Recent Advancements in Design of Flat Plate Solar Collectors

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Abstract. Solar collector is an important technology for the effective utilisation of solar energy that the earth is blessed with. Flat plate solar collectors present a simple and easy to maintain design and thus are widely used for low and medium temperature applications. But being less efficient than alternatives, justifying the initial investment of flat plate solar collectors becomes difficult in the long run. This paper presents the efforts of researchers in the past some years to improve the efficiency of flat plate solar collectors through the improvement and optimization of the existing design. The range of research work covered gives a general idea of the variety of techniques being developed, analysed and tested to increase the efficiency of flat plate solar collector through means such as new absorber design, design of absorber tubes, new coatings on glass cover, and other means to reduce heat transfer losses, increase heat transfer from absorber to working fluid and absorbing and retaining direct as well as diffuse radiation. Design and efficiency improvement for better adoption of flat plate collectors in building facades has also been discussed. This paper will be beneficial for exploring the range of research avenues in the field of optimization and efficiency improvement of flat plate solar collectors.

1. Introduction
The ever-rising demand for energy with rapid industrialization has put a strain on limited fossil reserves as well as our environment. This has compelled us to explore all possible avenues of renewable energy generation. Among renewables, the potential of solar energy to meet the energy demands is enormous, that too, without harming the environment. Various technologies have been and are being developed to exploit this potential [1].

The difficulty associated with solar energy is that though it is in abundance during the day, it is less than scarce at night and this necessitates that the collection of energy be efficient when it is available and the storage be effective so that it can be utilized at night. This difficulty is overcome using solar
One of the types of solar thermal collector is the Flat Plat Solar Collector (FPSC) which though has lower efficiency compared to other collectors but is widely used owing to its simple construction and cheap maintenance cost [2].

A flat plate solar collector comprises of a casing which houses the absorber plate and absorber tubes and the associated manifold. Insulation and glazing cover of a layer or layers of glass sheets are provided to minimize the loss of heat [3]. Glazing is essential to prevent loss due to irradiation as it allows short-range radiation through while blocking long-range radiation [4].

The parameters which govern the performance of FPSCs are numerous, like design of the absorber and absorber tube, thermo-physical properties of the working fluid, its inlet conditions, insulation, ambient conditions such as temperature, irradiation, etc. Volume flow rate of the working fluid is also an important parameter governing collector efficiency [5]. To enhance the performance of FPSCs various methods have been employed such as augmenting the absorptivity of the absorber, maximizing heat transfer between absorber plate and tubes, decreasing boundary layer in receiver tubes thus enhancing convective heat transfer and so on [6, 7].

Many efforts towards improving the collector efficiency through optimization of design parameters have been made. Optimization through exergy analysis [8], multi-attribute optimization through Taguchi ANOVA technique, TOPSIS technique, etc. have been carried out [9]. The optimal size of channels of flow for micro-channel absorber design has been obtained through exergy analysis [10]. Design of riser and header manifold has been optimized through a correlation model [11].

To enable mass adoption, the endeavor to make FPSCs friendly towards building integration has been pursued by various researchers. Several designs have been proposed and analysed to overcome the challenges involved in building façade integration of FPSCs namely architectural compatibility, inclusion of colour, safety for overheat, etc. [12, 13].

Though an old concept, evacuated flat plate collectors are gaining prevalence among researchers due to the fact that evacuated flat plate collectors combine the advantages of both the simplicity of flat plate collectors and better efficiencies of evacuated collectors due to minimized heat loss and thus are being explored as viable replacement of concentrating collectors that are currently used in Organic Rankine Cycle [14, 15, 16].

2. Advancements in FPSC Designs
Recent developments in the design of FPSCs based on the aforementioned factors have been discussed in detail in the following text. Techniques covered include ways to augment heat transfer from absorber to absorber tubes and ultimately to the working fluid, minimise heat loss from the absorber due to convection by the use of transparent insulation material or by evacuating the collector, boost capture of radiation by means of sun-tracking reflectors or coatings on the glass cover and some optimisation techniques to find optimal design dimensions for various components vital to performance of the collector.

Balaji K. et al. [17] investigated experimentally absorber tubes employing copper rod and copper tube thermal performance enhancers, figure 1. The convection effect was studied and found to be mixed mode but predominantly free convection though with diminished Grashof, Rayleigh and Richardson numbers in comparison to absorbers without thermal performance enhancers. For all Reynolds number, thermal enhancer with rod yielded greater efficiency compared to thermal enhancer with tube and also conventional absorber design collector. Also, the modified Richardson numbers were reported to be 37.5% and 25% lower for the rod and tube enhancer respectively as compared to conventional collectors. Two FPSCs, one with and one without the enhancers were used to power solar water heaters and they were experimentally probed by placing them in the sunlight with a slope angle of 13°. Temperature sensors were placed at various points and the solar radiation was measured using a pyranometer. Other ambient factors were measured by installing a weather station in the vicinity. Data acquisition systems were employed to record the measurements at frequent intervals.
T. Jatau et al. [18] employed Constructal Method of design to optimise the geometry of the absorber numerically by seeking to minimise entropy generation subjected to the constraints of fixed absorber area and fixed volume of absorber tubes while allowing spacing between the tubes, the length of the tubes and the diameter of the tubes to vary. For minimum entropy generation, optimal parameters of absorber design were obtained and further its variance with modified Reynolds number was studied and the authors concluded that the increase in modified Reynolds number results in an increase of optimal length of the tube while it results in the decrease of optimal diameter and optimal spacing of the tube, figure 2. As they also observed the entropy generation to be minimum and conductance to be maximum for increased modified Reynolds number, they thereby optimized the parameters based on this. The design of the FPSC was simulated in SolidWorks and computational fluid dynamics analysis was performed in ANSYS-Fluent R 16.0 which gave solutions for equations of mass, energy and momentum conservation integrated over each control volume. External irreversibilities were taken as constant and internal irreversibilities were minimized to obtain the optimum geometry. Heat flux incident on the absorber was taken as 500 W/m² and fluid entry temperature was taken as 300K for the numerical simulation that was done for the optimisation.

M. A. Oyinlola et al. [19] experimentally studied absorber plates with micro-channels for scaling effects and observed that Nusselt number was affected little by entrance effect and viscous losses. Conjugate heat transfer adversely affected Nusselt number and thus it was found to decrease with axial conductance number. Despite necessary conditions for neglecting entrance effects being met, an axial variation of local Nusselt number was seen and it became pronounced with an increase in Graetz number. Their experimental setup consisted of flow system with micro-channel test rig which acted as a simulation of a compact FPSC, figure 3. Coriolis mass flow meter, thermocouples and differential pressure sensors were used to capture various data.
R.W. Moss et al. [20] investigated numerous designs for an absorber for evacuated flat plate collector. The challenges encountered in designing an absorber for an evacuated collector included providing support for the glass cover as well as the necessity of the material being a low out-gassing one while providing better efficiency than conventional serpentine tube absorbers and at the same time the design must be easy to fabricate. Keeping this in view a flooded panel absorber was chosen and was fabricated from stainless steel sheets by hydroforming technique. CFD analysis showed that halving the plate and having the inlet and outlet at diagonal corners could optimize the distribution of flow. FE analysis showed that the operational pressure could be withstood by a sheet of thickness 0.7 mm. Hydroforming pressure of 25 MPa was sufficient to mould the sheet of 0.7 mm thickness. Minimum safe height of the absorber in the evacuated collector was evaluated using distortion testing, figure 4. Authors have predicted 3% higher efficiency of the collector employing this design as opposed to conventional serpentine tube design.

H. Bhowmik et al. [21] developed an FPSC with reflectors mounted on its two sides to concentrate diffuse as well as direct solar radiation on to the collector. The reflector panels were fitted such that their angle could be changed to track the sun. The authors report an improved efficiency of 10% over and above the conventional FPSC when tested with water heating prototype with the collector with reflectors at its core, figure 5. The collector with reflector invariably results in a higher outlet temperature of the fluid than the collector without reflector. The iron plate was used to make the collector and black paint was used as absorber coating and the final assembly was sealed off on top using transparent glass. Design of collector was done in a manner to obtain a parallel pattern of flow and constant rate of flow from entry to exit. Mercury glass was used for reflector panels. 25 l tank was utilized to supply water as working fluid. Using rotameters to measure and control the flow, flow rates of 0.1 l/min and 0.2 l/min were used for this experiment. The exit temperature of the fluid was seen to reduce with increase in volume flow rate. Thermometers were employed to measure fluid temperatures at entry and exit. Global average radiation was taken as 430 W/m². Collector surface area was 1.05 m² and reflector surface area was 1.85 m² and the mirror was assumed to have a reflectivity of 0.9.
I. Visa et al. [22] designed a new FPSC for better façade integration and architectural aesthetics with efficiency figures of 60.7% being obtained through optimisation of the isosceles trapeze-shaped design in terms of insulation, proper contact between absorber plate and absorber tubes, meander length of the tube, its diameter, etc., figure 6. The top surface of the glazing was spray-coated with a self-cleaning coating which improved performance. Certain characteristics of this design which make it apt for façade integration are that the geometry with an area of 0.63 m$^2$ makes it compatible for solar arrays. The absorber plate has been made into an assembly of 14 pieces and each can be coated with spectral selective coatings for a multi-colored design. An indoor testing rig with the capability to accommodate collectors with different shape and dimensions up to a maximum of $1 \times 2$ m$^2$ was used. A solar simulator with a maximum intensity of 1000 W/m$^2$ was employed. Pyranometer, temperature sensors, and linear actuators to rotate the frame holding the collector were incorporated in the rig. The flow of the working fluid was measured and controlled using a mass flow sensor. A standard mass flow rate of 0.012 kg/s was maintained and the water was taken as the working fluid in all iterations of the experiment.

![Figure 5. Solar water heating system using FPSC with reflectors](image)

**Figure 5.** Solar water heating system using FPSC with reflectors

I. Visa et al. [23] have further designed a FPSC with smaller area and triangular shape for improved façade integration by catering to the fact that facades of buildings have random shaped and

![Figure 6. Optimised configuration of meander tubes](image)

**Figure 6.** Optimised configuration of meander tubes.
small-sized sections. The area was taken as 0.083$m^2$. Difficulty in using internal pipes was seen because of the small size of the collector design thus a flooded mode was used by making a cavity below the absorber plate. The distribution of flow was analyzed and optimized through simulation of the design in SolidWorks and its analysis in ANSYS. The optimal gap between glazing and absorber and optimal insulation width was found by applying the radiative mathematical model. Indoor testing of three collectors with different spectral selective coatings of orange black and green resulted in efficiencies of $35\%$, $55\%$ and $42\%$ respectively, figure 7. To validate the results of the simulation, experiments were performed on a collector with the cavity being fabricated using steel and the absorber plate with aluminum. These were mounted on a steel frame using fasteners and water was filled in the cavity up to a pressure of 3 bar at 20$^\circ$C. A similar solar simulator as mentioned before was used to produce radiation of 800 W/m$^2$ to 900 W/m$^2$. Water with a specific flow rate of 0.02 kg/m$^2s$ was used. The black absorber plate was obtained using commercially available black absorber coating, orange was obtained using vanadium oxide pigment and green was obtained with a mixture of hydrated copper sulphates and copper sulphides.

![Figure 7. Solar thermal collector indoor testing rig.](image_url)

Do Ango et al. [24] investigated polymer absorbers for FPSC through numerical simulation and found that the thickness of air gap influences the collector performance and the optimal thickness was obtained as 10 mm. Efficiency was seen to vary proportionally with the mass flow rate of the fluid but elevated mass flow rates reduce outlet temperature obtained. Efficiency was unaffected by intensity of radiation but it was found to affect the outlet temperature and an approximately linear relation was seen, figure 8. The temperature of the fluid at inlet influences the collector performance and it must be no less than the ambient for good collector performance. A portion from the central part of the polymer FPSC was simulated in computational fluid dynamics software CFD Star-CCM+ with dimensions 1 m × 90.5 mm. The choice of the central portion was done with the objective to prevent edge effects. The equations of a balance of mass, energy, and momentum were the governing equations. Radiation effects were simulated using a Surface to Surface model on the underlying principle of enclosure theory for diffuse gray surfaces. Taking the values of the parameters of air gap, solar radiation, fluid entry temperature, collector length and fluid mass flow rate from a leading authority on manufacturing information of solar collectors, a parametric study was thus performed.
Figure 8. Variation of outlet temperature with incident flux

F. Giovannetti et al. [25] explored and analyzed various spectral selective and high transmittance glass coatings which are based on transparent conductive oxides, figure 9. Tin-doped indium oxide and aluminum-doped zinc oxide layers were analyzed. The spectral selective coating did not result in any enhancement of performance in single-glazed highly selective absorber collector; in fact, increased optical losses degraded the efficiency of the collector. But for other collectors, low emissivity coated glass resulted in improved performance. Thus single-glazed low selective absorber collector and double-glazed highly selective absorber benefit greatly from low emissivity, high transmittance spectral selective coating for the glass covers.

Figure 9. Emissivity versus transmittance plot.

H. Kessentini et al. [26] experimentally as well as numerically studied a design comprising of insulation of transparent material added between the absorber and the glass cover to minimize heat loss. They have added a system to protect the transparent insulation from overheat due to stagnation. The system uses a channel with a trap door which gets activated thermally. This has proven as an effective method of protection for transparent insulation material. The collector was then optimized through simulation and the optimized collector proved to be at par with existing designs in terms of performance while still being low cost. Experimental validation was done by performing tests on FPSC fabricated on the lines of conventional FPSCs with extra insulation of transparent material inserted between the glass cover and the absorber. Insulation material used was cellulose triacetate film arranged in the honeycomb structure. The thermally activated actuator was made of Nickel-Titanium shape memory alloy spring. The testing facility used had the capacity to perform
experiments up to 8 bar and 150°C conditions of the working fluid. Temperatures were measured by employing thermocouples and resistance probes.

Figure 10. Cross-section of FPSC with transparent insulation.

Another recent and major development in the field of solar collectors in general and FPSCs in particular has been the use of nanofluids to enhance the heat transfer to the working fluid, which has not been covered in this paper. Nanofluids are a special type of fluid which can be used as working fluid in solar collector systems with and without heat pipes. They are synthesised by dispersing a small quantity of solid nanoparticles often less than 100 nm in a base of traditional working fluids such as water or ethylene glycol [27]. A rigorous treatment of the models for explaining the heat transfer augmentation has been presented by S.M.S Murshed et al [28]. S. K. Verma et al. [29], M. A. Alim et al. [30], A. Zamzamian et al. [31] have experimentally as well as analytically investigated various metal oxide based nanofluids for solar collector applications.

Table 1. Summary of few main papers.

| Author         | Type of investigation | Description                                                                 | Performance                                                                                                    |
|----------------|-----------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| K. Balaji et al [17] | Experimental         | Absorber tube with tube and rod thermal performance enhancer                | Reynolds number, rod thermal performance enhancer yielded greater efficiency compared to tube design and also conventional absorber design collector. |
| T. Jatau et al. [18] | Theoretical          | Optimisation through constructal method                                     | Increase in modified Reynolds number results in an increase of optimal length of the tube while it results in the decrease of optimal diameter and optimal spacing of the tube. |
| R.W. Moss et al. [20] | Experimental and theoretical | Flooded panel design for evacuated FPSC                                    | Authors have predicted 3% higher efficiency of the collector employing this design as opposed to conventional serpentine tube design. |
| I. Visa et al. [23] | Experimental         | Facade integration of FPSCs                                                 | Three collectors with different spectral selective coatings of orange black and green resulted in efficiencies of 35%, 55% and 42% respectively |
Theoretical Numerical simulation of polymer absorbers Efficiency was seen to vary proportionally with the mass flow rate of the fluid but elevated mass flow rates reduce outlet temperature obtained. Efficiency was unaffected by intensity of radiation but it was found to affect the outlet temperature and an approximately linear relation was seen.

3. Conclusion
This paper presented a general overview of design advancements in FPSCs in the past five years. Studies conducted showed a great scope for improvement in the design of FPSC to make it suitable for wider adoption by making it more efficient. Techniques covered in this paper include redesigning of absorber plate for efficient flow with the maximum transfer of heat from absorber to working fluid. The use of optimization techniques to evaluate the optimal dimension of absorber and manifolds prove to be effective. Coatings for glass covers, use of transparent insulation between absorber and cover may be used to minimize heat loss. This paper will be helpful in looking for future fields of research to pursue.

References
[1] M. A. Sabiha, R. Saidur, S. Mekhilef, O. Mahian. Progress and latest developments of evacuated tube solar collectors, *Renewable and Sustainable Energy Reviews*, volume 51, pp. 1038–1054, (2015).
[2] K. Chopra, V. V. Tyagi, A. K. Pandey, A. Sari. Global advancement on experimental and thermal analysis of evacuated tube collector with and without hwt pipe systems and possible applications, *Applied Energy*, volume 228, pp. 351–389, (2018).
[3] Y. Tian, C. Y. Zhao. A review of solar collectors and thermal energy storage in solar thermal applications, *Applied Energy*, volume 104, pp. 538–553, (2013).
[4] S. Sumam, M. K. Khan, M. Pathak. Performance enhancement of solar collectors-A review, *Renewable and Sustainable Energy Reviews*, volume 49, pp. 192–210, (2015).
[5] Z. Chen, S. Furbo, B. Perers, J. Fan, E. Andersen. Efficiencies of flat plate solar collectors at different flow rates, *Energy Procedia*, volume 30, pp. 65–72, (2012).
[6] K. M. Pandey, R. Chaurasiya. Review on analysis and development of solar flat plate collector, *Renewable and Sustainable Energy Reviews*, volume 67, pp. 641–650, (2017).
[7] G. Colangelo, E. Favale, P. Miglietta, A. Risi. Innovation in flat solar thermal collectors: A review of the last ten years experimental results, *Renewable and Sustainable Energy Reviews*, volume 57, pp. 1141–1159, (2016).
[8] S. Farahat, F. Sarhaddi, H. Ajam. Exergetic optimization of flat plate solar collectors, *Renewable Energy*, volume 34, pp. 1169–1174, (2009).
[9] F. A. Boyaghchi, H. Montazerinejad. Multi-objective optimisation of a novel combined cooling, heating and power system integrated with flat plate solar collectors using water/CuO nanofluid, *International Journal of Exergy*, volume 21, pp. 202–238, (2016).
[10] R. W. Moss, G. S. F. Shire, P. Henshall, P. C. Eames, F. Arya, T. Hyde. Optimal passage size for solar collector microchannel and tube-on-plate absorbers, *Solar Energy*, volume 153, pp. 718–731, (2017).
[11] J. Facão. Optimisation of flow distribution in flat plate solar thermal collectors with riser and header arrangements, *Solar Energy*, volume 120, pp. 104–112, (2015).
[12] M. S. Buker, S. B. Riffat. Building integrated solar thermal collectors-A review, *Renewable and Sustainable Energy Reviews*, volume 51, pp. 327–346, (2015).
[13] R. O’Hegarty, O. Kinnane, S. J. McCormack. Review and analysis of solar thermal facades, *Solar Energy*, volume 135, pp. 408–422, (2016).
[14] R. W. Moss, P. Henshall, F. Arya, G. S. F. Shire, T. Hyde, P. C. Eames. Performance and operational effectiveness of evacuated flat plate solar collectors compares with conventional thermal, PVT and PV panels, *Applied Energy, volume* 216, pp. 588–601, (2018).

[15] F. Calise, M. D. d’Accadia, M. Vicedomini, M. Scarpellino. Design and simulation of a prototype of a small-scale solar CHP system based on evacuated flat plate solar collectors and Organic Rankine Cycle, *Energy Conversion and Management, volume* 90, pp. 347–363, (2015).

[16] P. Henshall, P. Eames, F. Arya, T. Hyde, R. Moss, S. Shire. Constant temperature induced stresses in evacuated enclosures for high performance flat plate solar thermal collectors, *Solar Energy, volume* 51, pp. 1038–1054, (2015).

[17] Balaji K., Ganesh K. P., Sakthivadivel D., Vigneswaran V. S., Iniyi S. Experimental investigation on flat plate solar collector using frictionally engaged thermal performance enhancer in the absorber tube, *Renewable Energy, volume* 142, pp. 62–72, (2019).

[18] T. Jatau, T. Bello-ochende. Constructual design of flat plate solar collector, *Proceedings of the Romanian Academy, volume* special issue, pp. 160–165, (2018).

[19] M. A. Oyinlola, G. S. F. Shire, R. W. Moss. The significance of scaling effects in a solar absorber plates with micro-channels, *Applied Thermal Engineering, volume* 90, pp. 499–508, (2015).

[20] R. W. Moss, G. S. F. Shire, P. Henshall, P. C. Eames, F. Arya, T. Hyde. Design and fabrication of a hydroformed absorber for an evacuated flat plate solar collector, *Applied Thermal Engineering, volume* 138, pp. 456–464, (2018).

[21] H. Bhowmik, R. Amin. Efficiency improvement of flat plate solar collector using reflector, *Energy Reports, volume* 3, pp. 119–123, (2017).

[22] I. Visa, A. Duta, M. Comsit, M. Moldovan, D. Ciobanu, R. Saulescu, B. Burduhos. Design and experimental optimisation of a novel flat plate solar thermal collector with trapezoidal shape for facades integration, *Applied Thermal Engineering, volume* 90, pp. 432–443, (2015).

[23] I. Visa, M. Moldovan, A. Duta. Novel triangular flat plate solar thermal collector for facades integration, *Renewable Energy, volume* 143, pp. 252–262, (2019).

[24] A. C. M. Do Ango, M. Medale, C. Abid. Optimization of the design of a polymer flat plate solar collector, *Solar Energy, volume* 87, pp. 64–75, (2013).

[25] F. Giovannetti, S. Foste, N. Ehrmann, G. Rockendorf. High transmittance, low emissivity glass covers for flat plate collectors: Applications and performance, *Energy Procedia, volume* 30, pp. 106–115, (2012).

[26] H. Kessentini, J. Castro, R. Capdevila, A. Oliva. Development of flat plate collectors with plastic transparent insulation and low-cost overheating protection system, *Applied Energy, volume* 133, pp. 206–223, (2014).

[27] M. J. Muhammad, I. A. Muhammad, N. A. C. Sidik, M. N. A. W. M. Yazid. Thermal performance enhancement of flat-plate and evacuated tube solar collectors using nanofluid: A review, *International Communications in Heat and Mass Transfer, volume* 76, pp. 6–15, (2016).

[28] S. M. S. Murshed, K. C. Leong, C. Yang. A Combined model for the effective thermal conductivity of nanofluids, *Applied Thermal Engineering, volume* 29, pp. 2477–2483, (2009).

[29] S. K. Verma, A. K. Tiwari, D. S. Chauhan. Experimental evaluation of flat plate solar collector using nanofluids, *Energy Conversion and Management, volume* 134, pp. 103–115, (2017).

[30] M. A. Alim, Z. Abdin, R. Saidur, A. Hepbasli, M. A. Khairul, N. A. Rahim. Analyses of entropy generation and pressure drop for a conventional flat plate solar collector using different type of metal oxide nanofluids, *Energy and Buildings, volume* 66, pp. 289–296, (2013).

[31] A. Zamzamian, M. KeyanpourRad, M. KianiNeyestani, M. T. Jamal-Adab. An experimental study of the effect of Cu-synthesized/EG nanofluid on the efficiency flat plate solar collector, *Renewable Energy, volume* 71, pp. 658–664, (2014).