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# Performance analysis and enhancement of solar flat plate collector: A review

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**Abstract**
Solar flat plate collectors are devices used to entraped solar thermal energy and use it for heating applications like water heating, room heating and other industrial applications. Flat plate collectors are popular for low and medium heating applications and there are undergoing constant development in terms of size reduction and enhanced efficiency. This paper presents an overview on the different techniques that are employed to enhance the efficiency of flat late collectors. Effect of using nanofluids as heat transfer fluid, effect of altering absorber plate design for better capture of radiation, methods of heat loss reduction, use of polymer, employing mini channels for fluid flow, using PCM (phase changing materials) to provide heat during night without tank and effect of use of enhancement devices like inserts and reflector have been discussed in this paper. A brief insight on various techniques used to analyse the effects and various designs has also been presented with the development methodology. Some analytical studies and CFD models have also been mentioned. This review paper also deals with the suggestions for the research work which can be carried out in the direction of heat transfer from solar flat plate collectors.

## 1. Introduction

Solar collector is a type of heat exchanger where in heat ex- change takes between a distance source and a heat transfer fluid flowing in the collector [35]. Solar radiation from sun hits the absorber plate of the collector and the thermal energy is then transferred to the fluid. Depending on their design, solar collectors can be classified as concentrating and non-concentrating type. Non-concentrating type can be further divided in flat plate collector and evacuated tube collectors. Flat plate collectors are the most common type of collectors and the most primitive too.

Work of Hottel and Woertz [36] in 1942 and by Hottel and Whiller [37] in 1958 can be looked as a first work on solar flat plate collector. They had developed the collectors consisting of a black flat plate absorber, a transparent cover, heat transfer fluid and an insulating case. Tabor [38] in 1955, employed selective black surfaces to increase collector efficiency. His experiments on optical concentra- tion revealed the ability of optical concentration to produce high pressure steam. Many studies have been done after that to analyse and improve the thermal efficiency of the collector.

Due to growing energy problems, solar energy is been looked at as source of infinite energy. Solar collector have been greatly studied in this matter. Many of the new designs have been de- veloped after 1990. Various research works are being carried out over the world to improve the thermal performance of flat plate collectors. Polymers are used to build novel collectors so as to reduce the weight. Use of nanofluids make the collectors compact by giving the same output as that of big collectors but in a com- paratively smaller sizes [33]. Absorber plates have undergone many modifications with the help of new and better techniques in manufacturing and material science [9,25]. Studies are also fo- cused to find the optimum spacing between the glass covers in multi-glazed collector. Indoor and outdoor tests are carried out based on the operating and design parameters to obtain the best possible design for desired working conditions. To increase the efficiency, it is very much important to decrease the heat loss from the collector. Many studies are oriented in this direction to study and reduce heat loss, with increased glazing, honey comb maze based absorber plate, considering wind velocity in analysis of collector etc.

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Analysing the performance of collector is equally important as it helps to further develop and improve the design. In fact, de- velopment and analysis always go hand in hand. Experimental analysis of all the different collectors developed is not feasible. Hence analytical and numerical methods have been employed, to approximately analyse the behaviour of collector in different conditions. CFD codes have helped researchers to a great extent. Ability to reduce lead time, to study system under hazardous condition and study of controlled experiments of systems which are difficult or impossible to perform practically are some of the unique advantages of CFD [39].In the present study, authors have made an overview of dif- ferent development and analysis techniques that have been em- ployed by the researchers to increase the overall performance of collector. Studies include designing and analysis of novel absorber plate designs, analysing the effect of nanofluids (as heat transfer fluid) on the efficiency of collector, ways to reduce heat loss to surrounding, analysis of collectors made up of polymers and effect of add-ons like reflectors and inserts have been discussed here.

## 2. Methods of analysis and techniques

Yasin and Hakan [1] did a comparative analysis of natural convection in flat plate and wavy solar collectors. Analysis was based on Rayleigh number, inclination angle, aspect ratio and wavelength. Laminar flow and thermal field simulation was done with the help of CFDRC commercial software. Mathematical model was developed neglecting the viscous dissipation and assuming constant fluid properties. Vertical walls were considered as adia batic. Results showed that shape and inclination angle of the col- lector greatly affected natural convection and heat transfer. Heat transfer in case of wavy collector was more than that of flat plate collector in all the cases. Variation of Nusselt number was found to be linear in case of flat plate collector while wavy in case of wavy collector. With the decrease in wavelength, the mean Nusselt number increased for same aspect ratio. Contrary to flat plate collector, Rayleigh number was found to be highest at the highest inclination angle. Selmi et al. [29] worked to find the usability and validity of CFD models for evaluating solar collector on the basis of their thermal performance. 3-D temperature was obtained distribution over the whole volume of collector and used it to validate the CFD model. An experimental setup was built in order to experimentally calculate the outlet temperature of the fluid which may be used to compare it with CFD model's result. The analysis was done with cover plate and without cover plate, with water flow and without water flow. Solar radiation flux was varied in the CFD model analysis, keeping other parameters constant, so as to make it more realistic as the experiment. Findings of this comparative study showed a good agreement in results from experiments and CFD despite the experimental imperfections. The results showed that CFD can be confidently used to evaluate thermal performance of flat plate collectors. Grine et al. [26] Worked with an air solar collector with a view to estimate the local and mean temperature field in the fluid, outlet fluid temperature, wall temperatures, heat flow from air to wall and coefficient of this convective heat transfer. Due to complications in numerical methods, authors developed an analytical model to simulate the thermal behaviour of flat plate solar collector operating in forced convection. A solution for energy equation was developed for a fluid flow inside the collector, based on the Green's function method. With the help of this model, it is possible to estimate the two dimensional air temperature profiles inside and outside the collector and also, we may calculate the local coefficient of heat transfer. Design parameters such as solar collector wall tempera- ture, the flow temperature and the local Nusselt number can also be calculated by this model. According to the results obtained, Nusselt number showed a decreasing trend after 1.2 m from leading edge and hence authors decide to add fins to their model after 1.2 m from the leading edge of the collector in order to in- crease the performance. The analytical model was confirmed by experimental results.

Flat plate solar collectors are normally used for applications such as water heating, space heating, for providing process heat in industries, etc. In these practical applications, collectors are bound to work under dynamic conditions. For proper analysis of thermal performance of such system, dynamic analysis is thus important. Steady state model derived from steady state test (SST) do not consider dynamic conditions, hence it's necessary to build a dy- namic model. Many researchers have worked on this topic to build various models. One such model was built by Deng et al. [13]. Many of the models built earlier, were not so accurate in de- termining the momentary thermal characteristics of outlet tem- perature and useful heat gain when the instantaneous solar ra- diation changed sharply. Authors worked on the issue and built an analytical model in the form of series expansion based on the consideration of effective thermal capacitance, to determine mo- mentary thermal characteristics of the collector. Model introduced a thermal inertia correction along with steady state useful gain to accurately predict the instantaneous useful heat gain. Experiment was performed on air solar collector and the data obtained was used to validate the model. Model was fund to accurately predict the momentary thermal characterises of air solar collector. Also, it could also be used for other collectors provided, they are eligible for SST. Cerón et al. [2] developed a 3-D numerical model for flat plate collector for calculating the efficiency of collector. Different heat interactions like solar radiation absorption, transmission and reflection;natural convection in the air cavity; heat conduction across the tube-absorber welded junction; mixed convection flow in the risers; and heat losses by convection and radiation to the ambient were taken into account and to check model reliability, the heat transfer results inside the risers and in the air cavity were contrasted with well-known experimental correlations. The re sults obtained from the numerical model was validated from the experimental data. Geometric model was based on the standard Turbulence modelling was employed to account for free convec- tion flow between glass cover and absorber plate and solar load implemented combined Solar Ray Tracing (SRT) algorithm and Surface to Surface (S2S) radiation model. Computational domain was divided into two subdomains to reduce grid size. One of them considered the working fluid tube-absorber assembly and the corresponding insulation volumes and the other looked for air gap and its lateral insulation. FLUENT was used to carry out calcula- tions based on FVM method. Discretization was done by second- order UPWIND scheme for momentum, energy and turbulent transport equations and the SIMPLE algorithm for velocity–pres- sure coupling. Results showed that the Nusselt number was found to be high in the fully developed region for the tube-side heat transfer case as compared to horizontal pipe with uniformly he- ated wall. Radiation model implemented, accurately reproduced the process of absorption-transmission of solar load. Similar trend was found for averaged Nusselt number obtained inside the air cavity with experimental correlation. Overall, numerical and ex- perimental results showed a good agreement in solar collector behaviour and accurate accordance in the optical factor and a good trend for the thermal loss coefficient was achieved.

Kessentini et al. [32] in their work demonstrated the perfor- mance of flat plate collector with plastic transparent insulated material and economic overheating protection system designed to work in the temperature range of 80–120 oC. Protection system consisted of a ventilation channel with a thermally actuated door which would protect the system to move to stagnation condition. Authors performed experiments on the collector prototype si- multaneously with a numerical modelling. Tests were carried out in indoor and outdoor conditions to observe the effectiveness of the system and validate the model. Numerical model implemented was based on the resolution of different components i.e. heat transfer analysis of separate components and then integrating each of them with modular object oriented tool. Main advantage of this tool is that each object or component could be replaced by high level CFD object in order to parallelize whole system and decrease computational time. There was a good agreement in the two results. Authors also carried out a parametric study to opti- mise the collector design by altering component configuration of FPC. 3125 configurations were tested by means of virtual proto- typing and the most promising of them was spotted. In- stantaneous efficiency of this collector was 0.518 and stagnation temperature of plastic transparent insulated material cover was 114.6 °C.

Investigations have shown that flow distribution has a great influence on efficiency of the solar collector. For a uniform flow, efficiency is high. In their study, Fan et al. [22], investigated the flow distribution and temperature distribution of the collector fluid, theoretically and experimentally. Authors studied the heat transfer and fluid flow characteristics of propylene glycol/water mixture, in the collector by means of a CFD model and experiment was carried out on a prototype of a proposed model to evaluate the flow distribution through absorber from temperature dis- tribution data obtained on the backside of the absorber tube. Parameters such as flow rate, properties of solar collector fluid, solar collector fluid inlet temperature and collector tilt angle were taken into account for the analysis. Results from both, CFD simu- lations and thermal analysis, showed a good agreement for high flow rates, but large differences were obtained for the lower once. It was revealed that for higher flow rates, flow distribution was uniform. With the decrease in flow rate and decrease concentra- tion of glycol in the mixture, the flow distribution became highly non uniform. Also, for increased tilt angle and inlet temperature, flow distribution turned worse, leading to increased risk of boiling in upper region of collector. But for higher flow rates, it did not affect much. The reason for this, according to authors may be the buoyancy effect which dominates for a lower flow rate and has less influence at higher rates.

## 3.Collectors Development

As discussed earlier, to effectively trap the heat from sun, new techniques and methodology has to be applied. These techniques aims at increasing the thermal efficiency and overall performance of the collector. Many studies have been done by various scholars to enhance collector performance. The techniques include, use of various different materials for the construction of collector, changes in absorber plate design, employing different heat transfer fluids to absorb heat etc.

### 3.1 Polymers uses

Martinopoulos et al. [3] worked on polymer solar collector. Authors developed a polymer solar collector and investigated it experimentally and with CFD. Advantage of polymer type over metal type is its low cost manufacturing and light weight. About
50% reduction in wt. can be achieved can be achieved by em- ploying this kind of collector and also, material cost is also greatly reduced. The polymer material used should be able to withstand liquid pressure and vast temperature variations. For effective heat transfer to the heat transfer fluid, which also acts as absorber, the polymer material in which fluid is flowing should have high re- fractive index, comparable with glass or better than that, should have low emissivity and durability to weathering from U.V. To cater these needs, hydraulic channels of transparent, U.V. stabi- lized, honeycombed LEXAN sheet was incorporated by the authors.
1000/1 solution of black Indian ink was used as heat transfer fluid, sides were insulated by polyurethane and whole assembly was packed in aluminium casing. For measurements, an ISO 9806-1 test bed was employed and data from various measuring devices and sensors was stored in computer. CFD modelling was done on a fully structured grid of 1.2 million computational cells and 13 computational block giving special attention to inlet and outlet pipes and regions close to solid walls. Collector channel region was modelled as porous medium region to account for honey comb structure and save computational power and time. Grid formation was done with NUMECA/IGG and computation was done with FLUENT. Gravity was considered with buoyancy effect in the mo- mentum equation due to large size of collector. Experimental re- sult of averaged efficiency showed great agreement with the computational results. With the help of computational model, it was found that there were certain problematic regions in the model which led to decrease in efficiency. A further study is pos- sible by modifying the computational model to remove or de- crease such regions so as to increase overall efficiency of collector. On similar grounds, Missirliset al. [11] investigated the heat transfer behaviour of polymer solar collector for different manifold configurations. For full utilization of collectors with minimum cost, either the materials should be chosen wisely or the design of the collector should be done so as to increase the performance. In their work, authors varied the manifold configurations, i.e. they varies positions of inlet and outlet pipes and studied their effect with the help of CFD. CFD model used by the authors was the previously developed and validated model. By varying the inlet temperatures such that the operational range is covered, they analysed the thermal behaviour and efficiency of the polymer collector with the help of CFD. Aim of the study was to optimise the flow field development and to improve thermal behaviour of the collector. The work revealed that by slight change in geometry, the thermal energy exploited that the collector increased con- siderably with zero manufacturing cost. This shows that CFD is a powerful tool to optimise the design leading to improved performance.

Mintsa Do Ango et al. [21] also worked on polymer solar col- lector and carried out numerical simulations with a view of opti- mising the design of the collector. Conventional collectors are generally manufactured from copper or aluminium and are costly. Using polymer to manufactures collector can overcome this issue. In their study, authors, studied the effect of design parameters such as air gap thickness and collector's length and operating parameters such as mass flow rate, incident solar radiation and inlet temperature on the efficiency of the collector. The collector used for the study was made up of polycarbonate absorber, cov- ered with polycarbonate glazing and insulated with glass wool. It was operated with 45° angle of tilt. Numerical study was carried out assuming constant physical properties, grey and diffuse solid surfaces and neglecting the buoyancy effect. Fluid was modelled as incompressible Newtonian fluid and flow was treated as laminar. Air was considered as ideal transparent gas and system to be stationary. The results revealed that the length of the collector didn't have much influence on the efficiency, but air gap did, and the optimum air gap for this particular type of set up was found to be 10 mm. increase in mass flow rate increased the efficiency but decreased the outlet temperature of fluid. Solar radiation did not had much influence on this type of collector. Efficiency was greatly affected by the inlet temperature and for better performance, this parameter should be at least equal to ambient temperature. Peña and Aguilar [44] studied a polymer solar collector developed by Modulo Solar, a Mexican company and found the thermal beha- viour of polymeric solar collector same as that of metallic collector for household applications. Also due to its high percentage of elongation, polymers can avoid usage of antifreeze external valve to resist low environmental temperatures.

### 3.2. Macro and micro channels for heat transfer fluid

Thermal analysis of minichannel-based solar flat-plate collector was undertaken by Mansour [5] to study the heat transfer char- acteristics and pressure drop of the working fluid. Collector was made up of an array of minichannels provided in the absorber plate covered by glass cover. Heat transfer fluid was selected as water. Main advantage of the minichannel/microchannel heat ex- changer which pulls researcher is its high heat transfer potential combining attributes of high surface area per unit volume, large heat transfer co-efficient and small working fluid inventory. Au- thors designed a square minichannel based solar collector with a view to maximize thermal performance with minimum power input to the circulating pump. Mathematical model developed for the analysis was divided into two parts. One for numerical mod- elling for calculating heat transfer coefficient and pressure drop of working fluid and the other for thermal analysis for the collector as a whole unit. The numerical model was build laminar flow of Newtonian, incompressible fluid in steady state heat transfer ne- glecting viscous heat dissipation heat generation and any type of body force or external force. Physical properties of solid material and fluid were considered constant and flow was modelled as hydrodynamically and thermally developing. ANYSIS FLUENT 12 was used to solve the set of equations numerically using finite- volume method. To solve pressure and velocity in continuity and momentum equations, pressure-correlation scheme was em- ployed using SIMPLE algorithm. Gauss-Seidel technique was used as an iterative method. In thermal analysis, classical fin analysis method is employed, in which the solid domain separating the two fluid channels is treated as thin film. EES was used for de- veloping a program code to predict performance of the collector at any operating conditions. Results revealed that minichannel based collector has higher heat removal factor as compared to the conventional collectors. At higher flow rates the thermal perfor- mance of the collector is improved on the expense of hydraulic performance. Deng et al. [17]

investigated the potential of novel flat plate collector consisting of micro-channel heat pipe array. Heat pipe based collectors went through many studies and has proved its performance in terms of efficiency and temperature distribution. But there are certain problems associated with it such as, high cost, technical difficulties in manufacturing, high thermal resistance due to lower circular contact area, effect on heat transfer due to fin efficiency, scaling problem etc. To get over these drawbacks, microchannel heat pipe array based collector was de- veloped. These channels was made by thin aluminium sheets with micro grooves to increase the heat transfer. The characteristics such as high heat transfer performance, high reliability makes these array superior, high compressive strength, low cost and small contact resistance makes it superior to the conventional type. Authors firstly performed the preliminary test to verify thermal performance of the proposed micro channel heat pipe array. Results showed instant temperature variation along pipe with a response time of less than 2 min for different testing po- sitions. In addition to quick thermal response, it also showed sa- tisfactory isothermal behaviour with a temperature difference of 1°C between evaporator and condenser. Preliminary test was thus a success and was followed by testing of collector installed with these pipes. The setup was installed in Beijing and performance test was conducted following the Chinese standard GB/T4271-2007. Results showed a maximum instantaneous efficiency of 80% which is 11.4% superior to required Chinese standard. Authors compared their results with 6 groups of 15 samples and found that their proposed collector design's maximum instantaneous effi- ciency surpasses 25% over avg. level of the selected samples. These results clearly demonstrate the potential of micro channel heat pipe array based collectors.

A new structure of flat plate collectors was developed by Wei et al. [7] in which one large wickless heat pipe was employed in- stead of separate heat pipes. There are many problems related to conventional type collectors in which heat transfer is done wither by forced convection or free convection. Freezing of water in colder climates, convective and radiative losses and deterioration of pipes due to corrosion are some of them. Heat pipes are now widely applied to flat plate designs to obtain better performance. The major advantage of the design provided by authors is the high stability and leak avoidance between the water cooling side and the solar heating side. Authors conducted an experiment to test the thermal performance of this new collector design and then theoretical energy balance analysis was done for each component followed by a development of transient heat transfer model to calculate collector efficiency, temperatures of water, the glass cover and the absorber plate. For the experiment, the setup con- sisted of solar heat collector, a water storage tank, a water pump, a valve, and a flow meter. The collector was composed of a glass cover, an absorber plate, an insulation layer and an integrated heat pipe in which had fifteen vertical pipes, two horizontal connected pipes on two ends of the vertical pipes and one working fluid- returning pipe. Alcohol was chosen as a working fluid. Experi- ments revealed that a maximum efficiency of 66% was achieved in heating 200 kg of water by 25 °C and could be increased by enhancing thermal insulation.

### 3.3. Nanofluid based Heat transfer fluid

There are many ways to increase the thermal performance of flat plate collectors. One of the way is to add nano-sized particles of high thermal conductivity like carbon, metals, metal oxides etc., into the heat transfer fluid to increase the overall conductivity of the working fluid. Thermal conductivity of water is low and hence it is important to find the alternative to improve performance of collector. With the advancements in nanotechnology, a new group of fluids came into existence, known as nanofluids which consists of a nano sized particles suspended in a base fluid. Effect of Cu nanoparticles on the efficiency of flat-plate solar collector was investigated by Zamzamian et al. [8]. Cu nanoparticles were formed from the one step reduction of $CuSO_4$ $5H_2O$ with $NaH_2PO_2$ $H_2O$ in ethylene glycol as a solvent. 10 nm particles were used with a wt. fraction of 0.2% and 0.3%. Experimental rig used had two type of working fluid i.e. ethylene glycol and nanofluid. Experimentation was done with a variable flow rate to analyse the effect and ASHRAE 93 standards was considered for testing the performance of the collector. Results showed that the efficiency decreased with the decrease in volume flow rate and was max- imum at 1 l/min. There was an increase in efficiency with the in- crease in concentration of Cu particles and absorption parameter also showed an increment with use of nano particle. At 1.5 l/min, absorption parameter was maximum. Optimum working condition was found to be 0.3 wt% Cu/EG nanofluid at 1.5 l/min. Another work on nanofluids as heat transfer fluid was done by Alim et al. [12] in which they investigated the rate of entropy generation, pressure drop and exergy destruction of flat plate collectors. Theoretical analysis was done to analyse the effect of nano- particles: $Al_2O_3$, CuO, $SiO_2$ and TiO dispersed in liquid, on the basis of capability of heat transfer enhancement, entropy generation and pressure drop. The flow of the nanofluid was considered steady, laminar and axial. To reduce complexity, parameters such as nanofluid property, overall heat loss and solar radiation was considered as constant with time. Analysis was done by varying the nanoparticle concentration and nanofluid flow rate and en- tropy generation and exergy destruction was then mapped as function of volume concentration of nanoparticles. The results showed that out of the four metal oxides, CuO could reduce the entropy generation by 4.34% and heat transfer enhancement is brought about by 22.15%. However, there was a small 1.58% in- crease in pumping power of CuO nanofluid which is tolerable. In addition, they found improvement in heat transfer phenomena and superior convection coefficient with the use of nanoparticles. There was an improvement in heat transfer feature with an in- crease in nanoparticle concentration but no considerable change was found in the friction factor as compared to the base fluid. It is clear that nanofluid especially CuO based, can be used to effec- tively to improve heat transfer characteristics without much in- crease in cost. Moghadam et al. [15] also undertook experiments on CuO-$H_2O$ nanofluid as a working fluid in collector to determine its effect on efficiency on flat plat collector. Authors selected 99.9% pure, 40 nm mean particle diameter and a volume fraction was fixed to 0.4%. Operating range of mass flow rate was 1–3 kg/min. ASHRAE standard 86–93 was used to evaluate the performance of collector. With the increase in mass flow rate, efficiency initially increased, but after a certain point it showed a decreasing trend. At optimum mass flow rate, efficiency was found to increase by 16.7% as compared to water type collector.

He et al. [18] also worked on the nanofluid as working fluid in solar flat plate collectors. Authors used a Cu-$H_2O$ nanofluid as a working fluid to study the thermal performance. Tests were car- ried out using ASHRAE standard 86–93. Particle diameter were chosen to be 25 nm and 50 nm, mass flow rate of water was maintained at 140 l/h and test was carried out in time interval from 9:00 to 16:00. Particle size and wt. fraction were the varying parameters in the tests. Results showed that the maximum in- crease in efficiency obtained was 23.83% greater than that of water type. Efficiency with 25 nm, 0.2 wt% was lower as compared to that with 25 nm 0.1 wt%. This shows that efficiency shows a de- creasing trend with increase in wt. fractions of particles. Also with the increase in particle size, efficiency decreased, the reason may be increased surface area for smaller particles and also micro- convection phenomena taking place between water and smaller particles. Water temperature and heat gained also showed an in- crease of 12.24% and 24.52% respectively compared to water type. Frictional resistance was a little high for nanofluids. A numerical analysis of various nanofluids in heat transfer in solar collector was done by Nasrin et al. [20]. They selected four nanofluids: Ag- $H_2O$, Cu-$H_2O$, CuO-$H_2O$, and $Al_2O_3$-$H_2O$. Solar collector used was flat plate insulated metal box type with dark coloured sinusoidal wavy absorber. Boussinesq model was used to approximate the density of the nanofluid. Study was aimed at investigating the behaviour of the above nanofluids related to performance such as temperature and velocity distribution, heat transfer coefficients, mean velocity and temperatures with respect to the solid volume fraction of the nanofluids. Numerical model developed based upon the heat transfer equation and Navier-Stokes equation. Governing equation obtained was solved by Galerkin's finite element method. The integrals of the obtained equation were solved by three points Gaussian quadrature while Newton-Raphson method was im- plemented to solve non-linear residual equation. Results showed, that highest rate of heat transfer was through the 5% Ag nano- particle. Collector efficiency raised from 65 to 85% for increase in Cu from 0 to 5%.

Effect of pH value of nanofluids on the efficiency of solar col- lector was studied by Goudarzi et al. [24]. CuO-$H_2O$ and $Al_2O_3$-$H_2O$ with concentrations of 0.1 wt% and 0.2 wt% respectively were used for the study. Nanofluids were prepared by a two-step process involving mixing the particle in distilled water followed by ultra- sonic vibration to homogenize the mixture. To improve the sta- bility of the mixture, sodium dodecyl sulfonate was added to it as a surfactant. Experiment was done in a novel cylindrical solar col- lector consisting of a cylindrical glass tube cover which has a minimum reflectivity and maximum transmissivity and black he- lical pipe made up of copper as a receiver. Results showed that with an increase in a difference between the pH value of nanofluid and its isoelectric point, the efficiency of the collector also in- creased. For CuO nanofluid having isoelectric point of pH ¼ 9.5, increasing in efficiency of about 52% was obtained at pH ¼ 3 as compared to that obtained at pH ¼ 10.5. The same goes for $Al_2O_3$ having isoelectric point at pH ¼ 7.4. Efficiency obtained at pH ¼ 10.5 was 64.5% greater than that obtained at pH ¼ 9.2. Faizal et al. [33] evaluated nanofluids on the base of economic and environment. Increasing the areaof the collector is one way to increase the performance, but it would make the collector bigger, heavier and bulkier. In their study, authors aimed to use nanofluids as heat transfer fluid to make a smaller, light and compact collector, de- livering same output temperature of that of bulker ones. With the use of numerical models, and previous literatures, size reduction, efficiency, energy savings and cost savings was calculated for CuO, $SiO_2$, $TiO_2$ and $Al_2O_3$, was calculated. It was found that there was 10,239 kg, 8625 kg, 8857 kg and 8618 kg reduction in weight for CuO, $SiO_2$, $TiO_2$and $Al_2O_3$ respectively for 1000 units of solar col- lector. Nanofluids with high density and low specific heat showed higher thermal efficiency, CuO was winner in this segment. Area reduction of 25.6%, 21.6%, 22.1% and 21.5% solar collector was achieved for CuO, $SiO_2$, $TiO_2$ and $Al_2O_3$ respectively. With the use of nanofluids as working fluid, 220 MJ of embodied energy can be saved with 170 kg less CO2 emissions in the manufacturing pro- cess of these collectors. The payback period for these type of col- lectors is 2.4 years while that of conventional ones is 2.49 years. Thus the use of nanofluids, makes the collector, more environmental friendly, cost effective and compact.

Shende, Sundara [34] studied the application of nanofluids in direct absorption solar collectors (DASC). Carbon nanostructures like CNT and graphene have high thermal conductivity, unique optical properties, good mechanical strength, large surface area, etc. which make them perfect to be used to prepare a nanofluid working for DASC. In their study, authors synthesized a nitrogen doped hybrid structure of reduced graphene oxide (rGO) and multi-walled carbon nanotubes (N-(rGO-MWNTs)), a nanoparticle to be used to create nanofluid for DASC. Base fluids for the nano- fluids were de-ionised water (DI water) and ethylene glycol (EG). Due to the percolation network between MWNTs and rGO through intercalation, the nanofluids were quite stable without any ag- glomeration or sedimentation. Test based on absorption and transmittance, was carried out and thermal conductivity of fluids was studied as a function of temperature. Results revealed a 17.7% greater conductivity for 0.02% of DI and a 15.1% rise for EG. Due to black colour and increased surface area, these fluids have an ability to absorb radiations ranging from far ultra-violet to far infra-red. A small fraction of these particles drastically enhance the optical properties of the fluid and with an increase in concentration, there was an increase in absorption. Also, with an increase in tem- perature and concentration, thermal conductivity of fluids was found to be increased.

### 3.4. Design of absorber plate

Absorber is the main component of the collector responsible for absorbing solar radiation of different wavelength. To improve the performance of collector, selective coating on absorber is ne- cessary. Jyothi et al. [25] designed a new tandem absorber made up of nanostructured TiAlC/TiAlCN/TiAlSiCN/TiAlSiCO/TiAlSiO for high thermal power applications. First three layers of the tandem absorber acts as an absorbing layer while TiAlSiCO acts as semi- transparent layer and TiAlSiO acts as anti-reflecting layer. The metallic behaviour decreases as we move from bottom to top. This tandem absorber was deposited on a W coated stainless steel substrate, having high absorptance of 0.961 and thermal stability upto 650 °C. Authors found the optimum thickness for the tandem layers with the help of cross-sectional images obtained from field- emission scanning electron microscope and later verified it by transmission electron microscope. Performance of the absorber was evaluated at different temperatures by heating it in air at vacuum. It showed a high thermal stability in air upto 500 °C for 2 h and long thermal stability upto 325 °C for 400 h. In vacuum, thermal stability upto 900 °C was obtained for 2 h and long term thermal stability upto 650 °C for 100 h was obtained under cyclic heating conditions.

Experimental and computational analysis of a prototype of a special type of glazed flat plate collector was done having roll bond aluminium absorber plate was done by Del Col et al. [9] roll bond absorber plates are canalised panels manufactured by ap- plying a special bonding technique in which a sandwich of two aluminium sheets is formed by a special hot/cold rolling. With the use of serigraphic process, desired patterns of channels are printed on the plate using a special ink which prevents the welding in printed areas. After welding the two plates together, the un- bounded region is inflated by passing high pressure air. A roll bond solar collector with integrated liquid channels is finally completed with inlet and outlet connections. These type of collectors help us to customize and optimise the flow patterns in the absorber leading to a better and uniform temperature distribution across absorber. In their study, authors did a comparative study of these collectors one with black coating and another with semi-selective coating, with the conventional sheet and tube type collectors, one with copper black paint and another with aluminium selective absorber. In all, four collectors were analysed, all having same aperture area. Thermal efficiency tests were performed in both steady-state and quasi dynamic conditions, according to the standard EN 12975-2. In the numerical model, collectors were treated as a series of overlapping parts and computational proce- dure based on the steady state hypothesis was divided in two steps: first, neglecting thermal conduction between adjacent control elements and second, considering thermal conduction. Experiments showed that the efficiency curve of roll bond col- lector with black coating was higher than copper collector for same paint. With the increase in no. of tubes of the conventional collectors, its efficiency increased and for twenty eight tube with same diameter as that of roll bond absorber, efficiency was found to be same. However, there are technical limitations for manu- facturing of such collectors. Such type of collectors are not cost effective and not viable solution. Higher number of channels in roll bond absorber, makes it better option. Numerical simulations have also revealed that ambient temperature also plays a vital role in thermal efficiency. With the increase in ambient temperature, there is a decrease in efficiency. For proper evaluation of collectors, this factor should also be taken care of. Air solar collectors are best suited for low temperature applications such as space heating, drying of agricultural products etc. Mostly, flat plate absorbers are employed in these collector. Design parameter which separates air collector with water, is the low heat transfer coefficient of a sur- face in contact in air type collector. Fluid-wall surface area is a minor concern in water type but is certainly the key parameter in air type. Due to low heat transfer coefficient, the thermal efficiency of these collectors is lower. One of the solutions to improve ther- mal efficiency is to increase the surface area and by increasing the turbulence inside channel. Based on continuous folding technique, El-Sawi et al. [14] presented an innovative design of chevron pattern absorber. Continuous folding technique is a technique wherein the metal sheet is pre-folded by passing it through a set of sequential and circumferential grooved rollers and then through cross-folding rollers to create cross fold. The technique is eco- nomical, continuous and produces minimum shredding. Authors undertook experiments to check the reliability of these novel collectors and compare with flat plate type. Theoretical analysis was done to compare flat plate, v-grooved and chevron type col- lectors. Mass flow rate and inlet temperature were the governing parameters in the experiment. Experimental results revealed that chevron type led to 20% improvement in thermal efficiency and 10°C increment in temperature, in comparison to flat plate col- lector. Theoretical results also agreed with the experimental result showing 10% and 20% improved thermal efficiency than v-grooved type and flat plate type respectively. Chevron pattern, due to its low overall loss coefficient, proved to an economical, efficient and a better alternate design for air solar collectors.

### 3.5. Retaining PCM

Main disadvantage of solar thermal systems is storage of solar energy. Systems work during day, but to get hot water during night time, storage tanks are needed to be fitted with these sys- tems which not only make the system bulky, but also make it costlier. PCM i.e. phase change material integrated solar collectors shows promising features which can eliminate the need of storage units. The main advantages of these collectors involve large space capacity and isothermal behaviour during melting. The drawback is the low thermal conductivity. Lots of research is going on to increase the effective thermal conductivity of these PCMs. A si- milar work is done by Chen et al. [10] to analyse the energy storage process of solar collector with an integrated porous structure filled with paraffin as the phase change medium. At day time the par- affin will absorb the solar radiation and store within. At night, this stored energy will be given to water in the capillary tubes which are embedded in paraffin. Aluminium frame and paraffin ae se- parately modelled due to different thermal diffusivities. For the numerical analysis of this design, momentum conservation equa- tion for paraffin was modelled with Darcy's law with Brinkmane- Forchheimer's extension. Heat transfer in aluminium foam with melting paraffin was modelled with two temperature model. Due to its small size and little effect, serpentine pipe was neglected in the mathematical model. Paraffin was modelled as isotropic and a Newtonian fluid when it's melted. Surface tension and curvature effects were neglected and bottom and side walls were treated as adiabatic. For single phase, physical properties were considered independent of temperature while for solid-liquid phase, proper- ties varies linearly with temperature. Governing equation was discretized by FVM and SIMPLEC algorithm was used to solve the coupled continuity momentum equation. Firstly, simulation was done by the authors to investigate the characteristics of paraffin as heat storage medium and later investigation of aluminium foam matrix saturated with paraffin was undertaken as an advanced storage system. Studies revealed that aluminium has a great effect in increasing the heat transfer rate and melting of paraffin. Tem- perature distribution in aluminium foam with paraffin was more uniform as compared to paraffin alone. Another study on appli- cation of PCM in solar collector was carried out by Serale et al. [27]. Authors used an earlier developed numerical approach to figure out the characteristics of slurry PCM based solar collector. Heat carrier fluid used in this study was composed off from the mi- croencapsulated PCM (mPCM) suspended in a mixture of water and ethylene glycol, the whole mixture showing a constant mac- roscopic fluid properties. Due to suspension of PCM, the fluid mixture shows enhanced thermal properties. Results from the study demonstrates an increase in instantaneous efficiency upto 0.08 compared to the conventional water based collector. There is need of a careful optimisation of the climate and the nominal melting point of the mPCM, as wrong value may lead to a dete- rioration in performance of the collector. To further improve the performance, optimisation of parameters like, locations, flow rate and mPCM can be done. Heat obtained is always between 20–40% (for various conditions) compared to the conventional ones. The only limitation of the proposed system as mentioned by authors, is that it is impossible to work with mPCM concentrations above 50% because the pumping energy demand might increase as compared to a conventional system.

### 3.6 Reduction of heatloss

Thermal performance is very much affected by heat losses from various sections. The upward region is totally exposed to en- vironment and hence, heat lost from this region is significant. Heat lost is mostly through convection and radiation. Due to wind, the influence of convection is greater. Unglazed and single-glazed collector are affected to a great extent by these natural winds, and to compute their performance accurately, it is necessary to find the convective heat transfer coefficient due to winds. Many wind tunnel test has been performed in order to investigate this para- meter, but as these collectors are always exposed to solar radiation and thus the natural winds, the actual affect may differ from that of wind tunnel. Kumar and Mullick [16] performed experiments on unglazed solar collector to estimate the heat transfer coefficient from upper region of collector. Experimental setup was mounted on rooftop of building at IIT Delhi, which is a low wind region. Experimental data was taken for the months from February to May for 2 years. With the help of Sigma plot software, linear regression and power regression between wind velocity and heat transfer coefficient was made using experimental data. The correlation obtained was compared with previous studies and theoretical studies for different values of wind heat transfer coefficient at same wind speed. There may be differences in correlation due to different experimental conditions and dimensions of collector, but authors could find good agreement with some of the previous studies. The results by the author can be successfully used for the estimation of wind heat transfer coefficient in outdoor conditions by taking care of collector size. An interesting study was under- taken by Vestlund et al. [4] regarding enhancing the performance of flat plate collector by replacing the air in between absorber and glass cover with some other gas, particularly some inert gas. The main advantage of using the gas in the space is decrease in the heat transfer rate and at the same time reduction in humidity condensate and dust due the enclosed space filled with gas. The main problem in using other gases lies in design complications. These gases require sealed spaces in which variation in pressure and volume of gas filling is needed to be controlled. Pressure and volume of the gas to be filled greatly affects the heat transfer properties and thus the performance of the collector. Authors did a computational heat transfer analysis of various gases in replace- ment to air. A mathematical model was formulated using single dimension heat transfer equation considering convection, con- duction and radiation, and calculations were done in Matlab. Di- mensions and physical properties used for the collector was that of a reference collector: a state of the art flat plate solar collector, which has antireflective glass and fairly less heat losses. Reference collector did not had side wall insulation and its heat transfer rate was accounted in the top and bottom heat transfer equation. To consider irregularities in the absorber plate, calculations were done by varying the distance between the absorber plate and glass cover, and final result was then averaged. Study showed that this technique of gas filling can be utilized to make a thinner collector with same performance or even better performance than the conventional collectors. $CO_2$ is a cheap gas and resulted in thinner collector, but its performance was not upto the mark of conven- tional once. On the other hand, inert gases i.e. Argon, Krypton and Xenon were far more attractive and showed better performance. They formed thinner collectors as the amount used was reasonable despite their prices. Solar radiation is received to the absorber plate after passing through glass covers of the flat plate collectors. While it's passing through glass covers, some amount of radiation gets absorbed and the rest is transmitted to the absorber plate. This absorption leads to increase in surface temperature of glass covers which may alter the heat transfer coefficients. A numerical study was undertaken by Akhtar and Mullick [19] to investigate the effect of absorption on heat transfer coefficient single and double gazed flat plate collectors. Study was focused in finding the effect of absorbed radiation on the inner and outer surface of the glass cover and thus on the convective and radiative heat transfer coefficients. The numerical model was developed on the basis of heat transfer equations considering conduction in glass cover(s), convection between cover(s) and space and radiation. The factors which affected the solar radiation incident and absorbed, such as, thickness of glass cover and incidence angle, hour angle, declina- tion, location of the place and the orientation of the collector, etc. were also considered. Based on the numerical study, empirical relations for computing the inner and outer temperatures were developed for both, single and double gazed collectors. The results from calculations, considering absorption in glass cover, and ne- glecting absorption were compared. Comparison revealed 6 °C increase in single glazed temperature while 14 °C and 11 °C in- crease in first and second glass covers of double glazed collectors respectively. The difference between the heat transfer coefficients of absorber plate for the two cases was as high as 49%.

Zhang et al. [30] carried out an experimental study considering heat shield in a direct-flow coaxial evacuated-tube solar collectors to find its effect on thermal efficiency of the collector. A heat shield was added beneath the coaxial pipe so as to prevent the heat loss. It was observed that using heat shield, thermal efficiency of col- lector increased to 54.07% at the highest temperature of 123.9 °C which is 31.49% higher than that of the solar collector without heat shield. Heat loss coefficient was improved by 50.08%. Thus heat shield is a good option and also an economical mean to increase the performance of evacuated solar collectors.

### 3.7. Use of enhancement devices

Inserting a heat enhancement device inside a solar collector pipe is one of the method to improve thermal performance of the collector without much modification and keeping size compact. These devices increase the turbulence in the flow thus increasing the heat transfer. A comparative study of few of insert devices with a combined effect of inclination on the efficiency of the collector was carried out by Sandhu et al. [28]. Authors selected different insert devices with varied configuration: 3 types of twisted-tape inserts, 1. twisted tape with shortest pitch, 2. twisted tape with medium pitch 3. twisted tape with largest pitch; 4. types of wire coils inserts, 1. Simple coil, 2. Coil away from the tube wall, 3. Concentric coils, 4. Conical coil and Mesh insert. The collector was tested over a wide range of Reynold's no. 200–8000 and Prandtl no. range 5–8, using water as a working fluid. Experiments showed that all the used devices led to an increase in Nusselt no. of the flow. Nusselt no. showed a heavy increase for transition and tur- bulent region while a little less in the laminar region. Considering the wire family, concentric wire insert showed the best perfor- mance and from twisted tapes, one with the smallest pitch ratio was more promising than the other two. Mesh inserts performed best in laminar region, increasing the Nusselt no. by 270%, whereas concentric coils showed best results in turbulent region with a 460% increase in Nusselt no. Mesh inserts showed a better per- formance at laminar level, but it did increase the pumping power requirement of the system due to increased friction. The authors thus recommended concentric coils as a better option with 110% enhancement in laminar region and 460% in turbulent. Test for the inclination showed that there is no significant enhancement of Nusselt no. due to the channel inclination. On the similar grounds, Hobbi and Siddiqui [41] studied the effect of passive heat en- hancement devices like twisted strip, coil-spring wire and conical ridges. No significant difference in heat flux was observed to the collector fluid. But a significant increase in Grash of, Richardson and Rayleigh numbers was observed indicating that the heat transfer mode in the collector is of mixed convection type, free convection being predominant. Authors concluded that due to the high damping effect of shear produced turbulence by buoyancy forces, the applied inserts were ineffective in enhancing the heat transfer to the collector. To see the effects of wire inserts in a liquid solar collector, Martı´n et al. [31] carried out a TRNSYS based numerical simulations of the collector. Operating parameters such as local losses, friction coefficients, Nusselt number were studied as a function of Reynolds number to observe their effects on thermohydraulic performance of collector. To take into account, internal heat transfer coefficient and friction factor, a new collector model was developed by authors. All the simulations performed was based on UNE-EN 12975-2 standards. To evaluate pressure drop and heat transfer in the tube, authors used their own cor- relations and experimental data. Analysis was done on 2 working fluids: water and propylene glycol/water mixture, with varied mass flow rates. Results showed an increase of 4.5% in efficiency of enhanced collector as compared to the standard collector. Pump- ing power for water increased for all the flow rates, but for pro- pylene glycol 44%, there was no increase below 80 kg/h. the in- crease in pumping power is surely due to an increased friction because of the inserts. Overall, wire inserts are better option to enhance the thermal performance and make the collector com- pacts in warm climatic regions or for warm water, or for small applications like household water heating where the pump is slight oversized and hence, there is no change in pumping power. Wire-coil insert was experimentally studied by García et al. [43], to observe its heat transfer enhancement abilities. Experiments were carried out on two collectors with 5 different mass flow rates. Authors found that with the help of wire-coil insert, there was an average increase of efficiency from 14–31% and an increase in useful power collected of upto 8–12%, with no additional pressure losses. The degree of enhancement due to inserts gets deteriorated with the increasing mass flow rates.

**Table 1:** Introduction in brief about solar collector enhancement.

| Sr. No | Area of research | Enhancements and discussions |
|---|---|---|
| 1 | Polymer as collector material | Advantages: cheaper than metal collectors (material and manufacturing cost is low), lighter than metal collectors.<br>Desired properties: high reflective index, Low emissivity and durability to UV, able to withstand liquid pressure, compatible with the HTF used.<br>Output of studies: similar performance as metal collectors. Length of collector does not affect the efficiency but air gap does.<br>Increase in mass flow rate increases efficiency but decreases outlet temperature. |
| 2 | Mini and micro channels | Advantages: high heat transfer potential combining attributes of high surface area per unit volume, large heat transfer co-efficient and small working fluid inventory.<br>Desired properties: high heat transfer performance, high reliability, high compressive strength, low cost, small contact resistance.<br>Output of studies: mini-channel based collector has higher heat removal factor. At higher flow rates, thermal perfor- mance increases on expense of hydraulic performance. Heat pipe channel array have low response time to temperature and show a very high efficiency as compared with the traditional collectors. |
| 3 | Nanofluids as HTF | Advantages: cost effective, environmental friendly, compact, light in weight collector can be built using nanofluids as<br>HTF. Higher efficiency than water based collectors.<br>Desired properties: nanofluid chosen should stable for long duration of time at varied temperatures i.e. they shouldn't go under agglomeration. Nanoparticles used for making nanofluids should have high thermal conduction, large surface area and good mechanical and optical properties.<br>Output of studies: increase in efficiency with the increase in no. of nanoparticles. Decrease in efficiency with decrease in volume flow rate of the nanofluid. Improved heat transfer phenomenon and superior convection co-efficient can be obtained without a considerable increase in friction factor and pumping power. Efficiency decreases with increase in weight fractions and size of particles. Overall heat gain increases.<br>Glycol based nanofluid stable for long duration.<br>CuO and Cu based nanofluid shows good thermal enhancements.<br>Area reduction of the collector can be achieved with the help of high density nanofluids. |
| 4 | Innovation in absorber plate design | Advantages: increase in heat absorbed from solar radiation.<br>Desired properties: must be capable of absorbing of different wavelengths effectively.<br>Output of studies: five layered tandem absorber showed high thermal stability at high temperatures for long duration of time.<br>Roll bond collector proved to be useful in customization and optimisation of flow patterns inside the absorber, however, it's difficult to manufacture.<br>Chevron pattern absorber, due to its unique design have low overall loss co-efficient making it economical and efficient<br>than the conventional collectors. |
| 5 | Employing PCM | Advantages: eliminates need for storage units making water heating systems less bulky. Provides large space capacity and has isothermal behaviour during melting.<br>Desired properties: suitablephase-transition temperature, Highlatent heat of transition, High thermal conductivity in both liquid and solid phases, High density, Small volume change, Low vapour pressure, chemically stability and cost effective. |

| | | |
|---|---|---|
| | | Output of studies: temperature distribution of aluminium foam matrix saturated with paraffin was better than that of paraffin alone. mPCM shows enhanced thermal properties. Have high thermal efficiency than the conventional PCM collectors. How- ever, it is not possible to work with mPCM with concentrations above 50%. |
| 6 | Heat loss reduction techniques | Advantages: increased efficiency due to decreased heat loss. Desired properties: technique used must be cost-effective, must decrease the heat loss by convection and radiation to the surroundings. Output of studies: use of other inert gases in the glass-absorber gap, instead of air proves to be effective. Thinner collectors can be manufactured at reasonable rates using this technique. Double gazed collector is better than single gazed collector. Adding heat shield beneath the fluid carrying tubes decreases the heat loss resulting in higher efficiency. |
| 7 | Use of enhancement devices | Advantages: improvement in thermal performance without any modification and keeping size compact. Increased turbulence in flow increasing heat transfer in fluid. Desired properties: should be able to increase the turbulence in flow without much increase in pumping power. Output of studies: insert devices leads to increase in Nu. no. in flow. Twisted tape inserts with small pitch were promising. Mesh inserts are better for laminar flow but increases pumping power. Concentric coils showed enhanced performance in laminar and turbulence flow without any significant improvement in pumping power. Wire inserts improved the efficiency. When propylene glycol is used as HTF with wire insert, there is no increase in pumping power below certain limits. Degree of enhancement due to insert gets deteriorated with increasing mass flow rate. Thermal and hydraulic resistance can be deceased by using heat pipes with groves and fins. Use of reflectors to direct radiation on collector increases the overall performance of the collector. |

Metal heat pipes by many researchers was reported as an effective solution to increase the thermal performance of the col- lectors. However, many of the collectors are heavy, non-versatile, have complex assembly and installation, possess high hydraulic resistance and low thermal efficiency and lack scalability and adaptability for design. To overcome these shortcomings, Rassa- makin et al. [40] applied extruded aluminium alloy heat pipe with wide fins and longitudinal grooves to the solar collector. Number of fins on absorber plate were taken as arbitrary. Opposite sides of the heat pipes had fins serving as a heat sink surface. Several tests were conducted on the new design. Results showed that with the help of this insert, it is possible to reduce the thermal and hy- draulic resistance. Thermal efficiency was also found to be high. The new light weight and inexpensive heat pipe showed high thermal performance.

Tanaka [6] theoretically analysed the effect of using a bottom reflector on the performance of absorber. A gap between a col- lector and reflector was maintained and were kept front facing to each other at an angle such that the collector receives the reflected radiations from the reflector along with direct and diffused ra- diation. By a graphical method, the amount of radiation reflected and then absorbed was calculated. It was absorbed that by placing the bottom reflector at some distance, it is possible to increase the amount of solar radiation absorbed. The distance between the two must be maintained such that the gap length is less than the lengths of collector and reflector. With the change in gap in var- ious seasons, optimum inclination of collector remains same while there is slight change in the inclination of reflector. There was a decrease in absorbed radiation with the increasing gap length for optimum inclination, while the decrease was drastic for other inclination. A brief extract of all the development technologies is presented in Table 1.

## 4. Scope of further research

All the above studies refer to analysis and development of solar

flat collectors. Various numerical models have been built to accurately evaluate the performance of solar collectors. Analysis is generally based on operating and design parameters. Studies have shown the effect of various parameters like solar radiation, in- clination angle, ambient conditions, water inlet temperature, air flow rate, etc. Based on these studies, a numerical model can be built considering each parameter as an independent variable and the effects of the required or the desire ones in a final equation to evaluate efficiency of the collector, which would be a function of all the above parameters or parameters which are more dominant. Optimisation study can be undertook to find the optimum values of the design parameters and operating parameters which are under our control to improve the performance of the collector.

Development of flat plate collector for improved heat transfer rate can be done by one or more of the following ways: improving absorber design, choosing material with high thermal conductivity and absorptance capacity for absorber, increasing turbulence in the flow by various means, using nanofluids for increased area and thermal conductivity, use of mini and micro channels for fluid flow, use of thermal enhancements and inserts, etc. Search for new materials for solar collector in a hot trend. In this context, gra- phene, a carbon structure, may be a good option. Graphene/water nanofluids, graphene oxide/water nanofluid or graphene nano- platelets mixed in some other base fluid like glycols, can be used as a heat transfer fluid in solar collectors very effectively. There is no work done to find the feasibility of graphene/water nanofluid as heat transfer fluid. Studies have shown that graphene has a very high thermal conductivity and the fluid is quite stable. Thermal performance of collector and stability analysis of this nanofluid can be done. Graphene in the form of TCPG (Thermal Conductive Pyrolytic Graphite) can be used in absorber plates to increase its absorbing and conducting ability. TCPG is costly in current times, so small strips of this novel material can be used in absorber plate.

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