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Double Pass Solar Air Heater: A Review

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Abstract

Improvement in heat transfer rate and effectiveness of a solar air heater is always a matter of concern in the scientific community. Different steps have been taken to improve it, including the application of artificial roughness, double glazing, colour coating, and multi-pass flow. In this article, a detailed assessment of the efficiency and effectiveness of a solar air heater has been conducted by applying various types of double-pass arrangements. The effects of various methods applied so far are deeply analysed and discussed to create a better understanding. Future opportunities, challenges, and concerns are also addressed, with a fruitful conclusion in the last.

Keywords: Solar energy, solar air heater, double-pass, artificial roughness, thermal performance

Nomenclature

$\dot{m}$	Air mass-flow rate (kg/s)	SAH	Solar air heater
β	open-area ratio	SP	Single pass
η	Efficiency	DP	Double pass
ΔT	temperature difference	STS	Solar thermal system
W/w	Relative width ratio	FPSTS	flat plate STS
Re	Reynolds number	DPPFSAH	Double pass parallel flow SAH
Nu	Nusselt number	DPCFSAH	double pass counter-flow SAH
f	Friction factor	LCA	Life Cycle Assessment

1. Introduction

Since the dawn of human civilization, humans have understood the use of energy in different forms for different applications. The social and economic growth of every nation is largely dependent on its access to energy. Along with the increase of industrial and agricultural operations, the need for energy is rising daily [1]. In the future, the world will require significantly more energy supply, particularly cleanly generated electricity. Despite being limited, conventional energy sources including coal, oil, natural gas, and nuclear power still account for the majority of the energy industry. However, there are other risks connected to nuclear power plants, such as the loss of coolant accident (LOCA)[2]–[5] under unfavourable circumstances. Human beings learned to harness energy from different renewable energy sources, such as solar, geo-thermal, hydro [6], and wind, as time passed [7]–[10]. Solar energy in various forms such as solar thermal, solar photovoltaic, and solar chemical were prime sources to harness this energy [11]. Solar thermal conversion includes lower, medium, and high-temperature solar thermal conversions. In low-temperature solar thermal conversion, natural and forced solar air heating, solar water heating, and solar drying all contribute significantly [12].

A solar air heater (SAH) is a setup that is generally used for heating the air that comes from the ambient and is further utilised for domestic and industrial processes and applications like room heating, water preheating, and the drying of different products, among many others [13]. The low thermal heat transfer coefficient between SAH and ambient air comes from the environment and is a major Several methods have been used by various research scholars and scientists working in the field of SAHs, such as the use of artificial roughness on the base plate, the use of different colours on the base plate and within the SAH to improve absorption coefficient, the use of extended surfaces, wedges, turbulators, secondary flow, multi-glazing, and multi-pass for increasing the travelling time of air within the duct and creating better heat transfer between the duct and the surrounding environment [14]–[20].

Since long, a single pass SAH (SPSAH) was utilised to extract heat from the duct of a SAH [21]–[24]. However, with the significant development of studies into air flow pattern, this method is becoming outmoded [25]. It has been demonstrated that a SPSAH is inefficient at extracting maximum heat from the duct and that minimal convective heat transfer persists between the solar collector and the air; consequently, numerous researchers have proposed additional flow patterns to enhance the heat extraction yield between the air and the SAH absorber plate [26][27]. Application of a DPSAH in parallel-flow, cross-flow, and recycle-flow with different roughness on the plate has been used to improve the efficiency and effectiveness of a SAH by different research scholars [28]–[32]. Several experimental and mathematical studies have been conducted to enhance the effectiveness of double-pass SAH (DPSAH) equipped with efficiency improvement approaches such as artificial roughness, packed bed media, extending surfaces, and corrugated absorbent textures [33], [34]. This research addressed the DPSAH system, design analysis, and thermo-hydraulic properties of DPSAH and discussed various approaches implemented so far [2].

According to the literature, DPSAHs of all types effectively improved the efficiency of a SAH with various sub-arrangements within the solar collector duct, such as artificial roughness, wedges, turbulators, mesh, extended surfaces, packed bed, or PCM.

This study mainly focused on familiarising the scholar by providing a detailed review of different approaches used to improve the effectiveness of DPSAH. This study also discussed classification and the working principle of the heat transfer mechanism, identified unexplored topics for future study, offered recommendations, and expressed concern for the most appropriate sorts of DPSAH and their defined criteria.

2. Solar Thermal Energy Converter

The solar thermal system (STS) captures and transforms solar thermal radiation into the thermal energy of the working fluid that moves through it. A solar air heater (SAH) is a device that converts radiation from the sun for the purpose of generating heat, which is then transmitted to a working fluid [35], [36]. Non-concentrating or stationary solar thermal collectors are distinguished from focusing solar collectors. Due to concave reflecting surfaces, concentrating collectors have a relatively small receiving area to intercept and concentrate the sunlight beam, thereby attempting to capture the radiation flux [37]. They are typically employed for high temperatures in solar thermal power stations as well as other systems [38]. STS are broadly classified according to the temperature of the working fluid, as follows: This category includes high-temperature STSs with temperature gradients exceeding 400 °C and medium-temperature STS with an operational range of 1000 °C to 4000 °C and includes parabolic dish collectors, dish-sterilising systems, and central receiver systems [9], [39], [40]. While, low temperature STS include SAH, solar pond, and solar updraft towers [41].

3. Low-Temperature Solar Thermal System

This section includes STS with a temperature operating range of 100°C. In such a system, solar energy is gathered using flat-plate collectors, solar ponds, and solar updraft towers, among other devices. Pressure gradient and the Rankine cycle are the main operational concepts for such systems [42]. The advantages of low-cost thermal concentrators include simple construction and installation, direct and distributed radiation, relatively rough operation, cheap maintenance and operating expenses, and simple operation [43]. Compared to medium- and high-temperature systems, the overall efficiency of these systems is quite low due to their low operating temperature range. It may be created for applications requiring energy at moderate temperatures, generally 100 degrees Celsius above ambient [38].

4. Flat-plate Solar Thermal System

A flat plate STS (FPSTS) is a common type of heat exchanger that transfers radiant solar energy from the sun into heat energy by use of the well-known greenhouse effect. It gathers or catches solar energy and converts it to working fluid, which may then be used for a variety of purposes, such as in the household for heating. This can also be utilized to heat low-boiling-point fluid for power generation [44].

The FPSTS consists of an absorber plate with substantial absorption for incoming solar radiation, clear glass coverings, and a fluid passageway. The absorber plate is a standard metallic plate that faces towards the sun to absorb an amount of solar energy, which converts it into thermal radiation, and simultaneously sends thermal energy to a working fluid that flows through the collector. The top cover is made of glass, which allows for the transmission of incoming insolation and inhibits infrared radiation and radiation losses. FPSTS use beam and diffuse radiation, are normally fixed permanently in position, do not necessitate real-time monitoring of the sun's direction, and can be characterised based on the kind of transmission fluids used for heat exchange, i.e., water and air collectors [45] as displayed in **Figure 1**.

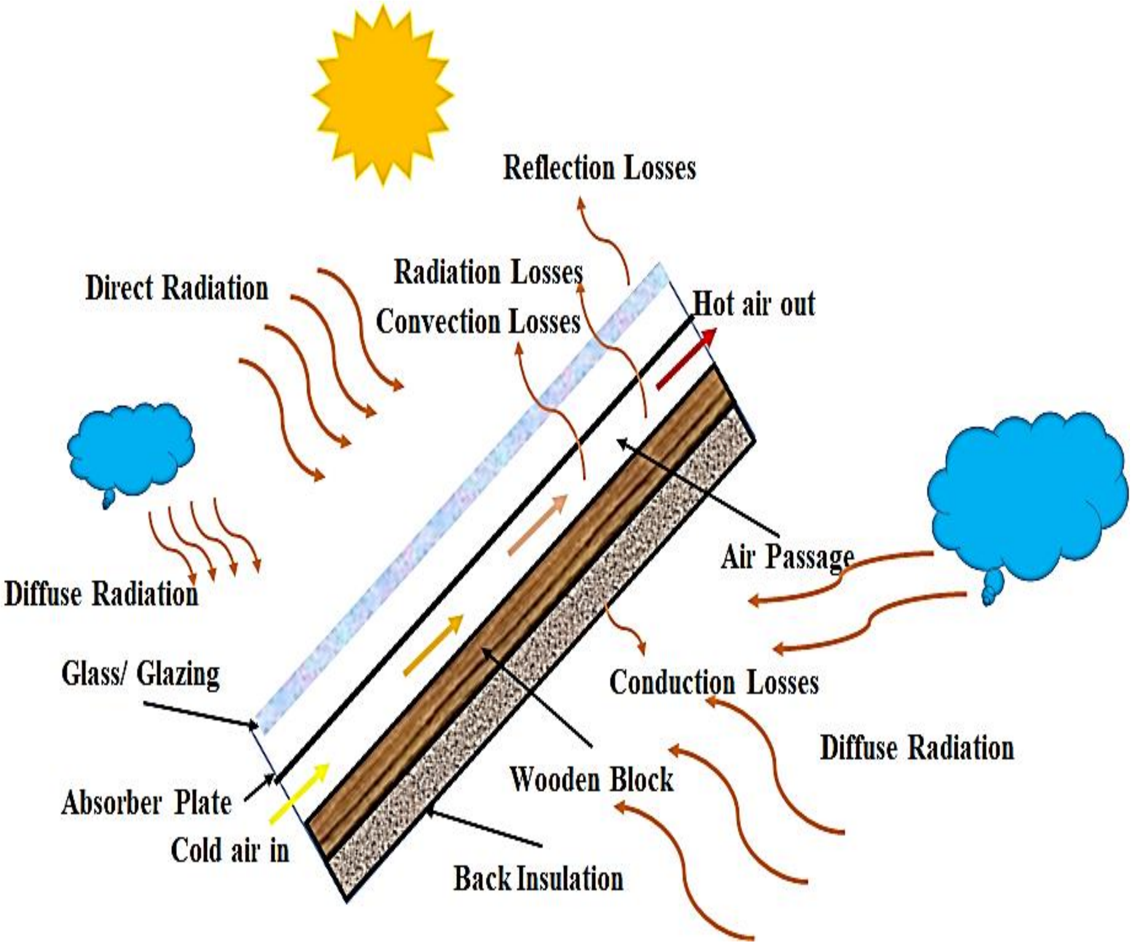

Figure 1: Illustration of a FPSTS working

5. Double Pass SAH Classification

As per the existing research [46], SAH may be classified as shown in **Figure 2**. As seen in the image, SAHs are divided as per their glass covers, absorbing material, flow pattern, flow kinds, absorber surface design, hybrid systems, and applications.

6. Double pass SAH

Satcunanathan [47] coined the double pass idea to restrict top heat losses to the atmosphere. In a double pass design, air passes on both faces of the absorber plate, removing heat from the absorber surface, and afterwards air moves in both directions of the absorber plate [32]. Due to the combinations that are considered to be the considerable factor that influences the effectiveness of a Double-Pass SAH (DPSAH) [28], [47]–[51], DPSAH is even further categorised according to the flow direction, as parallel flow [52]–[57], counter-flow [29], [58]–[61], and recycling or circular flow [61]–[65]. [66] Double-pass SAHs are 10–15% more efficient than SPSAHs. **Figure 3** displays a conventional DPSAH.

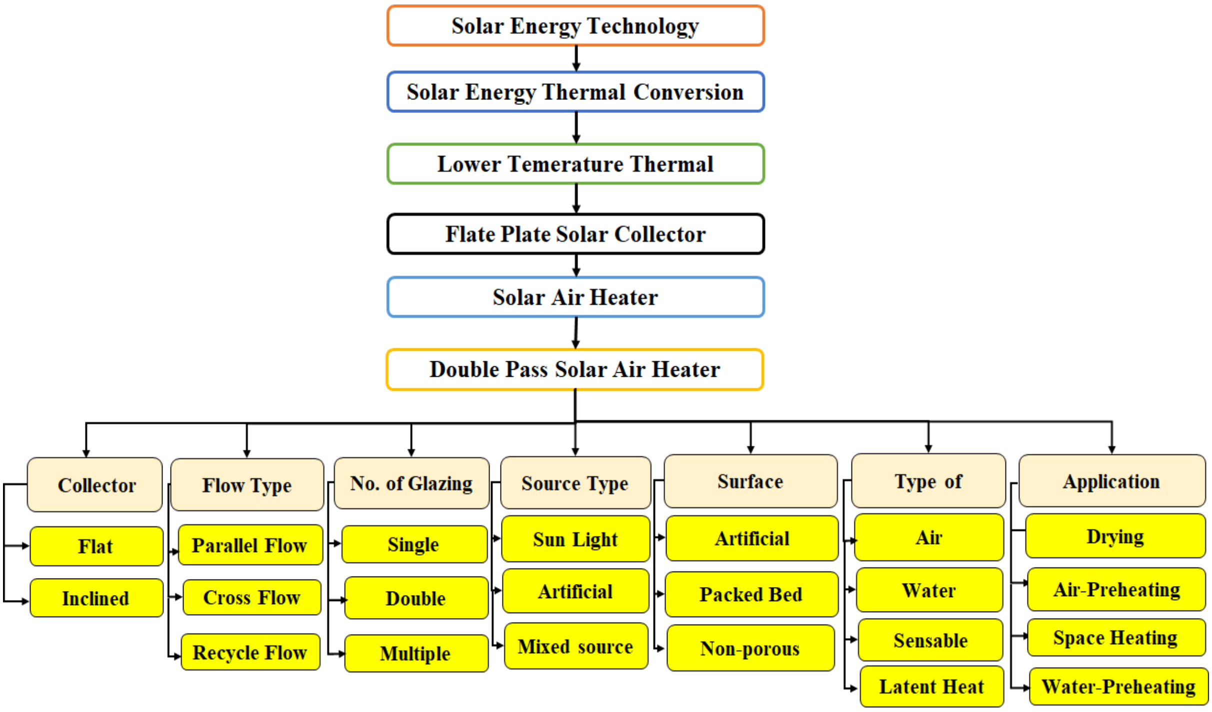

Figure 2: Solar thermal conversion and classifications of DPSAH

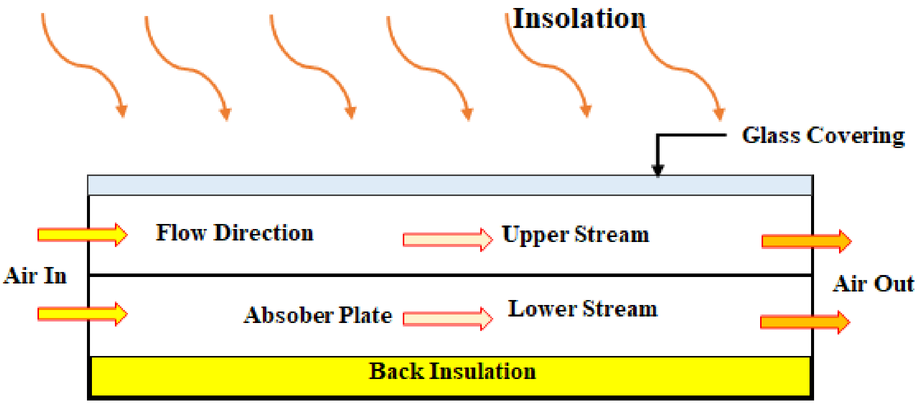

Figure 3: Conventional DPSAH

7. Air Pass Configurations and Theoretical Analysis

Initially, a SPSAH was used to remove heat from the collection plate. Current investigations [67] have demonstrated that SPSAH have poor thermal effectiveness due to considerable heat losses to the ambient. The air that travels down the duct and removes heat, and the air that passes from the top of the absorber plate reclaim a part of the heat that was delivered through the second pass of the DPSAH, resulting in a decrease in overall heat loss to the environment. As a result of less heat loss, overall performance is enhanced. The sequence of air passes has the most impact on the effectiveness of a double-pass SAH (DPSAH). The following sections look through several air pass configurations [28].

7.1 Parallel Flow DPSAH

Parallel Flow Double Pass Solar Air Heater (DPPFSAH) is a type of solar air heater system that utilises two air flows to transfer heat from the air to the solar collector. This system is capable of producing higher temperatures than single-pass systems, and is more efficient at transferring heat [36]. Advantages of this system include high efficiency, high temperature, and low maintenance, while limitations include being more expensive to install than single-pass systems, being more complex than single-pass systems, resulting in a longer installation time, and requiring more space than single-pass systems [68].

The future scope of the Parallel Flow Double Pass Solar Air Heater is very promising. With the increased awareness of the need to reduce our dependence on fossil fuels and the potential of solar energy as an alternative source of energy, the use of solar air heaters is likely to continue to increase. The development of more efficient systems, such as the double-pass system, will help to reduce the cost and increase the efficiency of solar air heaters, making them more accessible and cost-effective in the future [16].

In DPPFSAH, the working fluid passes through the absorber plate and glass covering. This setup is depicted in **Figure 4**. The airflow circulation is in the same direction in this setup. Potgieter et al. [69] provided a theoretical model for a DPPFSAH: “the outlet air mean temperature, mean airflow, heat transfer coefficient, and relative humidity could all be predicted using the model.”

Forson et al. [70] constructed a mathematical model for a DPPFSAH with two transparent coverings. Other theories on parallel flow in DPSAHs have also been developed [26], [70]–[76]. Moreover, research study [77]–[80] revealed that DPPFSAH performed better than Single Pass SAH (SPSAH).[77], [78].

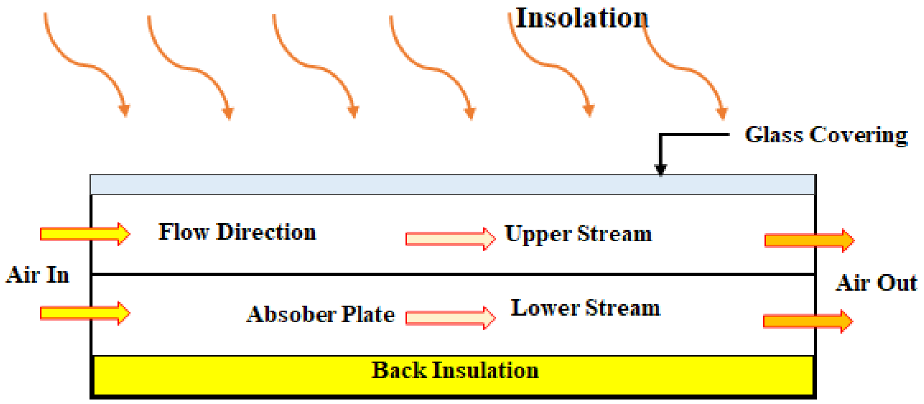

Figure 4: Parallel-flow, double-pass SAH

7.2. Counter Flow DPSAH

A double pass counter-flow SAH (DPCFSAH) is a type of air heating system that uses solar energy to heat air. They are comprised of a solar collector, a fan, and a heat exchanger. The solar collector takes in the sun's energy and turns it into thermal energy, which is then used to heat the air as it moves through the fan and heat exchanger. The air is then circulated back into the solar collector, allowing the thermal energy to be reused. Advantages of DPCFSAH include high efficiency, as the air passes through the heat exchanger twice, providing a greater amount of heat to the air. Additionally, they are a relatively inexpensive way to heat air, as the solar collector is the only component that needs to be purchased. Limitations of counter-flow Flow

Pass Solar Air Heaters include their reliance on solar energy and the need for direct sunlight to function. Additionally, they require regular maintenance to ensure that the fan and heat exchanger are functioning properly [71].

The future scope of the DPCFSAH is very promising. With the rising cost of electricity and the need to reduce our carbon footprint, solar air heating systems are becoming increasingly popular. As technology continues to advance, it is likely that the efficiency of these systems will increase, making them more cost-effective and viable in a wide range of applications. Additionally, the availability of solar air heating systems in more locations around the world will likely increase, as companies look to capitalize on the growing market for renewable energy [81].

The DPCFSAH design is desirable since it permits the extraction of more heat, resulting in enhanced thermal performance. A DPCFSAH consists of a glass surface, an absorber plate, and insulation. The structure closely resembles SPSAH. **Figure 5** depicts this configuration. The DPCFSAH conceptual framework proposed by Verma et al. [82].

As it can extract large thermal energy, the DPCFSAH configuration is a useful performance-enhancing solution [7], [10], [43], [83]. In DPCFSAH, the influence of several heat transfer improvement variables, including porous media [84]–[88], fins [89], packed bed wire meshes [90], and grooves [91] was also investigated. Several studies [92]–[94][95] also utilised double-glass covering to decrease total topmost layer heat losses and enhance performance.

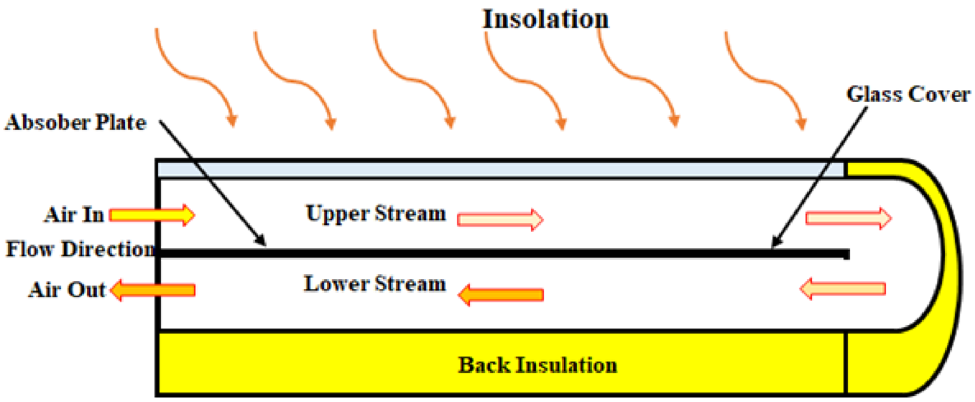

Figure 5: Counter-flow, double-pass SAH

7.3. Recycle Flow DPSAH

Recycle Flow Double Pass SAH (DPRFSAH) is a type of solar air heater that uses the double-pass effect to capture and retain more of the sun’s energy. This type of solar air heater uses two sets of fins that are arranged in a way that maximises the amount of solar energy that is absorbed. The fins are arranged so that the air passing through the first set is heated by the sun’s energy and then passes through the second set of fins, where it is heated again. This process of recycling the air increases the efficiency of the heater. The main advantages of using a DPRFSAH are that it is more efficient than single pass solar air heaters and can be used in cold climates. The double pass effect also helps to reduce the amount of energy that is lost due to convective heat transfer. Additionally, this type of solar air heater is relatively easy to install and maintain. The main limitations of using a Recycle Double pass solar air heater are requires more space due to the double pass effect and is more expensive than a single pass solar air heater [96], [97]. Additionally, the efficiency of this system is dependent on the amount of sunlight available in the area and the amount of insulation used in the building.

It has been demonstrated that air mixing and the intensity of forced heat convection play a crucial role in enhancing heat transmission. Similarly, in the DPRFSAH, a part of the hot outflow air is recycled to the intake channel and mixed with new air flow using a blower, a DPRFSAH is shown in **Figure 6**. Ho et al. [62] proposed the mathematical correlation for energy transfer and losses to recycling operations in the surrounding area.

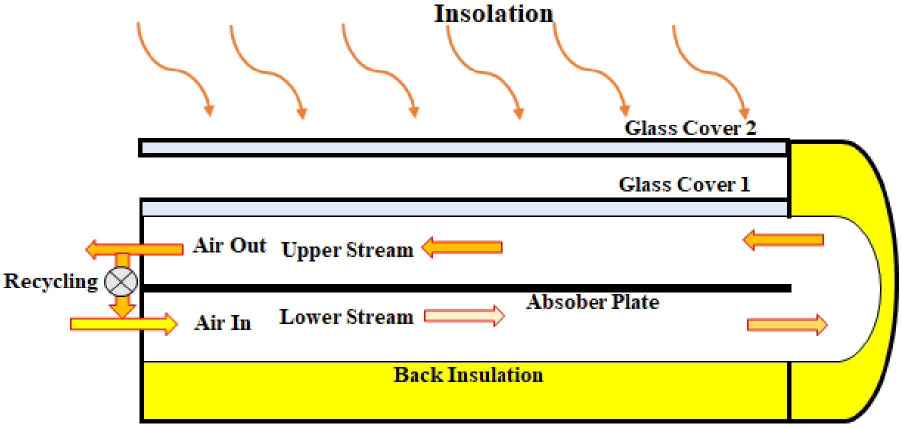

Figure 6: Recycled flow DPSAH

7.4. Multi-Pass Solar Air Heater

A multi-pass solar air heater is a device that utilises the energy from the sun to heat air that is then used to warm a building or a room. This type of solar air heater is different from conventional solar air heaters because it uses multiple passes of air to increase the efficiency of the heating process.

When a SAH runs at a moderate temperature or is subjected to wind flow, it is common practise to use two or more glass covers. This helps to avoid convective and radiative losses from the collector. The amount of solar energy that reaches the heated surface is reduced due to the absorption and reflection of insolation by glass [98].

8. Recent Development and Approaches Used to Determine the Performance of DPSAH

Several assessment approaches like experimental investigations, computational, numerical, and mathematical modelling, 3-D simulation, CFD analysis, life cycle assessment (LCA) analysis, ANN and CNN application, genetic algorithm (GA) application, and use of machine learning (ML) and artificial intelligence (AI) are used to determine the thermohydraulic performance and effectiveness of different DPSAH by various research scholars. In this segment, different approaches and efficiency enhancement methods are discussed in detail.

Naphon [89] studied the performance, entropy generation, and heat-transfer behaviour of the DPSAH with fins (**Figure 7**) by mathematical modeming at mass flow rate ($\dot{m}$) for 0.02-0.10 kg/s. This was observed that as fins number and height increases, so does thermal performance. The elevation and quantity of fins are inversely correlated with the transfer of heat.

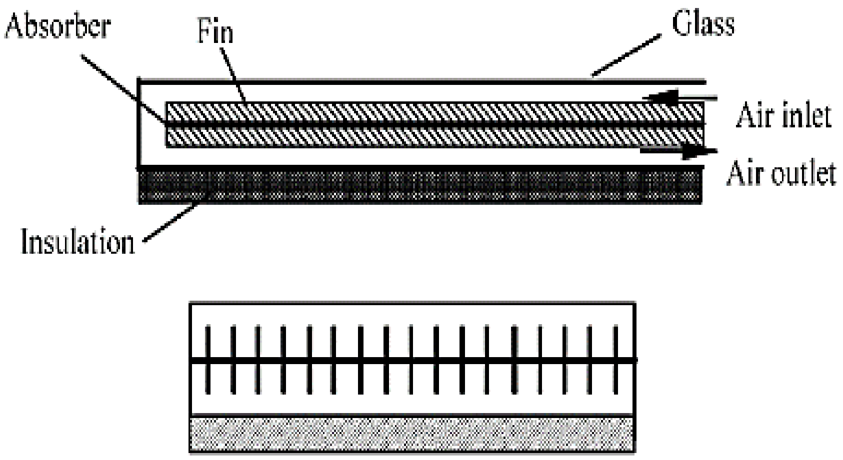

Figure 7: Schematic diagram of the DPSAH [89]

Mahmood et al. [99] constructed SPSAH and DPSAH with black colour 4 different transverse fins (**Figure 8**), with 16 wire meshing between these fins, The optimum thermal efficiency (η_{th}) achieved with the 75 mm collector was 62.50% for DPSAH and 55% for SPSAH and temperature difference (ΔT) was inversional proportional to air mass flow rate.

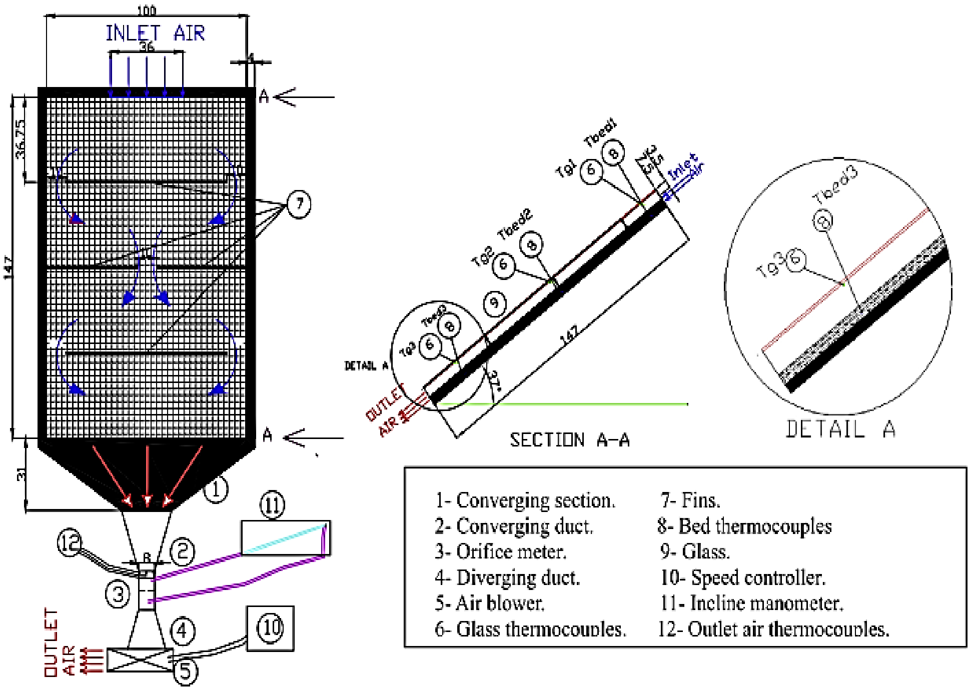

Figure 8: Schematic assembly of the SPSAH system used by Mahmood et al. [99]

Ho et al. [100][101] analysed (**Figure 9**) mathematically and experimentally the recycling effects on DPSAH performance with wire mesh packing and observed significant improvements in η_{th} as compared to smooth SPSAH and DPSAH running under similar working condition.

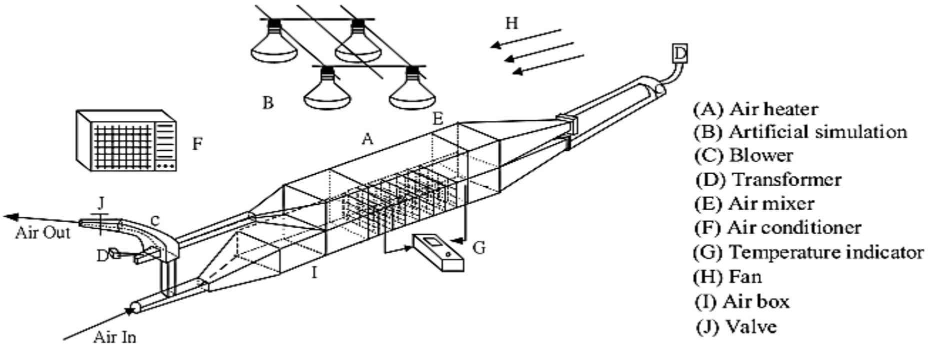

Figure 9: Experimental-setup of a DPSAH with wire-mesh packing [100]

El-Sebaii et. al. [102] investigate (**Figure 10**) DPSAH performance for finned-plates with geographical coordinates of Tanta, Egypt and observed that the v-corrugated DPSAH is 9.30%–11.90% higher effective as the DPSAH with finned plate. The optimum values of η_{th} of the DPSAH with fin and v-corrugate plate have been achieved with $\dot{m}$=0.01250 kg/s and $\dot{m}$ =0.02250 kg/s, correspondingly.

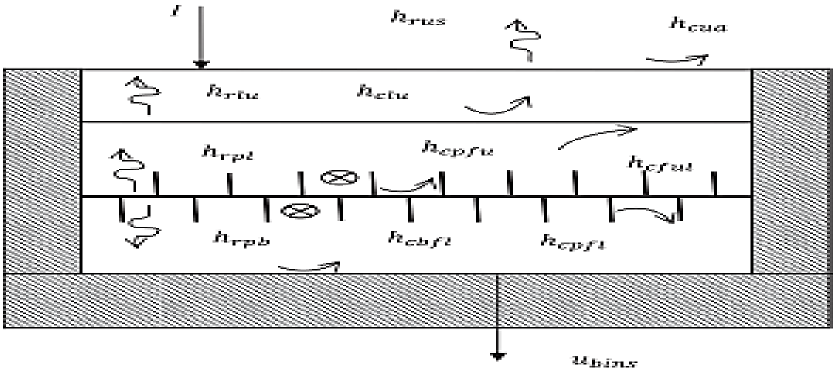

Figure 10: Finned plate DPSAH [102]

Sigh et. al. [15], [68], [103], [104] experimentally analysis (**Figure 11**) effect of perforation and variation in open area ratio (β) and relative width ratio (W/w) of perforated multi-V rib roughness under SPSAH and DPSAH and observed that DPPFSAH with perforated rib perform better then SPSAH and smooth DPPFSAH under similar operational parameters. The optimum thermal performance has been achieved at β=0.27 and W/w=6.

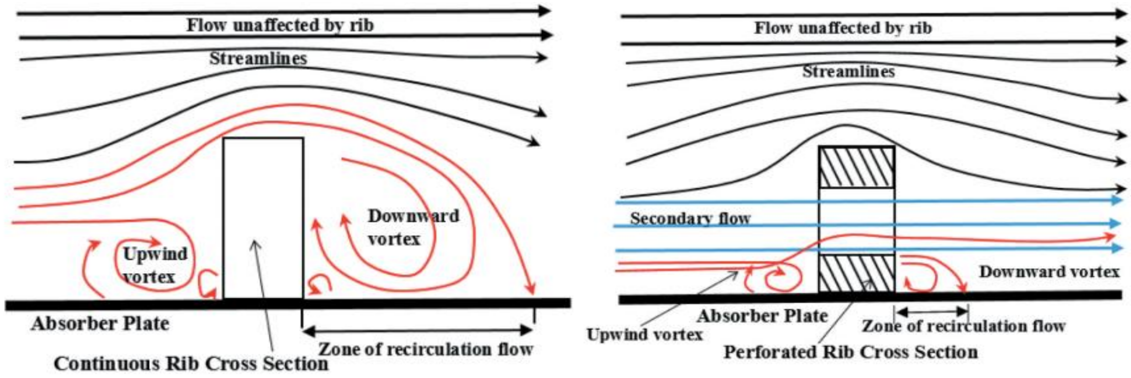

Figure 11:Visualization of air circulation, vortices formation and reattachment with (a) continuous and (b) perforated ribs in SAH duct [15]

Ravi and Saini [25], [105], [106] analysis the effect of discrete-multi V ribs with staggering in DPCFSAH under cross flow condition for Reynolds number (Re) from 2000 to 2000 and observed that double pass case enhanced heat transfer and frictional losses as compared to SPSAH (**Figure 12**).

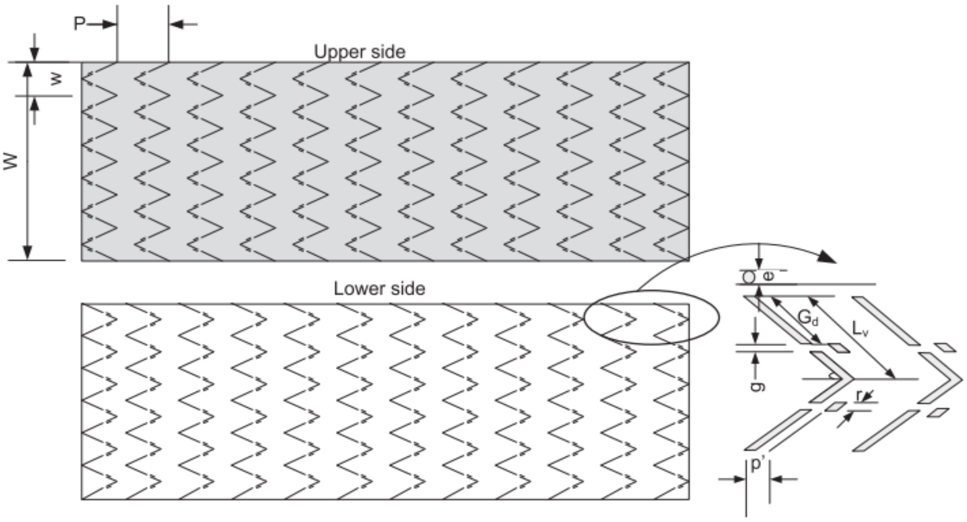

Figure 12: Orientation of discrete multi-V ribs with staggering in DPSAH [29]

Ramadan et. al. [107] studied the DPCFSAH with a packed-bed material (PBM) where Limestone with gravel are used as PBM (**Figure 13**), the η_{th} was observed rise with rise in $\dot{m}$ and reached an optimum value at 0.050 kg/s after further increase in $\dot{m}$ start reducing the η_{th}**.**

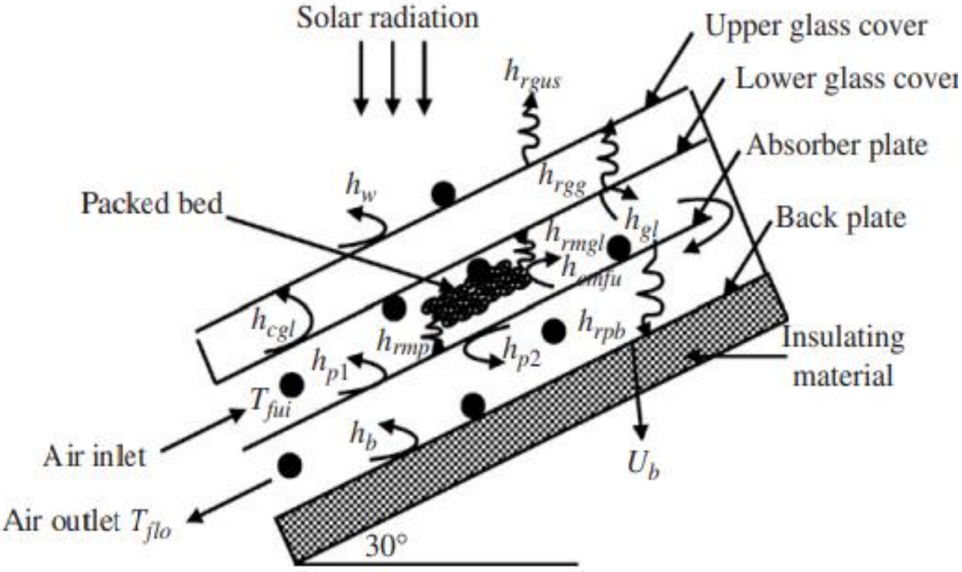

Figure 13:Schematic diagram of the DPSAH with a packed bed [107]

Ramani et al. [108] studied DPCFSAH with porous-material in the secondary air pass **Figure 14**, results shows that the η_{th} of DPSAH with porous-absorbing material is 20.0–25.0% and 30.0–35.0% better than the smooth DPSAH.

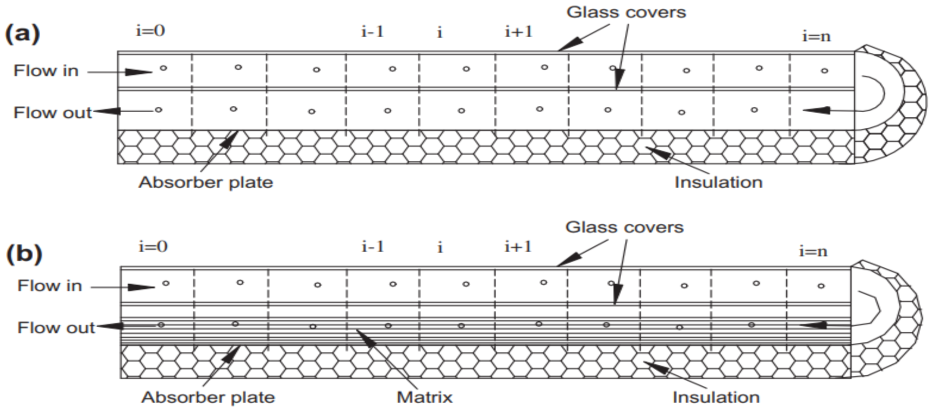

Figure 14: DPSAH, (a) without and (b) with porous-material

9. Conclusion

The performance of DPSAHs employing packed-bed materials, extended surfaces, corrugated surfaces, and perforations in roughness has been the subject of several experimental and theoretical investigations. DPSAH ducts were examined and experimentally verified in a number of investigations. The following conclusions are drawn:

- According to the review, it was shown that the majority of studies were conducted using double-pass systems that were merged with expanded surfaces. DPSAH using artificial roughness has only been the subject of a small number of investigations, and few investigations have been undertaken on corrugated or grooved absorbent surfaces.
- The thermo-hydraulic performance of the DPSAH was observed to be superior to that of traditional SPSAHs under similar working conditions. The DPSAH with a glass covering was the most economical option from a financial perspective. The highest thermal efficiency was attained in smooth DPSAH.
- Furthermore, the recycling approach can increase the DPSAH's thermal performance, but DPSAH with the recycling concept has its own limitations due to the recycling of air and observing a significant pressure drop.
- Rib elevation, frequency, and orientations, as well as other rib design configurations, are found to be critical characteristics in naturally roughened DPSAH, whereas pitch, frequency, and rib-height are found to be critical factors in DPSAH.
- Studies using DPSAH that has been artificially roughened have been observed, and few tests employing corrugated heat-collecting surfaces have been identified. However, employing computational models and correlations established by numerous studies under similar mass flow rates to evaluate the Nusselt number and friction factor of different kinds of DPSAH
- Perforation in artificial roughness improves DPSAH effectiveness significantly and has a high potential for further studies.

The future scope of double pass solar air heaters is to explore the potentials of using double pass solar air heaters in a variety of applications, such as in the residential and commercial sectors, as well as in industrial applications. Additionally, research into further improving the efficiency of these systems, as well as developing more affordable and efficient materials, should be conducted. Additionally, more research into the potentials of using these systems in combination with other renewable energy technologies, such as wind and geothermal, should be conducted. Finally, further research into the potential for using double pass solar air heaters for space heating and cooling should also be conducted. It is also point of investigation to study different heat transfer enhancement technologies and thermal storage devices using different advanced design and optimisation techniques i.e. FEA, RSM, ANN, Fuzzy Logic [108-112].

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