Study of Performance Enhancement of Single and Double Pass Solar Air Heater with Change in Surface Roughness

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Abstract: The performance of Solar Air heaters can be enhanced by placing ribs of different geometries over the absorber plate which increases turbulence and thereby increasing its heat transfer and friction factor characteristics. It has been reported by various researchers that Double pass solar air heaters are more efficient than single pass solar air heaters in terms of its Thermal performance. It is also reported that using discrete ribs over the absorber plate in place of continuous ribs gives more heat transfer. The present paper gives us the details of various artificial roughness provided over the absorber plate to increase turbulence. This paper gives a brief overview of various researches done on Single as well as Double pass solar air heaters in terms of its Thermal and Thermohydraulic efficiencies along with Nusselt Number and Friction Factor enhancement.

Keywords: Solar Air Heater, Double pass solar air heater, Nusselt Number, Friction factor, Thermal efficiency, Thermohydraulic efficiency

Nomenclature:

- e: Roughness element height (mm)
- W: Width of duct (m)
- A_c: Absorber plate area (m²)
- A_o: Throat area of orifice meter (m²)
- D_h: Hydraulic Diameter (m)
- H: Height of duct (m)
- Pr: Prandtl Number
- Re: Reynolds Number
- e/D_h: Relative roughness height
- f: Friction factor
- Nu: Nusselt Number
- Nu_max: Maximum Nusselt Number
- W/H: Aspect Ratio
- p: Pitch
- p/e: Relative Roughness pitch

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α  Angle of attack
η  Thermal efficiency
η_{th}  Thermohydraulic efficiency
HT  Heat Transfer
\eta_{\text{max}}  Maximum efficiency

1. Introduction

Energy is the most global measure of all kinds of work done. The energy sources are categorized into three ways. These are Primary, Secondary and Supplementary energy sources. Out of these, Primary energy sources are dependent generally upon fossil fuels and also if the present trend of energy consumption continues, fossil fuels will get depleted soon due to ever increasing demands. So, there is a need to switch over our focus to some other sources so that dependency on fossils get decreased. One such method is to shift towards Non-conventional energy sources like Solar energy, Wind energy, Ocean-Thermal energy etc. These sources are in plenty and are ecofriendly too. Out of these Solar energies is in abundance and also harnessing of solar energy to its maximum extent has not been achieved yet. One of the ways to use Solar energy is to change it into some other useful type of energy like Thermal.

One such method is to use Solar Heaters which converts Solar energy into Thermal energy by various arrangements. Generally, two types of solar heaters are there. One is Solar water heater and other is solar air heater. Out of these, as air is easily available from the atmosphere, so solar air heaters are the best way to harness it. Solar energy is available in plenty and is non-polluting also. The best way of using solar energy in solar air heaters is to convert it into Thermal energy thereby decreasing dependency in fossil fuels. In solar air heaters, energy from the sun is taken up by absorber plate which in turns heats up the air flowing in its periphery, which then be used for various purposes like drying of crops or Room heating etc. Many researchers have done their work in this regard.

There are two types of solar air heaters. One is single pass solar air heater in which the air passes once over the absorber plate taking the necessary heat from plate. Other is Double pass solar air heater, in which air passes two times over the absorber plate. Many researchers have done their experiments in both Single and Double pass solar air heaters to increase its thermal efficiency which is generally less due to less heat transfer between the absorber plate and air. It has been found out from the literature that thermal efficiency can be increased by increasing turbulence.

The easiest way to increase it is by using artificial roughness over the absorber plate in the forms of ribs and other restrictions. It can also be increased by increasing heat transfer area using fins or wire mesh. So, this paper presents the work done by various researchers on solar air heaters in terms of increasing its efficiency. Some of the researchers used Phase change material (PCM) like paraffin wax to store solar energy for further use during off sun periods. Many experimenters have done their experiments for increasing Heat transfer rate of solar air heaters by different methods to increase turbulence. Also, it was noted from the literature that Double pass solar air heaters are more efficient than single pass solar air heaters and using discrete ribs over the absorber plate in place of continuous ribs gives more heat transfer rate. So, this paper in brief presents the contribution of various researchers in the field of both single
and two-pass solar air heaters in terms of various type of artificial roughness employed to increase turbulence.

2. Review on Single pass solar air heater

A single pass solar air heater is a type of heater in which air flows over the absorber plate in a single pass only for taking heat from the absorber plate. Many researchers investigated its performance by taking ribs of different geometries over the absorber plate. Some of the contributions are given below. Schematic diagram is given below.

Fig.1. Single pass

Gupta et al. [1] did their experimentation by taking parameters \(e/D_h\) and Inclination of the ribs(\(\alpha\)) with respect to Reynolds number (Re) on Thermal performance of a solar air heater.

Fig.2. Inclined ribs [1]

They concluded that thermal performance increases with increase in relative roughness height. Following results are concluded form their experimentation:

- Heat Transfer increased by 1.8 folds than smooth plate.
- Friction factor increased by 2.7 folds than smooth plate.
- Angle of inclination is 60˚.
- \(e/D_h=0.023\).
- Reynolds No.=14000.

Bhagoria et al. [2] experimented on wedge shaped ribs and investigated its effect on various parameters. They have taken the following parameters:

Fig. 3. Wedge Shaped ribs [2]

- Reynolds No.=3000-18000
- \(e/D_h=0.015-0.033\)
- wedge angle= 8˚-15˚
- Observations: Nu increased by 2.4 times that of smooth plate.
Friction factor increases by 5.3 times that of smooth plate.

Momin et. al [3] investigated on v-shaped ribs. They have taken following parameters for their analysis:

- Reynolds No.= 2500-18000
- \( e/D_h = 0.02-0.034 \)
- Angle of attack= 30˚-90˚
- \( p/e = 10 \)

They concluded that with an increase in Reynolds No. friction factor goes on decreasing and Nusselt No. increases.

- Maximum enhancement is 2.30 times of Nusselt No. as compared to the smooth plate. (Angle of attack=60˚)
- Maximum enhancement is 2.83 times of friction factor as compared to the smooth plate. (Angle of attack=60˚)

Sahu and Bhagoria [4] did their experimentations on transverse broken ribs and analyzed their impacts on heat transfer characteristics.

- They have taken following parameters:
  - Roughness pitch=10-30 mm
  - Rib height= 1.5 mm
  - Aspect ratio= 8
  - Reynolds number= 3000-12000

![Fig. 4. Broken transverse ribs [4]](image)

Findings are as follows:
- Nusselt No.is maximum at roughness pitch of 20 mm.
- Thermal efficiency range= 51-83.5%
- Heat transfer coefficient is 1.25-1.4 times that of smooth plate.

Varun et.al [5] did their work on the combination of Discrete and Transverse ribs. They used following parameters:

- Reynolds No.=2000-14000
- \( p/e = 3-8 \)
- \( e/D_h = 0.030 \)

![Fig. 5. Inclined and transverse ribs combined [5]](image)

According to them the best thermal performance occurred at \( p/e \) of 8. He also developed mathematical correlations for Nusselt No. and Friction factor.
Aharwal et. al [6] experimented and analysed the effect of gap width and gap position on heat transfer and friction factor characteristics. They had taken inclined Discrete ribs for their analysis.

![Image of ribs with gap](image)

**Fig. 6. Ribs with gap [6]**

The observations are as follows:
Heat Transfer (Maximum) = At relative gap position of 0.25
At relative gap width of 1.0
p/e of 8
Angle of attack of 60˚
e/Dh of 0.037

Arvind et al. [7] did their work on W-shaped Discrete ribs over the absorber plate of a single pass solar air heater. Following parameters were taken:
W/H= 8:1
Re= 3000-15000
e/Dh of 0.0168-0.0338
p/e=10
α= 30˚-75˚.

![Image of W-shaped ribs](image)

**Fig. 7. Discrete w-shaped ribs [7]**

They concluded that Nusselt no. and friction factor is maximum at 60˚ and is 2.16 and 2.75 times of smooth plate for e/Dh of 0.0338 respectively.

Hans et. al [8] did their experiments on V-shaped ribs on absorber plate. They studied Heat transfer and friction factor characteristics over this shape. They have taken the following parameters:
e/D₀ = 0.019-0.043
Reynolds No. - 2000-20000
α= 30°-75°
Relative roughness width = 1-10
p/e= 6-12

Fig. 8. Multiple V-ribs [8]

The findings are as follows:
Maximum Heat transfer occurred at: Relative roughness width= 6
Maximum Friction factor occurred at: Relative roughness width=10
Correlations were also developed for the same.

Prashant et. al [9] worked on the analytical model to see the performance of parallel flow packed bed solar air heater where packed material is placed at the upper channel.

Fig. 9. Packed bed integrated [9]

They found that by comparing the efficiencies of packed bed type solar air heater with that of a conventional solar air heater, thermal efficiency was found to be 10-20% higher than the conventional heater.

Brij Bhushan et. al [10] gave the correlations for Nusselt No. and Friction factor. They have taken protrusions as roughness.

Fig.10. Protruded roughness geometry on absorber plate [10]

Findings:
Nusselt No. enhancement: 3.8 times that of smooth plate
Friction factor enhancement: 2.2 times that of smooth plat
They also developed correlations for the same.
Sukhmeet et al. [11] investigated heat transfer and friction factor correlations with discrete V-down ribs. Various parameters and their ranges are as follows:

- Relative gap width: 0.5-2.0mm
- Reynolds No.: 3000-15000
- p/e: 4-12mm
- α: 30°-75°
- Relative roughness height: 0.015-0.043mm
- Relative gap position: 0.20-0.80mm

Fig. 11. Discrete v-down ribs arrangement [11]

From experiment they concluded that the maximum value of Nusselt no. and friction factor comes out to 3.04 and 3.11 times respectively as compared to the smooth plate.

Lanjewar et. al [12] did their experiments on W-shaped ribs. They analysed the flow both up steams and down streams. The parameters taken were:

- Aspect Ratio(W/H) = 8
- e/Dh = 0.03375
- Angle of attack: 30°-75°
- Reynolds No.: 2300-14000
- p/e = 10

Fig. 12. W-shaped ribs [12]

Observations are as follows:

Thermohydraulic performance: W-Down Ribs> W-Up Ribs
For W-Down Ribs = 1.98 than that of smooth plate.
For W-Up Ribs = 1.81 than that of smooth plate.

Manivannan et al. [13] provided artificial roughness as v-shaped ribs at 60° on a single pass solar air heater.

Fig. 13. v-shaped ribs [13]
They concluded that maximum temperature difference between inlet and exit of collector is 25°C and 34°C respectively for smooth plate and roughened plate. He also concluded that thermal efficiency is enhanced by 14% than the conventional heater.

3. Review on Double pass solar air heater

A double pass solar air heater is that in which the air flows over the absorber plate in two passes. The schematic view is given below in figure.

![Diagram of Double Pass Solar Air Heater](image)

**Fig.14. Double pass**

Satunanathan et. al [14] did their work on double pass solar air heater having counter flow. The flow is between absorber plate and glass and then get into the duct. They concluded that Thermal losses can be minimized by placing one or more glass covers. They also concluded that Thermal efficiency of Double pass > Single pass Solar air heater.

Wijeysundera et. al [15] compared two pass solar air heater with that of the conventional heater. From his experiments he concluded that two pass mode is inexpensive method to improve the collector efficiency. It improves it by 10-15%.

Sodha et. al [16] studied the performance of Double flow type solar air heater with that of single pass for the same mass flow rate and parameters.

He found that for similar conditions Double flow type solar air heater is more efficient than single pass due to higher heat flux in double type.

Yeh et. al [17] did their experiments to study the collector efficiency of a double flow solar air heater. For this he attached fins and did both experimental and analytical approach.

![Diagram of Fins Attached](image)

**Fig.15. Fins attached [17]**
They concluded that due to fins the collector efficiency always increases. But while employing it, it must also be kept in mind that due to fins fan power must not be increased. So, fins attached must be as compared to the width of collector.

Naphon [18] focused upon the entropy generation integrated with longitudinal fins. Mass flow rate for the experiment was taken in between 0.02 kg/s to 0.1 kg/s.

He concluded that:
   a) Amount of entropy generated depends inversely upon height and no. of fins.
   b) Thermal efficiency increases with increasing no. of fins.
   c) Thermal efficiency increases with height of fins.

M. Samiev [19] did his experiments for finding the efficiency of solar air heater. He took a solar air heater having a non-stationary plate mounted on it.

His findings are as follows:
Heating temperature = Ranges from 40°C-60°C
Stationary efficiencies = Between 37%-50%

Khawajah et. al [20] experimented over a double pass solar air heater integrated with transverse fins. He experimented on thermal performance with 2, 4 and 6 fins attached.

Mass flow rate ranges = 0.0121-0.042 kg/s.
Fig. 18. Transverse fins on a double pass solar air heater using wire mesh as an absorber [20]

Findings:
Efficiency goes on increasing with increase in mass flow rate.

| Mass flow Rate (kg/s) | Fins attached | Maximum efficiency (%) |
|-----------------------|---------------|------------------------|
| 0.042                 | 2             | 75                     |
| 0.042                 | 4             | 82.1                   |
| 0.042                 | 6             | 85.9                   |

Chii Dong Ho et. al [21] did their investigations on collector efficiency. They took a double pass solar air heater for their analysis which was integrated with fins. From their experiment they found that collector efficiency increases with increase in mass flow rate. And by recycling operation it is further improved by 80%.

Fudholi et al. [22] experimented on the thermal efficiency of double pass solar air heater having longitudinal fins on the absorber plate. 3 types of solar air heater were used.
Type 1: Fins at upper portion.
Type 2: Fins at lower portion.
Type 3: On both sides.

Fig. 19. Longitudinal fins [22]

They found that the efficiency of collector always increases with mass flow rate. It also increases with no. and height of fins.
From going from 0.02 to 0.1 kg/s mass flow rate efficiency increases by 30%.
Efficiency is 36-73% for Type 1.
Efficiency is 37-75% for Type 2.
Efficiency is 46-74% for Type 3.
Prashant et al. [23] investigated the effect of Differential air mass flow rate on packed bed solar air heater. In this he measured the range of flow rate in which thermal performance of parallel pass system is higher than that of counter pass system.

They found that parallel pass packed bed system is 72% and 44% efficiency having 0.2 and 0.8 fixed and total mass flow rate of 0.01 kg/s.

Chabane et al. [24] experimentally studied the heat transfer and Thermal performance of solar air heater with longitudinal fins. For his experiment he placed longitudinal fins below the absorber plate. He has done experiments by varying the mass flow rate.

Mass flow rate: 0.012-0.016 kg/s.

From experiment they concluded that the efficiency gets its higher value when fins are attached to the absorber plate. The results are as follows:

| Mass Flow rate/ Type of SAH | With Fins | Without fins |
|-----------------------------|-----------|--------------|
| 0.012 kg/s                  | 40.02%    | 34.92%       |
| 0.016 kg/s                  | 51.50%    | 43.94%       |

They also concluded that efficiency is maximum when solar air heater is placed 45˚ to the horizontal and with increasing mass flow rate efficiency also gets into the higher side.

**Summarized report and contribution of other researchers in chronological order:**

| Researcher                  | Solar Air Heater Type | Parameters/Processes Used                        | Findings                                                                 |
|-----------------------------|-----------------------|--------------------------------------------------|---------------------------------------------------------------------------|
| Satcunanathan et al. (1973) [14] | Double pass         | Counter flow                                     | $\eta$ (Double pass) > $\eta$ (Single pass)                              |
| Wijeysundera et al. (1982) [15] | Double pass         | Comparison with single pass                      | $\eta$ (Double pass) > $\eta$ (Single pass) by 10-15%                    |
| Sodha et al. (1982) [16]    | Double flow type     | Comparison with single pass                      | Double flow type is more efficient                                       |
| Prasad et al. (1988) [25]   | Single pass          | Transverse ribs $p/e, e/D_h$                     | Maximum heat transfer at $e/D_h=0.033$ and $p/e=10$                      |
|                            |                       |                                                  | $[HT]_{\text{increase}}=2.38$ times $\eta_{\text{increase}}=4.25$ times of smooth plate |
| Prasad et al. (1991) [26]   | Single pass          | $p/e, e/D_h$                                     | $HT_{\text{max}}$ at $p/e$ of 10                                         |
| Author(s)          | Passage Type | Cost Analysis | Double Pass with Single Cover is Most Cost Effective |
|-------------------|--------------|---------------|------------------------------------------------------|
| Choudhury et al.  | Single & Two | Cost analysis  | Double pass with single cover is most cost effective |
| Gupta et al.      | Single pass  | Inclined ribs | [(HT) increase= 1.8 times (f) increase= 2.7 times] of smooth plate |
| Bhagoria et al.   | Single pass  | Re= 3000-18000 | [(Nu) increase= 2.4 times (f) increase= 5.3 times] of smooth plate |
| Yeh et al.        | Double pass  | Attached fins | Collector efficiency increases significantly |
| Momin et al.      | Solar Air heater | v-shaped ribs | [(Nu) increase= 2.3 times (f) increase= 2.83 times] of smooth plate at α= 60˚ |
| Inci et al.       | Single pass  | Integrated concentrator | Conical concentrator attained temp up to 150˚C |
| Sahu et al.       | Single pass  | Broken Transverse ribs | Nu max = At p=20 mm |
| Naphon            | Double pass  | Longitudinal fins with \( \dot{m} = 0.02-0.1 \) kg/s | [I] increases with height of fins and no. of fins |
| Mittal et al.     | Single pass  | Wire mesh packed | Thermohydraulic performance is greater in case of wire mesh |
| Jaurker et al.    | Single pass  | Rib grooved type artificial roughness | Maximum HT at p/e=6 and it decreases on either side |
| Karim et al.      | Collectors   | Flat plate collector | [I] is maximum for corrugated collectors and least for flat plate collectors |
| Bashria et al.    | Single & Double pass both | v-grooved absorber plate | Double pass [I] without porous = 4.5% [I] with porous =7% than single pass |
| M. Samiev         | Solar air heater with non-stationary plate | Non-stationary plate | Heating temperature= Ranges from 40˚C-60˚C |
| Pongjet et al.    | Single pass  | Ribs shape: Triangular, wedge and rectangular | Heat Transfer rate is more for inline arrangement |
| Varun et al.      | Single pass  | Discrete and Transverse ribs | Thermal performance is best at p/e of 8 |
| Authors (Year) | Type | Description | Re=2000-14000 | Notes |
|---------------|------|-------------|----------------|-------|
| Esen (2008) [35] | Double pass | $\dot{m}= 0.015-0.025$ kg/s Artificial roughness: Obstacle Thermocouple= T-Type Heater inclined at 38° with the horizontal | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Aharwal et al. (2009) [6] | Single pass | Discrete inclined ribs Maximum HT at= [Relative gap position= 0.25, Relative gap width=1.0, p/e=8, Angle of attack=60° and of e/D_h=0.037] | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Sharad et al. (2009) [36] | Solar heater | Arc shaped e/D_h= 0.0299-0.0426 Re=6000-18000 Solar intensity- 1000W/m² Relative angle of attack= 0.0333-0.666 | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Arvind et al. (2009) [7] | Single pass | Discrete w-shaped ribs W/H= 8:1 Re= 3000-15000 e/D_h of 0.0168-0.0338 p/e=10 Angle of attack= 30°-75° | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Esen et al. (2009) [37] | Double pass | $\dot{m}= 0.03-0.05$ kg/s Type 1: Aluminum cans in staggered form Type 2: Aluminum cans in arranged form Type 3: Smooth plate with no cans | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Hans et al. (2010) [8] | Single pass | Multiple v-ribs e/D_h= 0.019-0.043 p/e= 6-12 $\alpha= 30°-75°$ Relative roughness width = 1-10 Re=2000-20000 | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Omojaro et al. (2010) [38] | Single and Double pass | With fins and steel wire mesh $\dot{m}= 0.012-0.038$ kg/s | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Prashant et al. (2011) [9] | Single pass | Parallel flow packed bed | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| El Sebai et al. (2011) [39] | Double pass | v-corrugated ribs $\dot{m}= 0.0125-0.0225$ kg/s | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Khawajah et al. (2011) [20] | Double pass | Transverse fins $\dot{m}= 0.0121-0.042$ kg/s | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Brij Bhushan et al. (2011) [10] | Solar air heater | Protrusions as artificial roughness | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Sukhmeet et al. | Single pass | Discrete V-down ribs | ![Image of a table with data entries](https://via.placeholder.com/150) | ![Image of a table with data entries](https://via.placeholder.com/150) |
| Reference                        | Method      | Description                                                                 |
|---------------------------------|-------------|-----------------------------------------------------------------------------|
| Lanjewar et al. (2011) [12]     | Single pass | W-shaped ribs, $Re=3200-14000$, $p/e=4-12$ mm, $\alpha=30\degree$-$75\degree$, $e/D_h=0.015-0.043$ mm |
|                                 |             | Thermohydraulic performance: $[W_{Down Ribs}>W_{Up ribs}]$                   |
|                                 |             | $[W_{Down}=1.98 \text{ times and } W_{Up ribs}=1.81 \text{ times}]$ of smooth plate |
| Chii Dong et al. (2011) [21]    | Double pass | Integrated with fins                                                        |
|                                 |             | Through recycling, efficiency increases up to 80%                          |
| Fudholi et al. (2011) [22]      | Double pass | Fins: Type 1: Fins at upper portion, Type 2: Fins at lower portion, Type 3: On both sides. |
|                                 |             | $\eta$ (Type 1) = 36-73\%, $\eta$ (Type 2) = 37-75\%, $\eta$ (Type 3) = 46-74\% |
| Bhupendra et al. (2012) [56]    | Both Single and Double pass | Thermal Efficiency (Porous and Non-Porous media) |
|                                 |             | Double pass efficiency is more than single by 5\%                          |
| Yeh et al. (2012) [40]          | Double pass | Downward-type double pass                                                   |
|                                 |             | $\eta$ with fins attached is more                                           |
| Prashant et al. (2012) [41]     | Double pass | Packed Bed Parallel and Counter flow                                         |
|                                 |             | Efficiency of parallel flow is more than counter flow at mass flow rate of 0.01 kg/s |
| Prashant et al. (2012) [23]     | Double pass | Packed Bed Parallel and Counter flow                                         |
|                                 |             | Efficiency is 50\% which is less due to low mass flow rate                  |
| Krishnananth et al. (2013) [42] | Double pass | Paraffin wax for storage                                                    |
|                                 |             | Paraffin wax used above recorded highest efficiency                         |
| Gonzalez et al. (2014) [43]     | Double pass | Heater inclined at 40° to the horizontal                                    |
|                                 |             | Efficiency is 50\% which is less due to low mass flow rate                  |
| Chabane et al. (2014) [24]      | Double pass | Longitudinal fins, $n=0.012-0.016$ kg/s                                    |
|                                 |             | $\eta$ (with fins) = 51.50\%, $\eta$ (without fins) = 43.9\%               |
| Manivannan et al. (2014) [13]   | Single pass | v-shaped ribs at 60°                                                        |
|                                 |             | $\Delta T=25^\circ$C (smooth plate), $\Delta T=34^\circ$C (rough plate)   |
|                                 |             | $\eta$ enhancement = 14\%                                                  |
|                                 |             | $\eta$ (with fins) = 42.73\%, $\eta$ (without) = 36.04\% at 3:00PM and 2.2 m/s |
| Harshal et al. (2014) [44]      | Single pass | Comparison with and without fins Heater inclined at 27° to the horizontal  |
|                                 |             | $\eta$ enhancement = 14\%                                                  |
|                                 |             | Relationship between solar irradiations, heat flow, air outlet velocity, air flow rate etc. were accounted for thermal efficiency of collector.  |
|                                 |             | 50 min are required for air collectors with baffles of a double pass solar air heater to reach 50\% efficiency. |
| Budea (2014) [45]               | Double pass | Baffles and Longitudinal fins                                               |
|                                 |             | $\eta$ (with baffles) > $\eta$ (Longitudinal fins)                          |
| Kaushik et al. (2015) [46]      | Double pass |                                                                               |
### Findings

**Shameer et al. (2015) [47]**
- **Collector Type**: Double pass
- **Material**: Paraffin wax for storage
- **Findings**: Thermal efficiency reaches up to 75%.

**Bhushan et al. (2015) [48]**
- **Collector Type**: Double pass
- **Material**: Inclined at 60°
- **Findings**: Absorption coefficient: 0.95

**Alta et al. (2015) [49]**
- **Collector Type**: Single pass
- **Material**: Exergy and Energy analysis
- **Findings**: Temperature <sub>max</sub> = 1 m/s, Energy Efficiency <sub>max</sub> = 4 m/s, Exergy Efficiency <sub>max</sub> = 1 m/s.

**Manish et al. (2015) [50]**
- **Collector Type**: Double pass
- **Material**: W-shaped ribs
- **Findings**: η<sub>thermal</sub> = 1.45 times of smooth plate, η<sub>thermohydraulic</sub> = 1.4 times of smooth plate.

**Chaudhary et al. (2016) [51]**
- **Collector Type**: Double pass
- **Material**: Type 1: Without spring, Type 2: With spring, Type 3: In zigzag manner
- **Findings**: Air velocity: 2-10 m/s, η<sub>Type 3 > Type 2 > Type 1</sub>.

**Srivastava et al. (2016) [52]**
- **Collector Type**: Single pass
- **Material**: Thermocouple-J-Type
- **Findings**: Temperature <sub>max</sub> = 25° N, 81° E climatic conditions, η<sub>(avg collector)</sub> = 28.91%, η<sub>(thermal)</sub> = 79%, η<sub>(avg energy)</sub> = 0.75%.

**Kumar et al. (2016) [53]**
- **Collector Type**: Single pass
- **Material**: Discrete v-baffles
- **Findings**: Re = 3000-21000, α = 30°-70°, Relative pitch ratio = 1.0, Relative discrete width = 1.5, (Nu)increase = 4.2, (f)increase = 5.9 times of smooth plate.

**Wadhawan et al. (2017) [54]**
- **Collector Type**: Single pass
- **Material**: Lauric acid as PCM
- **Findings**: Rise in output air is 86.54%.

**Tamilselvan et al. (2017) [55]**
- **Collector Type**: Double pass
- **Material**: Sensible heat storage media
- **Findings**: Efficiency is maximum with sensible heat storage.

**Devecioglu et al. (2017) [56]**
- **Collector Type**: Single pass
- **Material**: Heater inclined at 15°,  m
- **Findings**: Re = 0.031-0.038 kg/s, Thermal efficiency: 25-57%, Thermohydraulic efficiency: 14-44%.

**Pramanik et al. (2017) [57]**
- **Collector Type**: Double pass
- **Material**: Longitudinal fins
- **Findings**: Absorber coating Inclined at 15°-17°, η = 69%, Temperature <sub>max</sub> = 94°C.

**Chii Dong (2018) [58]**
- **Collector Type**: Double pass
- **Material**: Cross corrugated double pass
- **Findings**: More turbulence and heat transfer area are there in cross corrugated double pass heater.

**Gajendra et al. (2018) [59]**
- **Collector Type**: Double pass
- **Material**: V-type Baffles
- **Findings**: Thermal performance is more in case of V-type baffles in comparison to smooth plate.

Also, a lot has been done in respect of solar collectors used in various systems to enhance the heat transfer characteristics. Some contributions are listed below.

| Researcher | Collector Type | Findings |
|------------|----------------|----------|
| Sharma et al. (2015) [60] | Solar collector review with nano fluids | Collector efficiency increases with nano-fluids if taken in optimum volume fraction. |
| Bhatia et al. (2017) [61] | Analytical investigation of various collectors | Increase in angle of tilt, transmissivity, absorptivity and intensity increases the efficiency of collector. |
4. Conclusion

From the experiments done by various researchers, it has been concluded that Double pass solar air heaters are more efficient than single pass solar air heater having similar geometries over the absorber plate. It also came to notice that employing discrete ribs over the absorber plate gives more Heat transfer than continuous ribs. In Double pass solar air heaters maximum thermal efficiency may reach up to 80% and with fins or wire mesh type of arrangement it may well reach above 85% too.

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