Analysis of advancement in Solar air heater (SAH) heat transfer expansion methods: A crisp review

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Abstract. The thermal efficiency of the solar air heater collectors is minimum when compared with liquid solar collectors due to the presence of a number of losses. There is a need to enhance the performance of these collectors. There are several techniques which are employed on the collectors to progress their performance by attaching different arrangement like turbulators, fins, porous matrix and using phase change material, etc. The modification on the collectors will also help in breaking the thermal viscous layer which is formed on the absorber surface. The thermal hotspots on the surface are reduced by acquainting with better thermal mixing of the fluids. The novel techniques are developed with the most innovative ideas by implementing the tubular collectors, double pass collectors, various geometrical ducts, etc. to reduce thermal losses. The Computational Fluid Dynamics (CFD) has become the effectual procedure to analyze the performance of these collectors. CFD has circumvented the experimental difficulties and is thus cost-effective. The parametric study of the different geometrical configurations supports in obtaining the optimum design and improved efficient device. This paper presents a crisp review of the recent works carried on the solar air heater (SAH).

KEYWORDS: Nusselt Number (Nu), Solar Air Heater (SAH), Reynolds Number (Re), Thermohydraulic Performance Parameter (TTHP), CFD

Abbreviation.
SAH: Solar air heater
TTHP: Thermo hydraulic performance parameter
HTC: Heat transfer coefficient
CFD: Computational Fluid dynamics
e/Dh: Hydraulic mean diameter
Nu: Nusselt Number
PR: Pitch Ratio
AR: Angle Ratio

1. Introduction.
The demand and consumption of non-renewable energy resources in our daily life are unceasingly increasing [1-4]. The non-renewable resources such as fossil fuels, earth minerals etc. are depleting slowly which in turn leading to a scarcity in energy production. Renewable resources such as solar thermal energy, wind energy, tidal energy can be viable alternatives. Renewable resources are incurred naturally free of cost. The operating and maintenance cost of these energy harvesting devices is...
relatively low than non-renewable energy resources. Further, these resources are non-pollutant with zero contribution of greenhouse gases and global warming and hence provide clean energy. SAH is used to heat the air to convert the solar thermal energy to heat the air. SAH’s are used in industries, space heating in greenhouse plantations, dry the timbers, crops, grains, theatres, warehouses, and offices during low ambient temperatures. SAH consists of the glass cover, which is transparent, high quality glass material is used to reduce the re-radiation and convection losses to the surrounding [5]. The absorber plate is located afterward to the glass cover for the absorption of the solar thermal radiation; it is made up of the Aluminium, Copper, or Steel with selective coatings such as black cupric oxide and black chromium on it to get higher thermal conductivity, high absorptivity and low emissivity [6-7]. The sides of the SAH are well insulated to avoid any kind of surrounding energy losses. Air leakage should be taken care of with better fabrication. The heat losses may also occur due to the corrosion on the air ducts and the mishandling of the equipment. The efficiency is also affected because of the deposition of the dust particles in the flowing air [8-9, 30]. The inlet duct is generally fitted with filters to avoid dust accumulation.

2. Advancement in the heat transfer expansion methods.

In recent years investigators studied SAH’s in order to improve its performance. This section deals with the summary of their work highlighting the methodology and conclusion. Various analytical, numerical, and experimental trials are used to boost the performance of these devices.

Shalini et al. (2017) analytically calculated the TTHP of the Solar Air Heater (SAH). A parametric variation was carried out for the height of the fin, spacing between the fins, flow rate, solar insolation for calculating the efficiencies. A matrix laboratory (MATLAB) code was developed to perform the analytical calculations. The system parameters and operating condition parameters were solved using the relevant developed correlations to get the performance data for the mass flow rate varying from 0.0139–0.083 kg/s. It is observed that the thermal efficiency rises with the increased airflow rate but the thermohydraulic efficiency increases only up to 0.028kg/s mass flow rate and then decreases. Variation of heat transfer coefficient and thermal efficiency shown in the figure 2a and 2b. The fins attached below the absorber plate augments the performance of the SAH, the thermal efficiency rises to 106.9%, and thermohydraulic performance parameter (THPP) up to 67.38%, 113.12% and 112.15% enhancement is noted in the thermal and thermo hydraulic respectively due to a reduction in the fin spacing and increment in fin height. Figure 1 represent the Absorber plate with offset fins. Figure 2 represent the autocad drafted figure.

Fig.1. Offset fin integrated absorber plate bottom view [10].
Fig. 2 AutoCAD developed Offset fin integrated absorber plate bottom view [10].

Fig. 3. Analytical and experimental values comparison of convective heat transfer coefficient (2a) and Thermal efficiency (2b) of finned solar air heater [10].

Kumar and Chand (2017) carried out the calculation for the SAH collector using the herringbone corrugated types fins. The fins were attached below the absorber plate. The energy balance equations were used to develop the theoretical model and are solved using the MATLAB code for the fluid flow rate of 0.01 kg/s - 0.06 kg/s. The operating parameter such as solar radiation, mass flow rate, the pitch of the fins, and fin ratio effects were studied. The herringbone corrugated fins increase the thermal efficiency from 35.2% to 55.6% when compared with conventional SAH for the airflow rate 0.0261kg/s having fin pitch 2.50cm with the penalty for increasing pressure drop. From the analytical study conducted, it is detected that the collector efficiency and fluid temperature increase depend on the SAH air flow rate.
Heydari and Mesgaspour (2018) performed the numerical and experimental study on the SAH using triangular cross-section turbulator. The triangular turbulator established the helical airflow within the SAH. The turbulator is designed to enhance the interaction of the air with the top and bottom surface of the absorber plate. The study shows that the performance of the helical flow model gave 14.7% better thermal efficiency than the simple duct SAH and 8.6% better thermal efficiency than the double pass finned SAH. The numerical study shows that the vortices formed during fluid movement between the above and bottom surface increases pressure drop locally. The overall heat transfer coefficient of 65.14 W/m²K is obtained for the mass flow rate of 0.026kg/s.

Chamoli and Thakur (2014) performed a mathematical study on the SAH. The SAH was modified with the baffles. The mathematical model was established to study the various performance parameters, ambient conditions, and design data. It is observed that the difference between effective efficiency and thermal efficiency is very less because the values vary marginally at lower mass flow rates but as the flow rate increases, the difference increased due to the extra pumping power. The thermal efficiency of the baffled SAH is up to 80% more than the smooth duct SAH. The increased flow velocity of the efficiencies in the SAH. The more the number of the collector glasses and the width of the collector the better the performance of the SAH.

Kumar et al. (2019) performed the arithmetical study on the SAH using the ribs as a turbulators. The triangular duct SAH was considered for the numerical study. The base model was validated with the Dittus-Boelter and Gnielinski equation. The commercially available CFD code was used to evaluate the results. Several turbulent models were used for the study out of which the k-ε renormalized model is relatively more accurate in comparison to the other models. The relative roughness height is defined as the ratio of the height of the fin to the hydraulic diameter (e/D) whose values were ranging from 0.013 to 0.05. The relative roughness pitch is the ratio of the distance between 2 ribs and the height of the fins (P/e) values varying from 5 to 13. The TTHP is found to be 1.97 for the P/e of 10 and e/D of 0.05 at Re17900.

Bopche and Tandale (2008) performed the experimental study on the SAH with the U-shaped inverted turbulators. The turbulators created the roughened artificial surface. The absorber plate is uniformly heated while the other sides of the ducts are insulated to avoid the heat losses to the surroundings. The experiment was performed for the Re varying from 3800 to 18000, the ratio of the height of the turbulator tip to hydraulic mean diameter (e/Dh)= 0.0186 to 0.03986 and ratio of turbulator pitch to its height (p/e) = 6.67 to 57.14. The angle of attack is maintained constant during the experiment. The analytical validation is carried out for the experimental data with the Dittus-Boelter equation and it is found to be ±8.27% deviated. The experimental friction factor validation was carried out with the Karman–Nikuradse equation with an average deviation of ±3.82%. The study shows that the turbulators enhanced the heat transfer of the SAH by 2.82% and friction factor by 3.72 times of the convention smooth duct SAH.

Thakur et al. (2017) performed a simulation of the SAH with hyperbolic ribs as the turbulators. The simulation results were validated with experimental work for the Re varying from 5000 to 15000. The validation of the model was done with the Dittus-Boelter equation and Blasius equation and found to have a deviation of less than 5%. The study was further extended with the inclined ribs, ‘V’ and ‘W’ shaped ribs. The ribs arrangement was varied for different inclination angles from 30° to 90°. The inclination of the ribs helps in better thermal mixing of the fluid due to flow parting and generation of the secondary flow along the ribs. TTHP is better for the V-shaped ribs having an inclination of 60° at Re 6000.

Kabee. et al. (2018) piloted the investigational reading on the single-pass SAH along with 19 longitudinal directional fins along the flow path. The longitudinal fins were deployed to intensify the heat transfer area on the absorber plate. The longitudinal fin height effect was studied for various dimensions of 3cm, 5cm, and 8cm. The opening was shielded with the glass at the place of the steel sheet cover to increase to the surface area which is exposed to sun radiation. The guided blades are attached near the inlet to ensure the equal distribution of the air over the absorber surface. The experiment was carried out for the mass flow rate varying from 0.013kg/s to 0.04kg/s. The smooth duct
SAH has 32% thermal efficiency, conventional finned SAH without entry region modification gave a 43.1% thermal efficiency, modified finned SAH with the guided blades at entry region gave a slightly better performance of about 57% thermal efficiency with 8cm fin height at 0.04kg/s air flow rate. Nems and Kasperski (2016) conducted the experimental investigation on the novel design SAH for space heating applications in Poland. The parabolic trough collector was used to concentrate the solar insolation on the absorber surface. The internal finned array evacuated tube absorber duct was imposed in the SAH. The polytetrafluorethylene mounting rings were fitted at the ends of the evacuated tube to minimize the heat loss. The collector performance was studied against the decreased temperature difference. The electric heater was used to heat the air at the inlet. The mathematical model was implemented to validate the experimental results and was found to be deviated by ±5.42%. The highest thermal efficiency achieved was 42.4%.

Sahar et al. (2018) conducted a numerical study on the SAH with triangular, rectangular, and elliptical fins. The Realizable k-ε turbulent model and Boussinesq model were used to capture the buoyancy force. The optimum angles were obtained to get higher mass flow rates. The highest mass flow rate is observed with inclination angles of 50˚ to 75˚ for rectangular fins and 45˚ to 60˚ for triangular and elliptical fins. It is observed that the narrowest inclination range is for rectangular fins and wide range for other configurations. The rectangular fins gave a better performance at the lower mass flow rate of about 59.18% thermal efficiency compared to other configurations. The study shows that decreasing the ambient temperature and increasing solar radiation gave better efficiency from the device.

Manjunath et al. (2017) performed experimental and numerical studies on the solar air heater. The spherical turbulators were used to check their influence on the performance. The analysis was performed for the Re ranging from 4000 to 25000. The diameter of the turbulators and relative roughness pitch (P/D) were varied parametrically. The validation is carried out with Dittus – Boelter equation using different turbulent models. The SST k-ω is found to be more suitable to solve the governing equations. The maximum efficiency increment is found to be around 23.4% when compared with conventional model. The thermal efficiency increases as the diameter of the turbulator increases and reducing the pitch. The highest Range of Nusselt number is to be 2.5 times more when compared to model for turbulator diameter 25.00 mm and P/D = 3.00 at Re 23560. The spherical turbulator causes the significant disturbance in the low and create the vortex flow inducing in the better thermal mixing.

Cuzminschi et al. (2018) designed the innovative SAH and carried out the numerical simulation. The SAH was tested for the 50 weeks to obtain an acceptable design. The SAH had an insulated case, plexiglass front glazing glass, Absorbent surface with U-shaped form profiles. The thermal efficiency obtained was nearly 60.41%. The exit mass flow rate was developed up to 59 ltr/s and the exit temperature of the air is 23˚C more than the ambient temperature.

Acır and Ata (2016) performed the experiment on the SAH having the circular tubes as the absorber ducts. The circular plate type turbulators were used to analyze system performance. The Pitch Ratio (PR) and Angle Ratio (AR) effects on the performance of the SAH is analyzed. The Re was varied from 3000 to 7500. It is found that the Nusselt Number (Nu) increased as the Re increases. The Nu decreases with increasing PR and AR. The performance boosted at the PR=2.0 and AR=0.1250. The newly designed SAH with turbulator gave an increment up to 4161 in heat transfer and friction factor of 511% when compared with conventional plane tube SAH. The numerical Nu predicted, and experimental data deviation is found to be less than 10.0%. The study shows that the contribution of the PR is relatively more than the AR in the SAH with turbulator.

Manjunth et al. (2018) carried out the numerical study on the sinusoidal type absorber plate SAH. The sinusoidal absorber plate has the Aspect Ratio (AR) which is defined as the ratio of the height of the absorber duct to the amplitude of one section of the plate. The base model is validated with the experimentation for thermal efficiency and is found to have a maximum deviation of 10.5%. The Reused for the simulation varied between 4000 and 24000. The AR is varied between 1.5 and 4. The average increase in thermal efficiency is found to be about 12.5% when compared to the base model. The
sinusoidal wave patterns on the absorber plate increase the disturbances in the flow and enhanced the better thermal mixing of the fluids. The modified SAH gave a better performance at the lower mass flow rates. The friction factor increased in the SAH thus the pumping power required is more in this type of arrangement.

Ansari et.al. (2018) studied the effect of the repeated ribs on the SAH absorber plate. A genetic algorithm was developed to find the optimum design to enhance the performance of the SAH. The empirical model was developed to validate the experimental data. The increment of 9% in thermal efficiency is obtained when compared with the base model. The SAH with ribs gave a better performance at the lower mass flow rate and the disturbance caused in the thermal viscous layer adjacent to the absorber plate. At a higher airflow rate, the temperature difference between the inlet and exit air is found to be very less and pumping power is more due to the more pressure drop in the airflow.

Wang et al. (2020) performed the analysis on the SAH having ‘S’ shaped ribs. The ribs were designed to obtain an optimum gap to reduce the air resistance in the flow. The height of the channel, solar intensity, the spacing of the rib, the width of the rib were certain parameters for optimizing the SAH. The thermal efficiency was 65% for the channel height of 30mm. The thermal efficiency decreased as the channel height was parametrically varied from 30mm to 50mm. The optimum design with artificial roughness gave an improvement from 13% to 48% in the thermal efficiency under various operating conditions.

Hassan et al. (2019) conducted the experimental analysis for the comparison of the Flat Solar Air Heater (FSAH) with Tubular Solar Air Heater (TSAH). The collector dimensions were maintained the same for both the models. The Aluminium tubular absorber ducts were 150cm in length with a 2.5cm duct diameter. The ducts were coated with black paint with 1mm thickness. The TSAH gave a better performance when compared to FSAH in thermal efficiency and output power. It was observed that there was a maximum increase of 13.2°C in the outlet temperature for the TSAH when compared with FSAH for the airflow rate of 0.025kg/s. The highest average daily thermal efficiency is found to be 82.6% for the airflow rate of 0.075kg/s. There was a reduction of 10.20% in top energy loss in TSAH when equated to FSAH.

Jouybari et.al. (2019) investigated the performance of the thin porous media on the absorber plate. They observed that the implementation of the porous media will give a significant improvement in the thermal and thermohydraulic performance. Numerical simulation was carried for various parameters such as Re, thermal conductivity. The Aluminium oxide (Al2O3) ceramic was used as the porous media because this material is generally implemented at higher elevated temperatures. The porous layer of thickness 1mm is applied. The numerical simulation is carried out using the k-ε turbulence model. The study showed that there is a major increase in the Nu at the cost of a minor increment in the friction factor. An increment up to 5.5 times in TTHP is observed when compared with plane duct SAH. The porous matrix reduced the thermal hotspots and aided in better thermal mixing of the fluid.

Singh et al. (2019) conducted the experimental analysis on the serpentine wavy channel SAH. The experimentation and numerical simulation were carried out for the SAH. The numerical simulation was performed with the k-ε with RNG group as a turbulence model. The maximum thermal performance of about 66.1% was observed at 0.040 kg/s. The air temperature was found to be nearly 54°C at the exit. Swirl flow takes place at the trough and crest region in the wavy channel. The recirculation zones near these regions enhance the momentum transfer and increased heat energy interaction at the cost of the minor pressure drop.

Khadraoui et al. (2016) experimental study on the SAH with the Phase Change Material (PCM) and another model without PCM. The Paraffin wax which is one of the (PCM) was used for the experimental study. The PCM acts as the latent heat storage system. The passive dehumidification occurs in the SAH with PCM because of the increase in the air outlet temperature during night times. The study reveals that low relative humidity is preferred for drying due to increased evaporative capacity. The daily thermal efficiency rises by 16.20% in the SAH with PCM when compared with the SAP without PCM.

Key findings of some research shown in table 1.
3. Result and discussion

Thermal efficiency and heat transfer coefficient variation is effected with the used of some advancement in the predefined shape of the solar air heater[31-35]. Shalini et al. noted the rise of 106.9% rise in the thermal efficiency of the SAH. Variation of thermal efficiency enhancement of different research work has been shown in the figure 3. Thermal efficiency vary from 42.4 to 106.9. Key findings of different research work shown in the table no 1.

| Author's                              | Descriptions                                                                 | Key findings                                                                 |
|---------------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Shalini et al. (2017)                 | ● TTHP of the Solar Air Heater (SAH) calculated analytically.               | ● Thermal efficiency rises to 106.9%.                                        |
|                                       | ● A matrix laboratory (MATLAB) code was developed to perform the analytical calculations [10]. | ● Thermo hydraulic performance parameter (THPP) rises up to 67.38% [10].    |
| Kumar and Chand (2017)                | ● SAH collector using the herringbone corrugated types fins investigated [11]. | ● The herringbone corrugated fins increase the thermal efficiency from 35.2% to 55.6% in comparison with conventional SAH [11]. |
| Heydari and Mesgaspour (2018)         | ● Numerical and experimental study on the SAH using triangular cross section turbulator [12]. | ● Helical flow model gave 14.7% better thermal efficiency than the simple duct SAH and 8.6% better thermal efficiency than the double pass finned SAH [12]. |
| Chamoli and Thakur (2014)             | ● The SAH was modified with the baffles [13].                               | ● The thermal efficiency of the baffled SAH is up                             |
| Study                                      | Details                                                                                                                                                                                                 |
|-------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Kumar et al. (2019)                       | • The triangular duct SAH was considered for the numerical study [14].                                                                                                                                   |
|                                           | • The TTHP is found to be 1.97 for the P/e of 10 and e/D of 0.05 at Re17900 [14].                                                                                                                                 |
| Bopche and Tandale (2008)                 | • Experimental study on the SAH with the U-shaped inverted turbulators [15].                                                                                                                               |
|                                           | • The study shows that the turbulators enhanced the heat transfer of the SAH by 2.82% and friction factor by 3.72 times of the convention smooth duct SAH [15].                                             |
| Thakur et al. (2017)                      | • Simulation of the SAH with hyperbolic ribs as the turbulators [17].                                                                                                                                       |
|                                           | • TTHP is better for the V-shaped ribs having an inclination of 60˚ at Re 6000 [17].                                                                                                                      |
| Kabee. et al. (2018)                      | • Piloted the investigational reading on the single pass SAH along with 19 longitudinal directional fins along the flow path [18].                                                                       |
|                                           | • 13.9% enhancement is noted in the thermal efficiency of SAH [18].                                                                                                                                        |
| Nems and Kasperski (2016)                 | • The parabolic trough collector was used to concentrate the solar insolation on the absorber surface [16].                                                                                              |
|                                           | • The highest thermal efficiency achieved was 42.4% [16].                                                                                                                                                  |
| Sahar et al. (2018)                       | • Conducted the numerical study on the SAH with triangular, rectangular and elliptical fins. The Realizable k-ε turbulent model and Boussinesq model were used to capture the buoyancy force [19]. |
|                                           | • Decreasing the ambient temperature and increasing the solar radiation gave a better efficiency from the device [19].                                                                                      |
| Manjunath et al. (2017)                   | • The spherical turbulators were used to check their influence on the performance [20].                                                                                                                   |
|                                           | • The maximum efficiency increment is found to be around 23.4% when compared with the smooth duct SAH [13].                                                                                               |
| Authors (Year) | Details |
|---------------|---------|
| Cuzminschi et al. (2018) | • The SAH was tested for the 50 weeks to obtain acceptable design [21]. • The thermal efficiency obtained was nearly 60.41% [21]. |
| Acir and Ata (2016) | • The circular plate type turbulators were used to analyse the system performance [22]. • The study shows that the contribution of the PR is relatively more than the AR in the SAH with turbulator [22]. |
| Manjunth et al. (2018) | • Carried out the numerical study on the sinusoidal type absorber plate SAH [23]. • The average increase in the thermal efficiency is found to be about 12.5% when compared to the base model [23]. |
| Ansari et al. (2018) | • Studied the effect of the repeated ribs on the SAH absorber plate [24]. • The increment of 9% in thermal efficiency is obtained when compared with the base model [24]. |
| Wang et al. (2020) | • Analysis on the SAH having ‘S’ shaped ribs carried out [25]. • The optimum design with artificial roughness gave an improvement from 13% to 48% in the thermal efficiency under various operating conditions [25]. |
| Hassan et al. (2019) | • Conducted the experimental analysis for the comparison of the Flat Solar Air Heater (FSAH) with Tubular Solar Air Heater (TSAH) [26]. • The highest average daily thermal efficiency is found to be 82.6% for the air flow rate of 0.075kg/s. There was a reduction of 10.20% in top energy loss in TSAH when equated to FSAH [26]. |
| Jouybari et al. (2019) | • Investigated the performance of the thin porous media on the absorber plate [27]. • An increment up to 5.5 times in TTHP is observed when compared with plane duct SAH [27]. |
Singh et al. (2019)  | • The numerical simulation was performed with the k-ε with RNG group as turbulence model [28].  

Khaderaoui et al. (2016)  | • Experimental study on the SAH with the Phase Change Material (PCM) and another model without PCM[29]  

| • The recirculation zones near these regions enhance the momentum transfer and increased heat energy interaction at the cost of the minor pressure drop [28].  

| • The daily thermal efficiency rises by 16.20% in the SAH with PCM when compared with the SAP without PCM.  

4. Closures.
A critical review of the heat transfer augmentation of the SAH is mentioned in the literature review. Several methods are implemented by modifying the duct geometrical shapes, turbulators, porous matrix, and PCM. The adjustment of these parameters leads to the augmented performance of the device to achieve better TTHP. The conclusion which can be derived from the review is:

- The CFD technique is generally used to numerically calculate the performance of the SAH. Many researchers have validated the CFD results with the experimental values.
- The CFD technique is found to be more cost effective because it evades the experimental difficulties.
- The SAH absorber plate is modified with turbulators and fins to enhance the TTHP of the SAH by creating the roughness on the surface.
- The tabulator’s of varying cross-sectional shapes such as rectangular ribs, triangular ribs, and circular ribs are used by many researchers.
- The tabulators’ provided on the absorber plate increases the thermal mixing by breaking the thermal viscous layer formed on the surface.
- The hotspots on the surface are evaded at the cost of the minor pressure drop.
- The innovative tubular absorber ducts and porous matrix is introduced in the SAH to augment the performance and are found to more effective compared to the conventional ducts.

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