaning immense energy can be

* Corresponding author.
E-mail address: P.Pardeshi@massey.ac.nz (P.S. Pardeshi).

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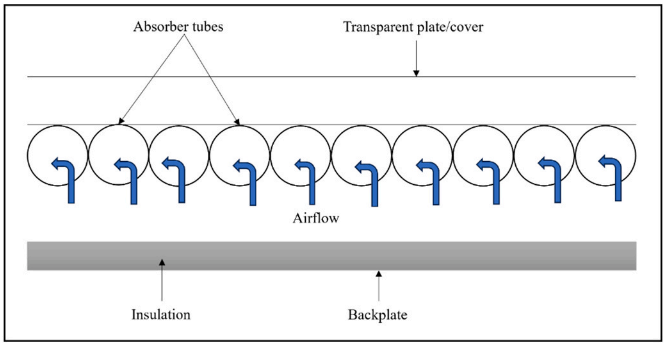

Fig. 1. Schematic diagram of tube-type SAH.

harvested from the sun contributing to the growing energy demand [12]. A positive trend in utilization of solar thermal technologies (10 %–40 %) is seen across European countries for the decarbonization of heating and cooling [13].

Solar energy can be converted to thermal energy using solar collectors [14]. Solar collectors are classified as concentrating types or non-concentrating types. Concentrating collectors use direct (beam) radiation and a tiny portion of the available diffuse (scattered by the atmosphere) radiation. Concentrating collectors must, therefore, track to follow the sun's location across the sky. Non-concentrating collectors use direct solar radiation at different angles and diffuse radiation. They can have a fixed orientation and do not need to track the sun's position. Non-concentrating types are further classified as flat plate collectors or tube-type collectors [15]. Flat plate and tube-type collectors are used for low-temperature applications, namely applications requiring air temperatures ranging from 45 °C to 100°C, and the more complex concentrating collectors are typically used for higher-temperature applications [16]. The solar collectors contain a heat transfer medium, which could be either liquid (solar liquid heater, SLH) or air (solar air heater, SAH). Solar liquid heaters have higher efficiency than solar air heaters but require higher construction standards to avoid a leakage of the liquid [14]. Heating air, rather than a liquid, has the advantage of being a low-technology system that does not use rare metals or moving components. SLH uses a pump to circulate liquid, and SAH uses a fan to circulate air around the system. The energy required to pump the heated liquid medium is higher compared to the fan energy required to move the heated air. Further, there is the need for a secondary heat transfer system such as radiator heaters to extract the heat from the liquid medium to space heat. With SAHs, there are no risks of liquid leaks from the pipework or liquid freezing in winter. SAHs avoid this risk as leaked air is unlikely to cause consequential damage [17]. In addition to the above-mentioned advantages, the heated air from the SAH can be used directly for space ventilation [18].

During the COVID pandemic, besides sanitising, masking, and social distancing, opening classroom windows to increase ventilation rate was the main requirement for reopening schools for maintaining healthy environment. A Report by Ministry of Education showed that only a third of the teachers opened windows during teaching time [19]. Achieving a suitable ventilation level should not rely on occupants awareness of the need to open windows. Mechanical ventilation systems are not affordable for most schools. Consequently, an alternative and affordable method will be needed to increase the ventilation rate in under-ventilated school buildings to decrease virus transmission [20]. A field study conducted in twelve NZ classroom showed that SAHs can be used effectively in preheating and ventilating the classrooms [21]. However, there is need for additional research and evidence on the effectiveness of using SAHs for heating and ventilating buildings, and the technologies available to increase the efficiency of the SAH. It was found that the SAHs have low thermal efficiency (from 38 % to 45 %) due to heat losses; hence, SAHs are limited to space heating, preheating, and crop drying [22].

A systematic literature review was conducted to understand the available thermal efficiency improvement techniques of tube-type SAH for low and medium-temperature space heating applications and modify it further for efficiency improvement. Thermal efficiency equations are also discussed to identify the modifiable factors affecting the SAH performance. One finding was that few studies have been published on tube-type SAHs, but that this is an emerging and promising area of research. When compared with flat panel designs, tube-type solar panels have two theoretical advantages due to the curvature of the tube: greater surface area, and better orientation to the sun's path during the day. These advantages can be further enhanced to produce positive effects on thermal efficiency.This review provides up-to-date information on design innovations for tube-type solar air heaters, which will be helpful for engineers and researchers alike to engineer improved SAHs. Based on the analysis of various techniques for improving the thermal efficiency of solar air heaters (SAH), a new roughness geometry is proposed to be investigated in the future.

To allow comparison between papers and the factors that impact the efficiency of the tubes, the research started with a description of typical SAH components.

2. Tube-type SAH components and airflow through SAH

A typical SAH consists of a transparent top plate, an absorber, an insulated frame, and a backplate. Fig. 1 shows the schematic diagram of SAH. The transparent top cover can be made from either glass or a transparent polymer to absorb solar radiation. The solar energy is then transferred to the absorber tubes. Substantial heat is lost through various SAH parts; therefore, the insulating material is applied to the sides and the back plate to increase the thermal resistance and subsequently reduce the heat losses. Different SAH systems have used various insulating materials such as mineral wool, glass wool, natural fiber, or foam to reduce heat loss. Due to the heat losses, most SAHs have low thermal efficiency (from 38 % to 45 %); hence, SAHs are limited to space heating, preheating, and crop drying [22].

As shown in Fig. 1, the ambient air is typically admitted at the lower edge of the SAH and flows through the absorber tube, using the natural buoyancy of the air as it is heated. The heat from the absorber surfaces is transferred to the air circulating inside the SAH, which is then supplied to an adjacent area for space heating and ventilation. The airflow through the SAH can be either a single or double pass. In a single-pass flow, the air passes through the absorber only once, and in a double-pass flow, the air passes twice through the absorber to increase the time that the air is in contact with the absorber surfaces [23]. A typical double-pass SAH is 10–15 % more efficient than a single-pass SAH due to the increase in heat transfer area [24].

3. Equation used to determine the thermal efficiency of SAHs

The thermal efficiency of SAH can be calculated using equation (1) [17].

$$\eta = \frac{\dot{m}Cp(To - Ti)}{IAc} = \frac{\rho v A d C p(To - Ti)}{IAc} \qquad 1$$

For tube type SAH, the collector area is calculated from equation (2) [25].

$$A_c = n\pi DL \qquad 2$$

Where.

A_c, Solar air heater effective area (m^2)
A_d, Outlet duct cross section area (m^2)
C_P, Specific heat capacity of air [J/(kg*K)], constant = 1007 J/kg*K
I, Solar radiation on the tilted solar air heater surface (W/m^2)

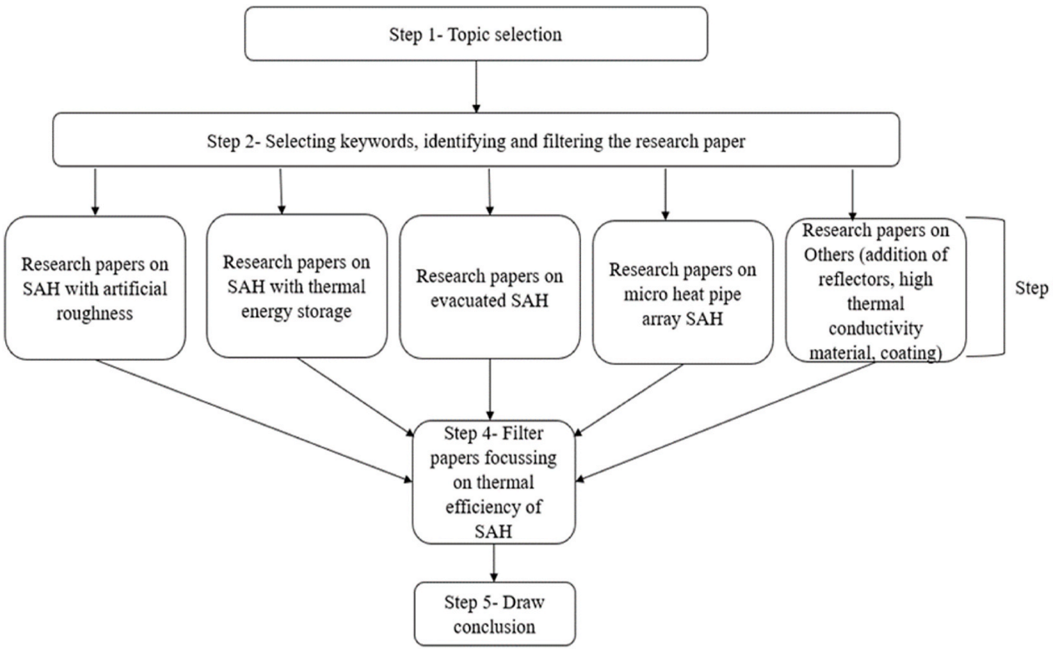

Fig. 2. Five step-review process.

T_i, Inlet air temperature (K)
T_o, Outlet air temperature (K)
$\dot{m}$, Air mass flow rate (kg/s)
η, Efficiency (%)
ρ, Density of air (kg/m^3)
v, Air velocity (m/s)
n, Number of tubes
π, Pie (constant) = 3.14
D, Outer diameter of tube (m)
L, Tube length (m)

Equation (1) shows that the thermal efficiency of SAH depends on the air mass flow rate, the collector area, and the ratio of temperature difference between the air at the outlet and the inlet air (that is the ambient temperature) to global solar radiation.

4. Review methodology

A systematic literature review was conducted by searching journal papers published in relevant research areas through search engines (Google Scholar, Web of Science, Scopus, and Discover – the Massey University library database) from January 1, 2010 to July 31, 2023. Fig. 2 shows the process for conducting the review study. The research methodology involved a five-step review process. The first step for the study was to identify the research area demanding 1) explore cost effective solutions for heating and ventilating low rise buildings as more energy is used in space heating and cooling and 2) extensive research which will contribute to reducing the greenhouse emissions and help in combating energy poverty which is a major concern worldwide. From extensive research, it was found that solar air heaters could be a potential technology which could be used for heating and ventilating buildings. In step 2, keywords were grouped in different combinations to create search string. The keywords were selected and grouped to appear at least once in the title or the article. The chosen keywords were "solar air heater," "tube type solar air heater," "thermal efficiency", "artificial roughness," "coating," "evacuated tubes," "micro heat pipe array" and "reflectors. The keywords grouping was crucial. Using the keywords simultaneously gave no results. The keywords were grouped randomly. The keywords in group 1 were "solar air heater," "tube type solar air heater," and "thermal efficiency", group 2 were "artificial roughness," "coating," and "evacuated tubes," and group 3 was "micro heat pipe array" "reflectors." A total of one hundred and fifty-three papers were identified. These papers were filtered by year in the date range of January 1, 2010–31 July 2023. Filters were also applied to exclude review articles and citations but include peer-reviewed articles (filter). On applying the filters, the number of papers identified were eighty three. In step 3 the articles were categorized into five categories based on the techniques used to increase the thermal efficiency.

The papers were categorized as a) SAH with artificial roughness, b) SAH with thermal energy storage, c) evacuated tubes SAH, d) micro heat pipe arrays SAH, and e) application of coatings, high thermal conductivity material, or reflectors. The papers focusing on the thermal efficiency of tube-type SAH were selected (Step 4). Only thirty seven papers focussed on the thermal efficiency of tube-type SAH for space heating. The remaining papers focussed on agricultural drying, hot water generation, and industrial applications and are excluded from this paper. Step 5 was the critical review and identification of conclusion drawn from the thirty seven papers.

In this review study, some solar air heaters are a combination of two improvement techniques. For example, SAHs with artificial roughness and thermal energy storage. If the major thermal efficiency is influenced by the application of artificial roughness and not the thermal storage, then it is categorized under the artificial roughness sections and vice versa.

5. Results: different techniques to improve the thermal efficiency of the SAH

The literature review showed that 60 % of research papers identified in step 1, investigated the thermal performance of flat plate SAHs and 40 % focussed on tube type SAHs, but this is an emerging and promising area of research. When compared with flat panel designs, tube-type solar panels have two theoretical advantages due to the curvature of the tube: greater surface area, and better orientation to the sun's path during the day. These advantages can be further enhanced to produce positive effects on thermal efficiency. Therefore, this review synthesises the results of experimental modifications to tube-type SAHs and identifies further advantages which might be delivered through innovative design

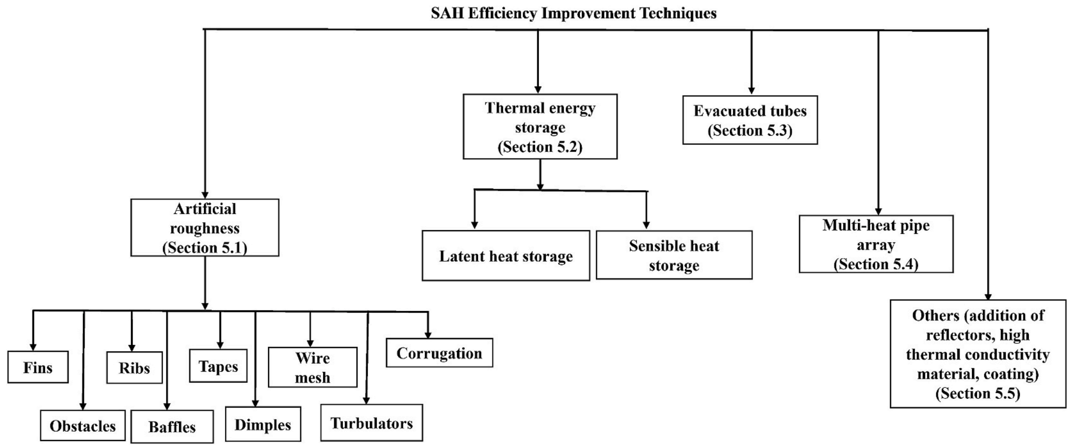

Fig. 3. SAH efficiency improvement techniques.

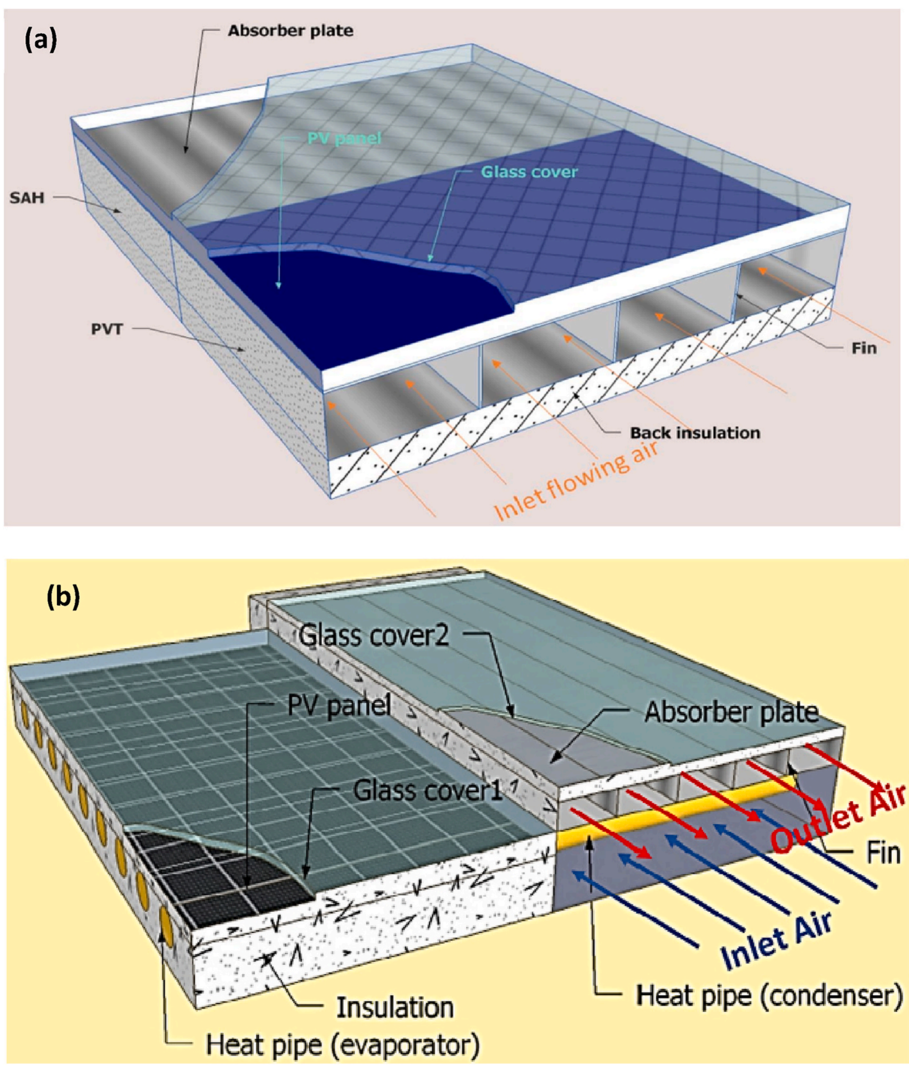

Fig. 4. Schematic diagram (a) SAH-I, and (b) SAH-II, adapted from Ref. [35].

additions. The literature review showed that the thermal efficiency of SAH could be improved by the following.

1) providing some artificial roughness, which increased the absorber surface area and air turbulence,
2) adding reflectors to focus the solar radiation on absorber,
3) integrating the SAH with thermal energy storage to make the heat available after sunset,
4) using evacuated tubes, and multi-heat pipe arrays to improve heat absorption, and

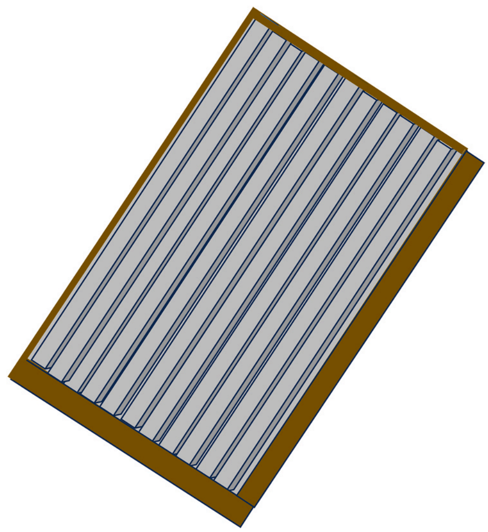

Fig. 5. SAH with increased roughness from ribs [36].

5) using high thermal conductivity material or selective coatings to increase heat transfer between the absorber and the airflow.

Fig. 3 illustrates SAH's different thermal efficiency improvement techniques, which are detailed in the below sections.

5.1. Adding artificial roughness to a tube-type SAH

Providing artificial roughness on the absorber tube increased the surface area available for the transfer of heat from the absorber to the airflow. Increased surface area results in higher heat transfer and converts the laminar sublayer to turbulent airflow, thereby increasing the SAH thermal efficiency. Artificial roughness could include fins [26], ribs [27], baffles [28], obstacles [29], dimples on the interior surface of tubes [30], tapes within the tubes [31], corrugation [32], wire mesh [33], and turbulators [34]. Each type of roughness is discussed in this section.

5.1.1. Application of fins

Fig. 4a shows SAH without fins (SAH I) and Fig. 4b shows the SAH with fins and heat pipes (SAH II). The thermal efficiency of both the SAHs were evaluated and it was found that the thermal efficiency of SAH-II was increased by 7.5 % compared to SAH-I. It was concluded that inserting the longitudinal fins increased the surface area, and the heat pipe transferred heat to a longer distance. The higher heat transfer efficiency of heat pipes increased the outlet air temperature of SAH II. Uniform temperature difference and stronger cooling effects of photovoltaic panel was observed using heat pipes. However, integrating heat pipes to SAH in not economical solution [35].

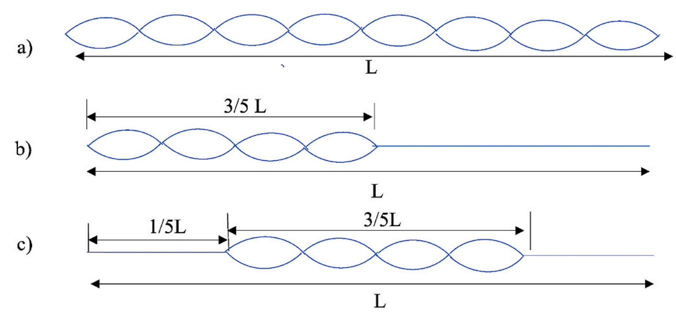

Fig. 8. Angular twisted tape of varying length; a) full-length, b) .short-length, and c) short-length middle [31].

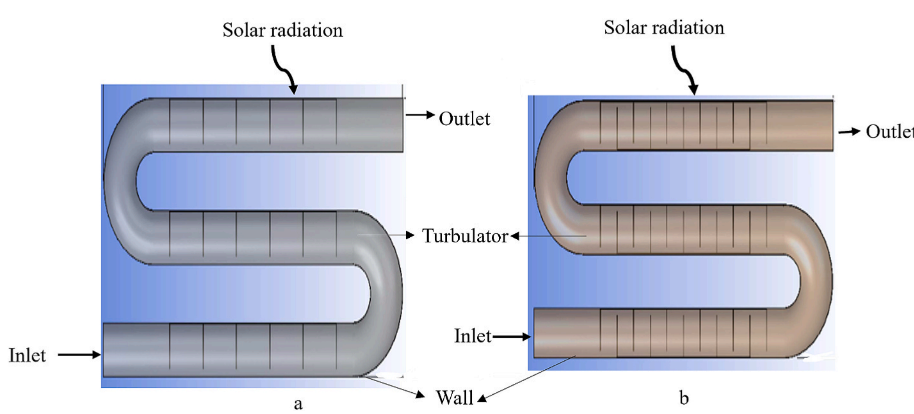

Fig. 6. Geometry of (a) half finned turbulator and (b) full finned turbulator [34].

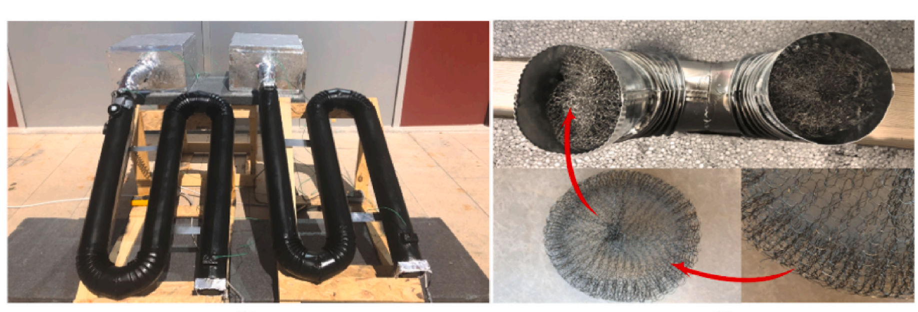

Fig. 7. (a) SAH experimental setup, (b) modified-iron mesh [33].

Table 1
Summary of the review studies mentioned in Section 5.1.

Sr No	Author	Year	Research Methodology	Finding	
1.	[35]	2019	Analytical	**1. SAH without heat pipe and fins**	ηth = 60.2–61.7 %
				2. **SAH with heat pipe and fins**	ηth = 67.2–69.2 %
3.	[36]	2019	Experimental and Numerical	**SAH with rectangular rib roughness on the black coated absorber plate integrated with copper chrome pipes**	ηth = 14.0–56.5 %
4.	[34],	2020	Experimental and Numerical	η_{th}(full finned) > η_{th}(half finned)> η_{th}(no fin)	
				1. . **SAH with smooth tube type**	η_{th} = 47.7–60.7 %, at 0.009 kg/s – 0.015 kg/s
				2.. **SAH with half finned turbulator**	η_{th} = 53.0–64.1 %, at 0.009 kg/s – 0.015 kg/s
				3.. **SAH with full finned turbulator**	η_{th} = 67.6%–72.4 %, at 0.009 kg/s – 0.015 kg/s
8.	[33]	2020	Experimental and Numerical	**SAH with iron mesh**	ηth = 59.9–67.6 %
				9. **SAH without iron mesh**	ηth = 51.1–56.5 %
10.	[32]	2020	Experimental	**SAH with and without helically corrugated tubes with perforated disc**	SAH with helically corrugated tubes with perforated discs augmented heat transfer by 50–60 % compared to SAH without corrugated tubes and perforated tubes.
11.	[31]	2021	Experimental and Numerical	**A triangular SAH tube fitted with angular cut and varied length twisted tape inserts**	Full length angular cut twisted tape performed better compared to small length twisted tape and small length and middle length twisted tape.

5.1.2. Application of ribs

Another technique used to increase the thermal efficiency was rectangular rib roughness on the black-coated absorber plate integrated with copper pipes. Fig. 5 shows the SAH with ribs roughness. The study proved attachment of ribs on black coated absorber plate increased the surface area and provided uniform air mixing, thus increasing the collector efficiency. The maximum thermal efficiency was 56.5 %. The author did not explain the reason why copper pipes were selected except for passing the air through the tubes. However, the copper pipes have a thermal conductivity of 390 W/m-k as well as corrosion resistance, and it is assumed these were the preferred material characteristics [36].

5.1.3. Application of turbulators

A comparative study of three types of SAH was conducted: 1) a smooth tubed SAH, 2) SAH with half finned turbulator inside the tubes, and 3) SAH with full finned turbulator inside the tubes. Fig. 6 shows the geometry of (a) half finned turbulator and (b) full finned turbulator. A turbulator which consists of fins is a device that would change a laminar airflow into a turbulent flow. The application of turbulator, increased thermal efficiency to 60.7 % when there was no turbulator, to 64.1 % when there was a half-finned turbulator to a maximum of 72.4 % when there was a full finned turbulator. Using elbow shaped tubes decreased the occupied space compared to the straight tubes, thus needing only forced convection for airflow. However, the effect of various placement angles of turbulators on the thermal efficiency of TSAH needs to be further investigated. It can be concluded that the SAH with full finned turbulator had the maximum thermal efficiency (72.4 %) compared to other artificial geometries discussed in section 5.1 [34].

5.1.4. Application of iron mesh

Fig. 7a. Shows the experimental setup of SAH and Fig. 7b shows the iron mesh inserts used in the modified SAH. The results showed that adding iron mesh increased the thermal efficiency by 10 % (from an average of 53.8 % to an average of 63.8 %). However, the modified solar air heater did not have a transparent cover, insulation, backplate and frame which reduced the fabrication cost for the experiment but increased the effect of wind chill and heat loss. Therefore, it can be concluded that the effects of the above-mentioned techniques are difficult to compare to other SAHs which have insulation and a transparent cover. A separate study to investigate the effect of the orientation of the tubes is warranted [33].

5.1.5. Using corrugated tubes

A SAH with a helically corrugated tube and a SAH with a helically corrugated tube and a perforated circular disc insert as shown in Fig. 8 were tested The study revealed that the addition of the perforated circular disc insert augmented heat transfer by 50–60 %. The authors did not estimate the thermal efficiency of the developed SAH. However, studies have indicated that augmented heat transfer results in higher thermal efficiency [32].

5.1.6. Application of twisted tape inserts in the tubes

A SAH with varied length twisted tape inserts and angular cut, and plain triangular tube was investigated experimentally. Three geometrical configurations of twisted tapes, full-length, short-length, and short-length middle are shown in Fig. 8. The results showed that the heat transfer in the triangular tube equipped with different configurations of twisted tapes and angular cut had higher heat transfer compared to the plain triangular tube. The three geometries have shown improvements in the heat transmission. The flow field is disturbed by the presence of tape inserts, leading to improved heat transfer. The tape inserts boost fluid mixing, which breaks the thermal and hydrodynamic boundary layer and increases secondary flow. It was concluded that the solar air heater with full length twisted tapes performed better compared to the other twisted tape geometries. The thermal efficiency values are not discussed in the article. However, the thermal performance factor is estimated. The Thermal Performance Factor, which measures the relationship between the relative impact of change in heat transfer rate to change in friction factor, can be used to assess the effectiveness of a heat transfer enhancement technology [31].

The summary of the roughness geometries is given in Table 1. It can be concluded from the studies discussed in section 5.1 that adding roughness to the absorber increased the surface area, thereby increasing the heat transfer rate and the thermal efficiency of SAH.

5.2. Adding a thermal energy storage to increase thermal efficiency

The above studies have shown that SAHs can provide heating during

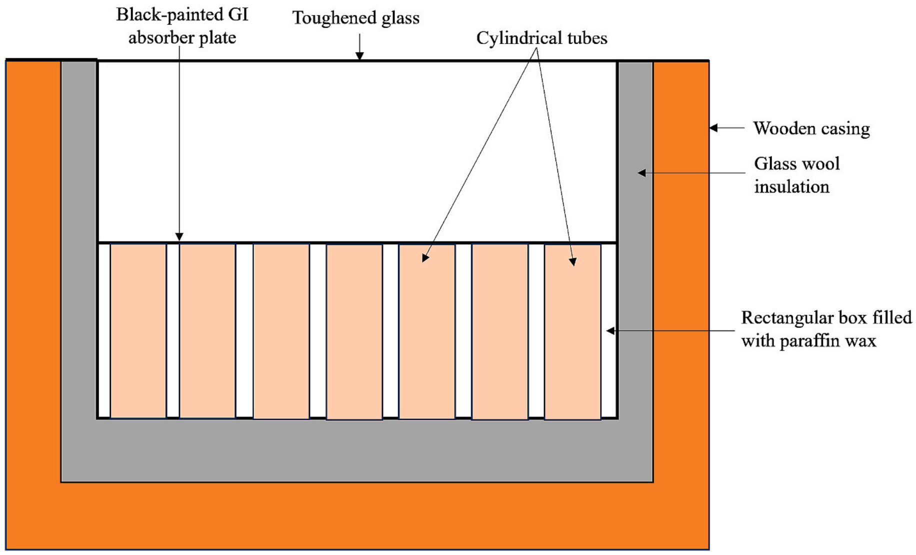

Fig. 9. A sectional view of SAH with PCM filled cylindrical tubes (adapted from Ref. [42]).

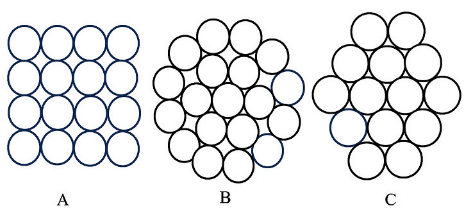

Fig. 10. Tubes arrangement: A) Inline shape, B) Circular shape and C) Staggered shape (adapted [44]).

the day, which makes these technologies especially useful for schools and low-rise workplace buildings. SAH can add warmth to a home during the day but does not provide evening or night time heating unless there is a means of thermal energy storage (TES). High-quality TES was shown to overcome a lower level of solar energy harvesting [37]. Different types of material could be used as TES media. Paraffin wax, a latent heat storage phase change material (PCM), is used for TES [38]. Sand [38], gravel [39], tin cans [40], and synthetic fluids like therminol [41] can be used as sensible heat storage materials.

5.2.1. SAH with latent heat storage

SAH with a bed of small cylindrical hollow tubes (Type –I) and SAH with a bed of small cylindrical tubes filled with PCM (Type –II) are shown in Fig. 9 studied. The results showed that the Type-II SAH thermal efficiency was 12 % higher than Type-I. The PCM stores the useful heat for a longer time but solidifies after sunset due to a higher mass flow rate. PCMs have a limitation due to super cooling effect which is the process of cooling a liquid or a gas below its freezing point without it becoming a solid. The study showed that integrating SAH with TES and a phase change material was an effective method to increase the thermal efficiency during periods of lower solar radiation. However, the authors have not addressed the effect of super cooling and this may not give more accurate results [42].

A SAH with copper tubes filled with Lauric acid (which has a melting temperature of 85 °C) as a PCM and SAH without any PCM were investigated experimentally and numerically for the output temperature rise. The results showed that the SAH with PCM performed better compared to SAH without PCM in terms of temperature level rise (average temperature rise of 86.47 %). The authors did not calculate the SAH efficiency. However, it can be concluded from equation (1) that, the SAH efficiency depends on the temperature difference [43]. TES integrated into SAH with PCM-filled tubes was investigated. The tubes are arranged in an inline, staggered, and circular pattern as shown in Fig. 10. The PCMs considered were paraffin wax, n-octadecane and calcium-chloride hexahydrate. Compared to paraffin wax and n-octadecane, the calcium chloride hexahydrate showed better results when arranged in staggered pattern. The same study also showed that the tube arrangement impacted on the heat transfer with circular pattern due to the uniform air flow. The tubes in circular pattern increased the heat absorption by 1.08 %, 1.55 %, 9.17 % using calcium chloride hexahydrate, n-octadecane and paraffin wax. It can be concluded that the higher heat absorption is due to its high thermal conductivity and heat capacity per unit volume. It was noted that when compared to air inlet velocity, the air inlet temperature had a significant impact on the heat transfer rate between air and PCM. However, the author did not calculate the thermal efficiency. The numerical results should be validated with the real condition experiment work [44].

5.2.2. SAH with sensible heat storage

A porous medium like aluminium fibres could also be used to increase thermal efficiency. The thermal efficiency was increased from 60 % to 90 %, when a porous material was used. These were tested at a mass flow rate of 0.075 kg/s [45]. Another study used aluminium strips and black pebble stones as TES. Aluminium strips had 6.8 % higher thermal efficiency compared to black pebbles at a mass flow rate of 0.025 kg/s. The same SAH without any TES showed lower thermal efficiency (60.0 %). It can be concluded that the aluminium strips have higher thermal conductivity, thereby increasing the SAH efficiency. TES with aluminium strips was found to give the highest thermal efficiency compared to SAHs with phase change materials studied in this research. However, the high air mass flow rate may slowly erode the aluminium strips, thereby needing the airflow to be filtered before supplying the occupied space. While pebble stones are a low-cost option compared to aluminium strips, the weight of the SAH will be increased [40].

Three types of TES were investigated: graphite powder, brick powder, and desert sand. The SAH with graphite powder as TES showed the highest thermal efficiency (37.62 %) compared to brick powder (35.02 %) and desert sand (30.15 %). The thermos physical properties of graphite are higher compared to brick and sand, thereby raising its efficiency. The thermal and mechanical stability of the TES materials should be studied [46].

The studies mentioned in section 5.2 showes integrating SAH with TES and PCM was an effective method to increase the thermal efficient during periods of lower solar radiation. The summary of section 3.2 is

Table 2
Summary of the review studies mentioned in section 5.2.

Sr No	Author	Year	Research Methodology	Finding	
1.	[42]	2021	Experimental	**SAH with a bed of small cylindrical hollow tubes**	Average. η_{th} = 53.3 %
				SAH with a bed of small cylindrical tubes filled with PCM	Average. η_{th} = 59.0 %
2.	[43],	2018	Experimental and Numerical	**SAH with PCM**	SAH with PCM performed better than SAH without PCM
3.	[44]	2021	Numerical	**SAH with PCM-filled tubes**	$CaCl_2 \bullet 6H_2O$ absorbed higher heat (48.03 %) compared to paraffin wax and n-octadecane when arranged in staggered pattern. Higher heat augmentation increased the thermal efficiency of SAH with $CaCl_2 \bullet 6H_2O$.
4.	[47]	2021	Experimental	**SAH without porous medium**	Average. max η_{th} = 61 % at 0.025
				SAH with porous medium	Average max. η_{th} = 90.8 % at 0.075
5.	[40]	2020	Experimental	ηth (with Aluminium)> ηth (with pebbles)> ηth(without strips)	
				SAH without strips	Maximum ηth = 60 %, at 0.025 kg/s
				SAH with pebbles	Maximum ηth = 63 %, at 0.025 kg/s
				SAH with aluminium	Maximum ηth = 69.8 %, at 0.025 kg/s
6.	[46]	2022	Experimental	ηth (graphite)> ηth (brick powder)> ηth(sand)> ηth (no TES)	
				SAH with graphite powder	ηth = 37.62 %
				SAH with brick powder	ηth = 35.02 %
				SAH with sand	ηth = 30.15 %
				SAH without TES	ηth = 23.1 %

given in Table 2.

5.3. Using an evacuated tube to increase the thermal efficiency of the SAH

Fig. 11 shows the evacuated tube collector with inserted tubes. Evacuated (vacuum) tubes (ET) have low conduction and convection losses between the absorbing surface and the air and can deliver high thermal efficiency compared to conventional SAHs [48]. The operating temperature range of evacuated tube collectors (ETCs) is between 50 °C and 200 °C [49]. It was estimated that the SAH average thermal efficiency was 50.0 % for heating purposes on sunny days [50].

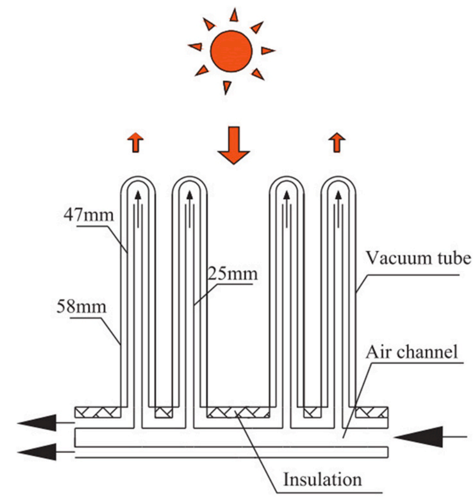

Fig. 11. ET collector with inserted tubes [50].

Fig. 12 shows three ET configurations: (a) control system, (b) tube coated with copper coil, and (c) tube with aluminium fins. As discussed in Section 5.1, the use of fins increased the heat transfer area. Abu et al. [25], found that the adding fins with ET increased the thermal efficiency from 24 % to 37 %. The maximum thermal efficiency of the plain ET, the ET with copper coil and the ET with aluminium fins on the outside of the tube was 24.0 %, 29.0 % and 37.0 % at mass flow rate of 0.0127 kg/s. However, the author has not explained the effect of varying the tube material, fin size, and shape on the thermal efficiency of the evacuated collector [25].

SAHs with evacuated tubes, energy storage and fins were tested experimentally. The thermal storage efficiency of the modified ET SAHs during the experiment period ranged from 56.1 to 67.5 %. It was concluded that integrating fins to ET with TES improved the thermal efficiency of the SAH. The study found that more SAHs are required to meet the heating demand which is not a cost effective solution [51]. Thermal storage ET heat pipe solar collector, as shown in Fig. 13, was investigated experimentally. The maximum thermal efficiency for the system was 89.8 %, at a mass flow rate of 0.3 kg/s. The results indicate that the air mass flow rate significantly affects the collector's performance. The high efficiency is due to the experiment conducted in Chennai in the month of March where the average ambient air temperature ranges between 25°C to 29°C and has a bright solar radiation. Efficiency will be affected during the winters and rainy season due to the cloud cover, lower ambient temperatures, wind, and humidity. The author has not considered the SAH efficiency under various weather conditions [52].

Fig. 14 shows the geometry of ET with helical inserts. The performance of inserting a helically coiled components was investigated for SAH with evacuated tubes. The addition of the helical coil inserts increased the maximum thermal efficiency by 6.1 % (from 64.8 % to 70.9 %) at the mass flow rate of 0.015 kg/s. The authors did not consider the efficiency between 3 p.m. and 5pm due to higher and unrealistic efficiency values at low solar radiation. It can be concluded that the helical coils are made of aluminium wires which stores the heat for a longer period. Therefore, the thermal efficiency kept increasing even at low solar radiation giving an unrealistic efficiency value [53].

Fig. 15 illustrates an experiment on a SAH with ET with and without reflectors. A reflector, made of galvanized steel sheet coated with zinc was used to increase the thermal efficiency of the collector. Reflectors are used to concentrate more incident solar radiation onto the tube. The tilt angle had a remarkable effect on the performance of ET-SAH. The maximum efficiency of ET-SAH at 45° with and without reflectors, was 68.46 % and 63.59 %, respectively. The maximum efficiency of ET-SAH mounted at 30° with and without reflectors was 79.59 % and 64.98 %,

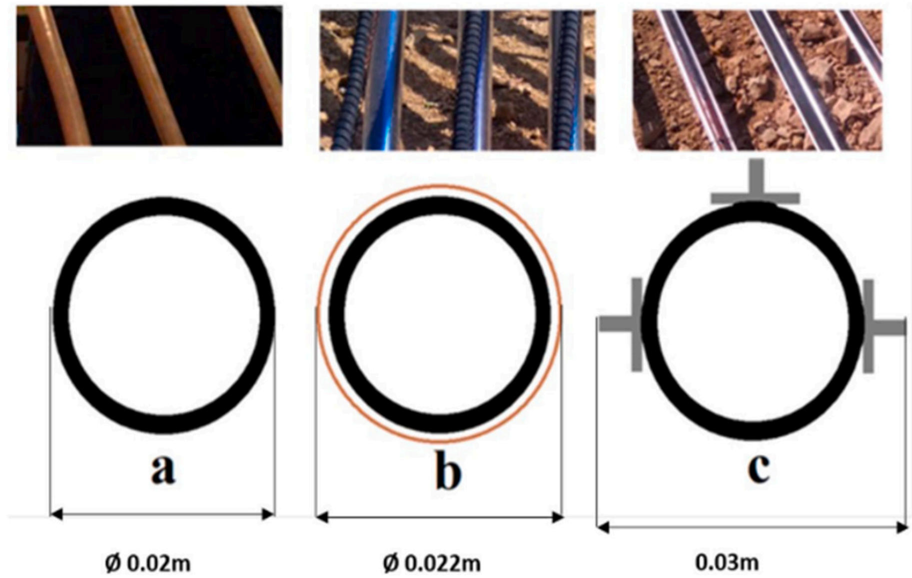

Fig. 12. Cross section of ET; (a) control system, (b) system with copper coil, (c) system with aluminium fins [25].

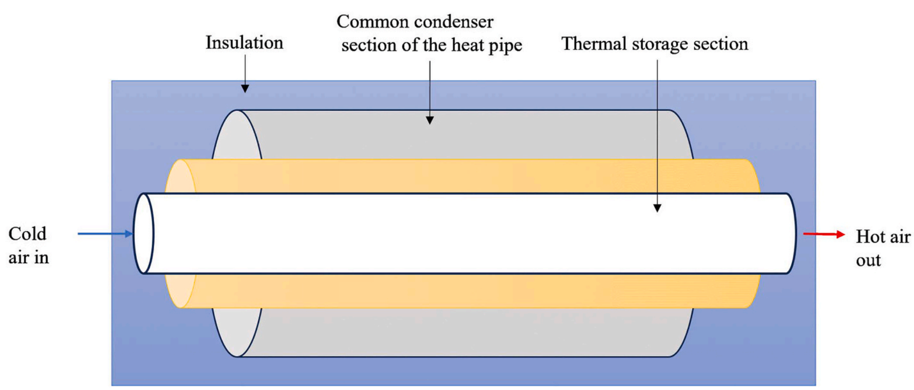

Fig. 13. Schematic diagram of thermal storage ET heat pipe solar collector with header section [52].

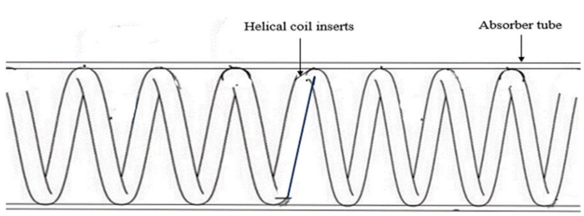

Fig. 14. Evacuated Tube with helical tube inserts [53].

respectively. It can be concluded that the addition of the reflector increased the efficiency for both selected tilt angles. Latitude plays a critical role in determining the tilt angle of the SAH. The experiment is conducted in Krukshetra, India (29° 58′ North and 76° 53′ East). Therefore, the ideal tilt angle for ET-SAH is 30°.

[54].

Fig. 16 shows an ET-SAH with simplified (compound parabolic concentrator and a concentric tube heat exchanger that was tested experimentally. The thermal efficiency at 80 °C, 150 °C and 200 °C was 52 %, 35 % and 21 % respectively for air mass flow rate ranging from 0.16 kg/s - 0.03 kg/s. The efficiency of collector falls to 0 when temperature exceeds 220 °C due to the low air flow rate. A variable speed fan can be employed to change the air flow velocities and tested for air flow rates. Inner tube can be insulated to reduce the heat losses and solar tracking system can be employed to increase the efficiency [55].

Fig. 17 show a parabolic trough SAH with an ET inserted with a U-shaped tube heat exchanger and fitted with reflector. Comparative performance was evaluated for aluminium U-shaped heat exchangers and copper U-shaped heat exchangers with and without fins. Copper has higher thermal conductivity, thus copper U-shaped heat exchangers performed better than aluminium U-shaped heat exchangers. The maximum thermal efficiency for aluminium U-shaped heat exchangers with and without fins was 14.4 % and 10.7 %, respectively and for copper U-shaped heat exchangers with and without fins was 14.7 % and 11.6 %, respectively at air flow rate of 0.0013 kg/s. The results showed the application of fins, reflectors and high thermal conductivity materially improved the efficiency of the collector. However, what percentage of efficiency is improved by application of reflector needs to be studied [56].

A blower increased the air velocity in a U-shaped copper tube fitted into an ET Fig. 18 shows the schematic diagram of ET with U shaped Copper tube insert. The minimum average thermal efficiency was 15.2 % at a mass flow rate of 0.0062 kg/s, while the maximum average thermal efficiency was 21.3 % at a mass flow rate of 0.0082 kg/s. The maximum temperature obtained was 151 °C, at a mass flow rate of 0.0062 kg/s. It was concluded that the air mass flow rate is an important parameter affecting the collector performance [57].

The studies provide evidence that integrating roughness geometries to ET SAHs, using materials with high thermal conductivity, reflectors,

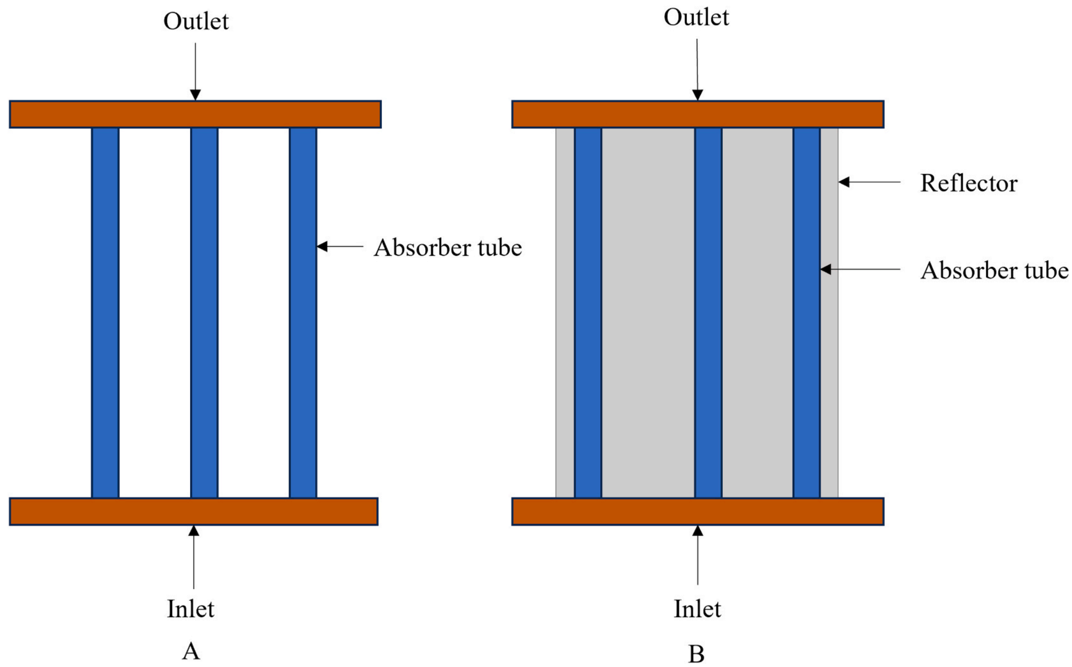

Fig. 15. A) ET SAH without reflectors and B) ET SAH with reflectors (adapted from Ref. [54]).

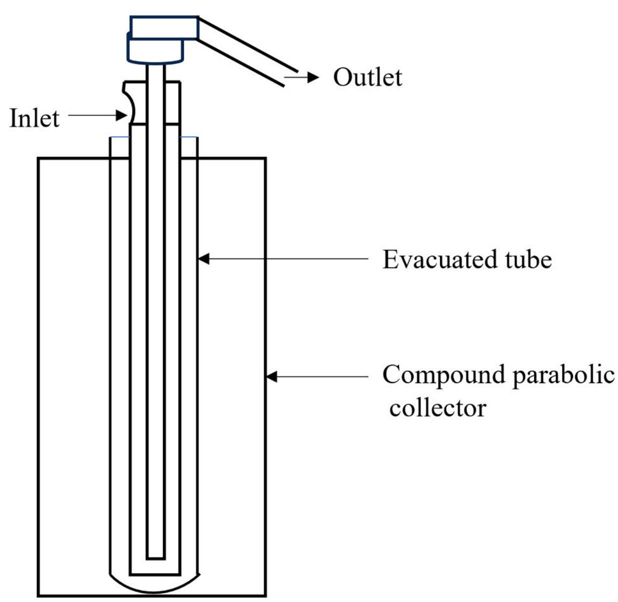

Fig. 16. Schematic diagram of ET-SAH with CPC (adapted from Ref. [55]).

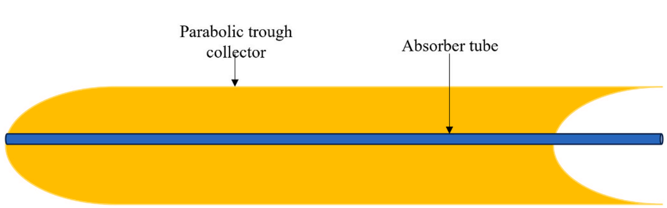

Fig. 17. Schematic view of parabolic trough SAH (adapted from Ref. [56]).

and TES material improved the thermal efficiency of ET SAH. Air mass flow rate, collector and tube tilt angle, outlet air temperature, and solar radiation affected the performance of ET SAH. The use of a synthetic fluid (Therminol) showed the highest thermal efficiency (89.89 %) than

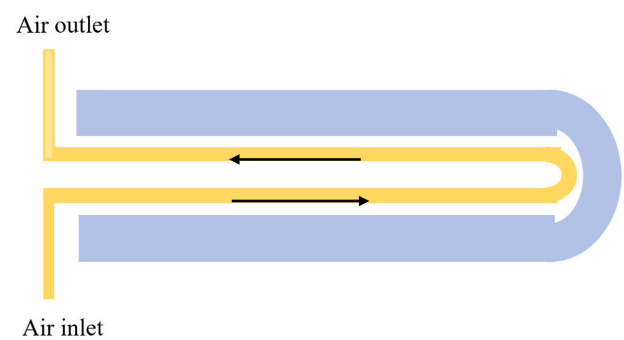

Fig. 18. Schematic diagram of ET with U shaped Copper tube insert (adapted from Ref. [57]).

all the studied ET-type SAHs. The summary of section 5.3 is given in Table 3 below.

5.4. Micro heat pipe array type SAH

A micro heat pipe array (MHPA-SAH) can act as a heat transfer element and can transfer a large amount of heat energy [58]. A study showed flat micro-heat pipe arrays SAH (FMPHA-SAH had 73 % and 56 % thermal efficiency rates in summer and winter, respectively. The efficiency is higher in summers due to the clear sky and the bright solar radiation [58]. [59]. tested a flat micro heat pipe array compound parabolic collector solar air heater. The flat micro heat pipe array acted as a heat transfer element and the compound parabolic collector reflected the solar radiation to the tubes. The average thermal efficiency of the collector was approximately 52 % during the test period. It can be concluded that combining flat micro heat pipe array with compound parabolic collector increased the thermal efficiency of the heater.

A MHPA integrated with thermal energy storage was tested for its thermal efficiency. Lauric acid was used as a latent heat storage material. The daily mean thermal efficiency increased from 59.8 % to 72.4 % for airflow rates between 0.022 and -0.050 kg/s for a SAH integrated with thermal storage. The result showed that the mass flow rate

Table 3
Summary of the review studies mentioned in section 5.3.

Sr No	Author	Year	Research Methodology	Finding	
1.	[50]	2012	Experimental	**ET SAH**	Maximum ηth = 50.0 %
2.	[25]	2020	Experimental	**ET-SAH -control**	Maximum η_{th} = 24 %, I = 1000 W/m^2
				ET-SAH - with copper coil	Maximum η_{th} = 29 %, I = 1000 W/m^2
				ET-SAH - aluminium fins	Max. η_{th} = 37 %, I = 1000 W/m^2
3.	[51]	2020	Experimental	**ET-SAH with TES and fins**	ηth = 56.1–67.5 %
4.	[52]	2021	Experimental	**Thermal storage ET heat pipe solar collector**	Maximum ηth = 38.11 %, 77.04 %, 85.69 %, 89.89 % at 0.03 kg/s, 0.1 kg/s, 0.2 kg/s, 0.3 kg/s respectively
4.	[53]	2021	Experimental and Numerical	**ET collector with helical coil insert**	Maximum ηth = 70.9 %, at 0.015 kg/s
				Simple ETC	Maximum ηth = 64.86 %, at 0.015 kg/s
6.	[54]	2018	Experimental	**ET-SAH**	η_{th} with reflector, at inclination angle (θ) = 45°, = 68.46 % η_{th} without reflector, at θ = 45°, = 63.59 % η_{th} with reflector, at θ = 30°, = 79.59 % η_{th} without reflector, at θ = 30°, = 64.98 %
7.	[55]	2015	Experimental	**ET- SAH with simplified compound parabolic collector and concentric tube heat exchanger**	ηth = 52 %, at T_o = 80 °C ηth = 35 %, at T_o = 150 °C ηth = 21 %, at To = 200 °C
8.	[56]	2021	Experimental	Aluminium U-shaped heat exchangers **with fins**	Maximum ηth = 14.4 %
				Aluminium U-shaped heat exchangers **without fins**	Maximum ηth = 10.7 %
				Copper U-shaped heat exchangers **with fins**	Maximum ηth = 14.7 %
				17. Copper U-shaped heat exchangers **without fins**	Maximum ηth = 11.6 %
9.	[57]	2021	Experimental	**ET-SAH with parabolic tough type collector**	Maximum average η_{th} = 21.3 %, at 0.0082 kg/s Minimum average. η_{th} = 15.2 %, at 0.0062 kg/s

considerably influences the collector's thermal efficiency. However, the SAH should be tested for different ambient air temperatures [60]. A SAH with vacuum glass tube, MHPA, fins and selective absorption film is shown in Fig. 19. The SAH was investigated experimentally and numerically. The MPHA SAH's maximum efficiency was 85.2 %, at 0.044 kg/s and the average efficiency was 82.7 %. The results inferred that mass flow rate affected the collector efficiency [61].

Fig. 20 shows the schematic diagram of two types of flat micro-heat pipe arrays: transparent-tube collector and conventional tube collector). To increase the solar energy absorption in both SAHs, FMHPA was coated at various locations. Compared to T- TC, C-TC had a greater absorption coating, which improved its capacity to absorb solar energy. The maximum average thermal efficiency of C-TC and T-TC was 77.6 % and 85.0 %. It can be concluded that the thermal efficiency of T-TC is higher due to low thermal resistance from the absorption coating to the FMHPA evaporation portion and negligible heat transfer.Integrating coating with MHPA improved the thermal efficiency of SAH [62].

A numerical model of MHPA- SAH with fins attached was studied. The thermal efficiency of the MHPA-based SAH increased with increasing ambient temperature and decreasing wind speed. Maximum thermal efficiency was 66.5 %, at an air velocity of 3.3 m/s and air layer thickness value of 25 mm. The air thickness value above or below 25 mm reduced the SAH efficiency, as higher heat loss was observed between air and the glass cover. The optimal fin height, fin spacing, and aspect ratio values were achieved at 12 mm, 6 mm, and 0.25 mm. It can be concluded that appropriate fin spacing allows for a trade-off between heat transfer area and air flow dispersion [63]. [64].showed, that integrating FMHPA and TES to SAH further improved the thermal efficiency of the collector. The thermal performance of solar air collection-storage system with PCM based on FMHPA was investigated for its performance. The solar air collection-storage system had the latent thermal storage device having Lauric acid (PCM). SAH outlet temperature ranged from 67.8 °C to 88.2 °C, and the thermal efficiency of the collector was 34.50 %, 38.60 %, and 50.70 %, for airflow rates of 0.021, 0.042, and 0.084 kg/s It can be concluded that a high air flow rate influences the SAHs thermal efficiency. Due to the low mean temperature of the SAH, an increased air flow rate with significant air disturbance improved the heat transfer effect and reduced heat loss [65]. A thermal storage SAH was proposed by Ref. [70]., as shown in Fig. 21. The system consisted of a vacuum tube (which acts as thermal insulation), flat micro heat pipe arrays (FMHPA-acts as heat transfer element), and paraffin (PCM) was filled inside the vacuum tube to make it compact. The PCM has low heat transfer coefficient limiting the heat transfer rate; therefore, louvre aluminium fins were used to improve the heat transfer rate. It was observed that the thermal collection efficiency of TSSAH was 80.5%. It can be concluded that the flat MPHA integrated with thermal storage improved the SAH efficiency [64].

Section 5.4 showed that the thermal efficiency for SAH integrated with MHPA improved from 35 % to 85 %. Applying transparent tube, MHPA, coating and TES further improved the SAH efficiency. The airflow rate, and the ambient temperature, dominated the MHPA-SAH performance. Different design configurations such as integrating MHPA, coating and TES or vacuum tube, MHPA and TES or all should be investigated. A study on high thermal conductivity material to design MHPA to improve efficiency should be investigated. The summary of section 5.4 is given in Table 4.

5.5. Other techniques including application of reflectors, coating and using high thermal conductivity materials

5.5.1. Coating with paints (black paint, matte paint) and nanofluids

Nanomaterials, such as nanofluids, nanocomposites, and nanofluid PCM s, can improve heat transfer phenomena by changing heat transfer fluids' thermal and optical characteristics. SAH can be coated with paints (black paint, matte paint) and nanofluids to increase its efficiency. The theoretical and experimental studies show that combining

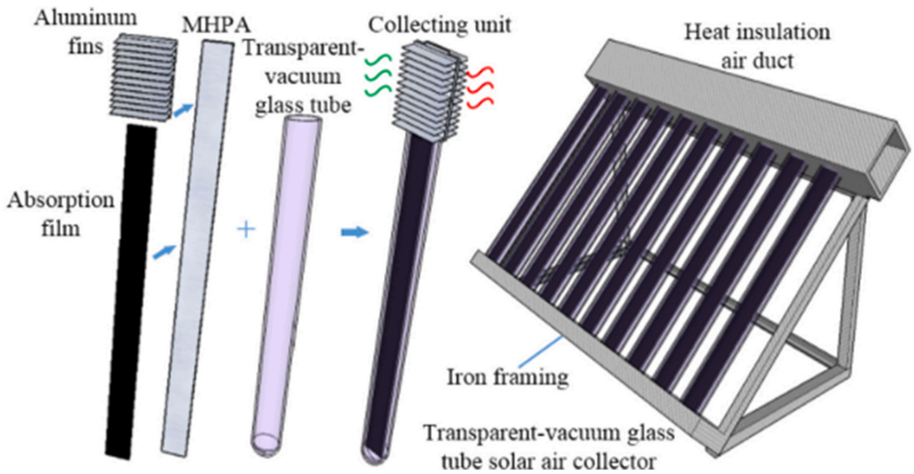

Fig. 19. Schematic diagram of the SAH with MHPA transparent-vacuum glass tube [61].

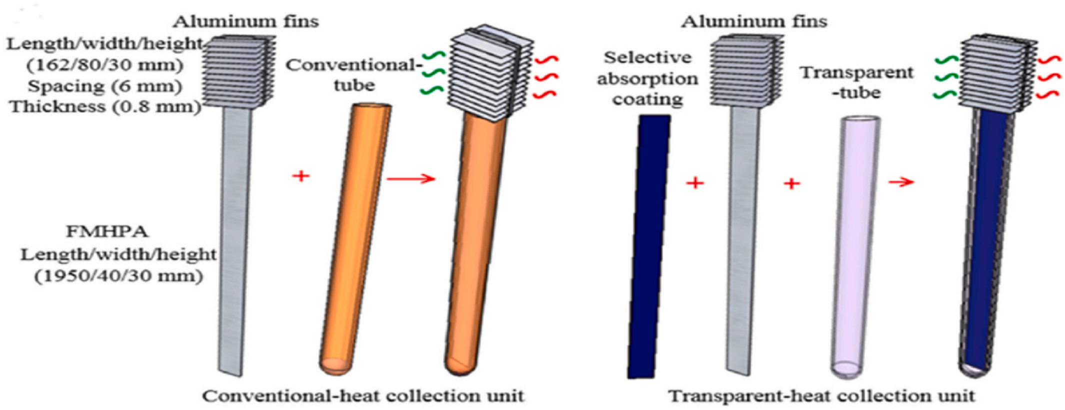

Fig. 20. Schematic diagram of the conventional tube collector and transparent tube collector [62].

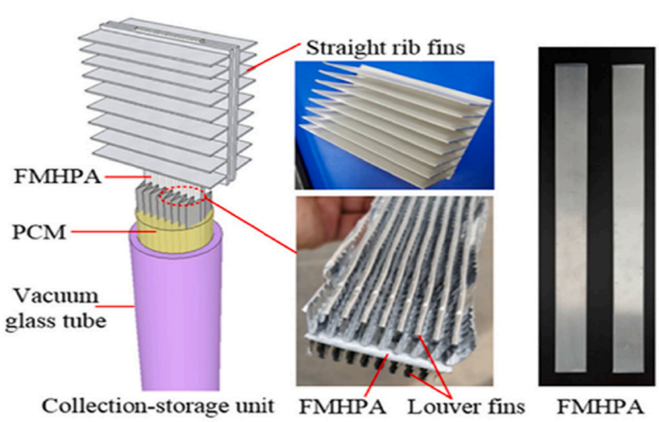

Fig. 21. Schematic diagram of the MPHA [64].

nanoparticles with base fluids may significantly increase the performance and efficiency of solar heaters [66]. Two SAHs were experimentally tested in Wuhan (China). Aluminium plates were used as absorbers: one set was painted with black paint, and the other was painted with a nanofluid which was a mixture of black paint and nanoparticles. Nanoparticles, cupric oxide (CuO) and carbon nanotubes (CNTs) powder or CNTs with a mass ratio of 1:1 were mixed and then other mass percentage ranging from 0 % to 5 % of CNTs powder, or the composite was distributed in black paint. The study revealed the addition of CuO or CNT's is a cheap and easy way to improve the efficiency of SAH [67]. A triangular solar air heater was experimentally tested for its thermal efficiency. One side had a glass cover, whereas the other had two aluminium plates (absorber plates) that collect solar energy from the sun. One set of aluminium plates was sprayed with black paint, while the second set was sprayed with 1 % graphene nanomaterial embedded in black paint. Investigation revealed that for 1 % graphene nanoparticles black paint coating, the maximum value of efficiency was found to be 48.23 % at the time of 12 h at the airspeed of 1 m/s and for black paint coating to be 43.15 %. Applying graphene nanomaterial coating on the absorber plate increased average thermal efficiency by 4.9 %. The authors have conducted experiment using 1 % graphene mixed in blackm paint. It is recommended to test the SAH with different concentration of graphene coatingas the nanoparticle concentration affects the SAHs performance [68].

The studies in section 5.5.1 shows that SAH with the nanofluid coating could be more efficient than SAH with black paint coating. This is because the nanofluid coating increases the heat transfer area and has higher thermal conductivity. A study on SAH with nanofluid coating needs more attention. The effect of varying nanofluid volume concentration, nanoparticle size and stability should be further investigated.

5.5.2. *Utilizing high thermal conductivity material*

Using high thermal conductivity material (metals) to design the absorber (tubes/plate) improved the thermal efficiency of the collector [56]. Two SAHs were designed and fabricated from plastic and metal materials. The experimental results showed that the maximum average thermal efficiency of plastic and metal SAH was 47.74 % and 50.96 %,

Table 4
Summary of the review studies mentioned in section 5.4.

Sr No	Author	Year	Research methodology	Findings	
1.	[58]	2015	Experimental	**Flat MPHA-SAH**	• η_{th} = 73 % and 56 % for summers and winters, respectively.
2.	[59]	2016	Experimental	**Flat MHP array compound parabolic collector SAH**	• Average. ηth = 53 %
3.	[60]	2019	Experimental	**SAH integrated with storage**	• Daily mean ηth = 59.8–72.4 %
4.	[61]	2019	Numerical	**MPHA based SAH**	• Maximum ηth = 85.2 %
5.	[62]	2020	Experimental	**Conventional tube collector**	• Maximum average ηth = 77.6 %
				Transparent tube collector	• Maximum average ηth = 85.0 %
6.	[63]	2021	Experimental and numerical	**MPHA based SAH**	• Maximum ηth = 66.5 %, at velocity = 3.3 m/s
19.	[65]	2017	Experimental	**Latent thermal storage device -Flat MHPA**	• ηth = 34.50 % • ηth = 38.60 % • ηth = 50.70 %
8.	[64]	2021	Experimental	**Thermal storage SAH based on Flat MHPA**	• $\eta_{th\ (collection)}$ = 80.59 %, at Ta = 30.3°C and I = 810 W/m^2 • $\eta_{th\ (collection)}$ = 70.22–77.28 %, at Ta = 20.8–23.3 °C and I = 675–835 W/m^2

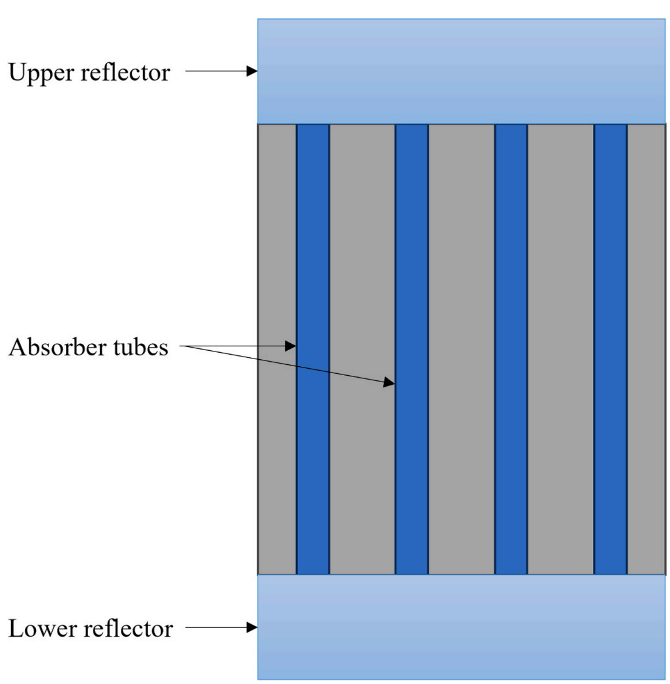

Fig. 22. An experimental set of ETSC-HP (adapted from 70).

respectively, at a mass flow rate of 0.012 kg/s and a tilt angle of 32° off the horizontal. The airflow rate, tilt angle and solar radiation affected the SAH thermal efficiency. The thermal conductivity of metal is higher compared to plastic, thereby increasing the thermal efficiency of the heater [69]. The effect of tube material on the thermal efficiency of parabolic trough collectors (PTC) was investigated. Six different materials, including the aluminium, brass, copper, steel and nickel were used for the tube, and their effects on results were studied. It was found that the aluminium tube had higher thermal efficiency (15 % higher) and was lighter in weight compared to other tubes. Steel had the lowest thermal efficiency compared to other tubes. Copper has higher thermal conductivity compared to the aluminium, however it loses a large amount of heat and therefore, its efficiency is lower compared to aluminium. An extensive study for selecting material to design TSAH that is low cost, light and highly efficient is required [70].

5.5.3. *Application of reflectors*

The heat energy input to SAH can be improved by using reflectors, thus increasing the SAH efficiency [71]. A study found that adding reflectors to double pass solar water heater improved its efficiency by 9–15 % compared to single pass water heater [72]. A solar collector was fabricated, integrating flat plate reflectors made of aluminium oriented at the bottom, top, left, and right. The objective was to find the optimum tilt angle for the solar collector and the inclination angle for reflectors to get maximum solar concentration. The results concluded that the bottom reflector had a higher effect (double) than the top reflector, and both contributed to increased solar intensity to about 50 %. The solar radiation intensity on the solar collector increased to about 80 % using the reflector at the top, bottom, left and right (in summers), thus improving the collector efficiency. It can be concluded that solar tracking could further boost the thermal efficiency of the SAH with reflectors [73]. ET solar collector heat pipes integrated with and without reflectors for water heating were experimentally tested. Reflectors were attached to the collector's upper and lower sides, as shown in Fig. 22. The daily average thermal efficiency of ET solar collector heat pipes with and without reflectors was 76.25 % and 60.57 %, respectively. It can be concluded that in summers, the lower reflectors showed a greater effect on the performance of ET solar collector heat pipes compared to the upper reflectors, due to the greater beam width on the lower reflector. The opposite happens in winters. Therefore, two reflectors (upper and lower) are integrated into ET solar collector heat pipes. It was found that combining reflectors to SAH improved its thermal efficiency and reduced the convective losses from the collector tubes. However, the effect of integrating the reflectors to left or right side and different reflector materials should be investigated [48].

The studies mentioned in section 5.5.3 showed that integrating reflectors into the solar collector improved efficiency. Solar collector placed with reflectors at the bottom performs better than upper reflectors. Incorporating reflectors on top, bottom, left, and right further increases its thermal efficiency, but at the expense of cost and weight. More investigation is required to design and implement SAH's tracked reflectors, with reduced cost, weight, design, material, and improved efficiency.

6. Conclusion

From the review of the above papers, it can be concluded that.

1) Under-ventilated and under-heated indoor spaces can cause health issues to occupant and be damp and mouldy. With 10 % of the world living in energy poverty and studies reporting that most energy is used in heating the buildings, there is a dire need to identify heating solutions that are both renewable and low-cost. Tube-type SAH's could be the potential technology that can be used for heating and ventilating the low-rise buildings.

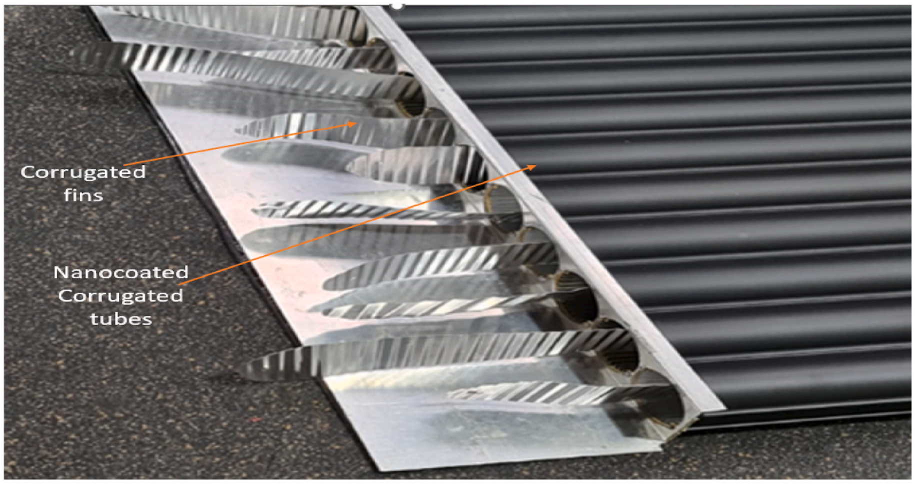

Fig. 23. Picture of proposed SAH.

2) The air mass flow rate, temperature difference, solar radiation, and air layer thickness affected the thermal efficiency of the SAH. However, the airflow rate dominated the thermal efficiency of SAH. The slower the air moved through the SAH; more heat could be absorbed into the airflow. The optimum mass flow rate must be investigated in relation to the climatic conditions and thermal efficiency techniques used.
3) The study showed that the latitude plays an important role in determining the SAH tilt angle. The ideal tilt angle for the SAH is equal or close to the latitude of the experimental setup location. Tilt angle plays a significant role in evaluating the thermal efficiency of the SAH.
4) Artificial roughness (fins, ribs, turbulators, corrugations) increased the surface area, resulting in an improved heat transfer rate, and thus, improving the thermal efficiency of the collector. However, the limitation with tube type SAH could be a large pressure drop which needs to be investigated.
5) Integrating thermal energy storage (TES) into SAH improved its thermal efficiency. It was found from the literature that SAH with aluminium fibers (porous material) have higher thermal efficiency (90.8 %) than SAH with other TES materials discussed in this study. Using material that store energy for longer time improves the thermal efficiency of SAH.
6) Supercooling effect is a major issue when using SAHs with phase change materials. Supercooling is the process of cooling a liquid or gas below its freezing point without it becoming a solid. Supercooling effect may not give more accurate results due to change in thermophysical properties of PCM,
7) The literature study revealed that SAHs with evacuated tubes integrated with heat pipes, and thermal energy storage have higher efficiency of 89.8 % compared to other evacuated tubes SAHs studied in this review.
8) The Maximum efficiency of 85 % was achieved using a transparent tube flat micro heat pipe array (FMHPA) collector. The literature study revealed that minimum pressure loss was found in a SAH integrated with FMHPA compared to other SAHs.
9) Attaching reflectors to SAHs improved their efficiency, however this will impact on the aesthetics and space required for the SAH. The weight and cost of the SAH increases when using reflectors. However, it boosts the solar radiation absorption by 80 %.
10) The application of black paint and nanofluid (nanoparticles dispersed in black paint) coating improved the collector's efficiency. High thermal conductivity materials improved the SAH efficiency. Copper has high thermal conductivity than aluminium, but the cost of copper is higher. Therefore, application of low cost materials is needed.

7. Future scope

1) Extensive research is required to optimize the different artificial roughness geometries for tube type SAH, roughness material, and orientation to improve thermal efficiency and reduce the pressure drop.
2) There is a scope to explore low-cost and lightweight thermal energy storage materials that are eco-friendly and will boost the thermal efficiency of SAH.
3) Investigation of the supercooling effect on the thermal efficiency of SAH is required when using phase change materials.
4) The application of black paint and nanofluid (nanoparticles dispersed in black paint) coating improved the collector's efficiency. However, the literature showed research on SAHs with a nanofluid coating is limited and research is required. Different concentrations of nanoparticles mixed in black paint and hybrid nanofluid technology should be investigated.
5) Extended research under a range of ambient conditions, for all the techniques used to improve the thermal efficiency of SAH is required.
6) It is important to evaluate the thermo economic benefits and the life cycle analysis of SAHs.
7) Thermal efficiency of proposed SAH needs to be investigated.

8. Proposed SAH design

In this review paper, thirty-seven papers were reviewed focusing on tube-type solar air heaters mainly for space heating. It is noted that the research on tube-type SAHs is limited but has been growing in recent years as the demand for renewable energy grows. In the last 5 years, the number of papers on tube-type SAH has increased, however, the research is still exploratory compared to the flat plate collectors. The degree of sophistication of techniques to increase thermal efficiency has increased from the use of internal roughness to coatings and phase change materials. The application of a nanofluid coating to the SAH tube could significantly improve the performance of the SAH. Considering the advantages of artificial roughness and nanocoating a new roughness geometry is proposed. The proposed SAH design consists of nanocoated corrugated tubes with corrugated fin inserts. The absorber tubes are coated with different concentrations of copper oxide and aluminium oxide nanoparticles mixed in black paint. The corrugated tubes with corrugated fin inserts are shown in Fig. 23. This type of geometry will be studied and experimented in near future.

Authors' contributions

Conceptualization: Mikael Boulic, Robyn Phipps, Poonam Pardeshi. Methodology, literature reviewing, writing: Poonam Pardeshi. Supervision and editing: Mikael Boulic, Andries (Hennie) van Heerden, Chris Cunningham, Robyn Phipps.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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