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Review Article

Thermal and Economic Analysis Review on Flat Plate, Parabolic Trough and Evacuated Tube Solar Collectors for Process Heat Applications

Chandraprabu Venkatachalam, Samuel G. Mariam and Abdi Chimdo Anchala

Department of Mechanical Engineering, Adama Science and Technology University, Adama, Ethiopia

Abstract

Energy plays a pivotal role in our society because of new life trends which are accompanied with high energy consumption. To meet these needs renewable energy technologies such as solar energy systems have proven to be advantageous in many ways. This paper presented a review of thermal and economic analysis of solar energy collectors and processes. Three non-concentrating and concentrating collectors have been analyzed, which includes flat-plate collectors and evacuated tube collectors from the first category and heat transfer enhancement from the second category. Initially, an introduction into the nature of solar energy was attempted followed by a description and working principle of all three collectors. This was followed by an optical, thermal and thermodynamic analysis of the collectors and a description of the methods used to evaluate their performance. Another important consideration for solar collectors will be the economic analysis, which includes the manufacturing, operation and maintenance costs, etc. Beside these, complexity, uniform flux distribution and working fluid selection of some other important factors in solar collector systems. Typical applications of the various types of collectors have also been reviewed and presented. Through the literature review, it is shown that exergy analysis gives a representative performance evaluation method and is emphasized as a valuable method to evaluate and compare possible configurations of these systems.

Key words: Solar collector, flat-plate collectors, thermal and economic analysis, solar energy collectors, heat transfer enhancement

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Corresponding Author: Chandraprabu Venkatachalam, Department of Mechanical Engineering, Adama Science and Technology University, Adama, Ethiopia Tel: +251 967724433/+91 9677804500

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INTRODUCTION

Due to the ever increasing energy demand, our society has been on the lookout to find different kinds of energy sources that are affordable and efficient to meet the specific needs of the people. At the moment, coal, natural gas, woods and oil, are among the most used and exploited energy sources. The main disadvantage of these technologies arises from the different kinds of energy related environmental and economic problems they cause on the earth. Acid rains, ozone layer depletion and global climate changes are one of the main environmental problems that have a lot to do with the emission of various air pollutants which are toxic chemical substances[1] such as CO, CO_2, SO_2 and NO_2. As a result, throughout the history of people have proposed different kinds of solution to solve this issue and the sun have standout to be the best, reliable and efficient energy source for our world.

The sun can be described to be large sphere of extremely hot gaseous matter having a diameter of 1.39×10^9 m and away from earth by 1.5×10^{11} m. It has a total energy output of 3.8×10^{20} MW but only a small fraction, 1.7×10^{14} of the total radiation will reach the earth surface because the sun radiation will be attenuated two times by the clouds (3% of which is by absorption and 20% by reflection) and the atmosphere (16% of which is by absorption and 6% by reflection)[2]. Solar energy can be converted into either electrical energy or thermal energy by using solar thermal collectors. For thermal systems, the solar thermal collectors are also known as solar water heaters (SWH) and it can convert solar energy into heat and transfer it through a transfer medium, such as water, to a heat storage tank[3]. Typical applications of the various types of solar collectors include water heating, space heating and cooling, industrial process heat, thermal power systems and chemistry applications. This paper presented a review of three different solar energy collectors. These include flat plate collectors, evacuated tube collectors and parabolic trough collectors.

THERMAL AND ECONOMIC ANALYSIS

Solar water heaters: Solar collectors are devices that are used to harness the energy from the sun, converting the incoming solar radiation into useful heat energy. Being the key element in solar energy utilization systems, solar energy collectors act as heat exchangers that converts the solar radiation energy into internal energy of the transport medium. The solar energy will be collected by absorbing the incoming solar radiation and converting it into heat and transferring this heat to a fluid. Then, this heat energy will be transferred from the fluid to the heat application processes or the storage tank[4].

There is a high consumption of non-renewable primary energy for domestic hot water systems. Therefore, a potential solution is needed for the accelerating surge in the share of the energy demand. This led to development of energy-saving technologies and the use of renewable energy sources such as solar energy[5].

Exergy analysis has been performed for different types of solar collectors. Most of it, were in the field of flat-plate solar collectors. The second most popular area of study referred to combined photovoltaic and thermal collectors. Also, a few studies has been done on parabolic trough collectors and evacuated tube collectors too. Parabolic dish collectors had been analyzed and optimized by a number of researchers and showed to have high exergetic efficiency. Other types of collectors less often researched. are compound parabolic collectors, heat pipe collectors and cavity receivers[6].

Flat plate collector: Flat plate collectors are primarily composed of a glass cover, absorber plate and insulation material. The glass cover is used to trap the hot air by reducing the radiation and convection losses to the surrounding, the absorber plate has tubes filled with the working fluid whereas the insulation material is used to reduce conduction losses. For flat plat collectors, the materials, dimension, number and size of tube, dimension and number of glass covers can vary for different application and were selected based on the chosen criteria of the specific application[4].

Sint *et al.*[7] did a study on flat plate collectors and they found that the maximum collector efficiency is found when the value of overall heat loss coefficient and heat removal factor is at its minimum and maximum, respectively. For the collector's nanofluid, the optimal load will be a 2% volume concentration. By increasing the size of the nano-particles in the nanofluid, it is observed that it is possible to increase the efficiency of the collector slightly. According to the study, the collector efficiency is a function of particle volume concentration loading as opposed to particle size in nano-fluid in CuO-water nano-fluid, with a 25 nm particle and at an optimal particle concentration of 2% (vol), the collector efficiency can increase by 5%. Chandraprabu *et al.*[8] identified that the CuO/Water nano-fluid enhanced the heat transfer rate by 35%.

By increasing the mass flow rate of the working fluids the efficiency of the flat plate collector can be increased. Due to the flow regime change from laminar to turbulent for water, higher efficiency can be achieved even at lower flow rates such as below 0.016 kg sec^{-1} using nano-fluid as opposed water but at and above this flow rates, water had a higher thermal efficiency[9].

An experiment was conducted in Budapest to study the effect of using CeO_2-water nano-fluid on the efficiency of flat plate collectors with 3 different volume fractions of CeO_2 nano-particles and found the optimal volume fraction to be around 0.0333%. The CeO_2-water nano-fluids stability was maintained by using an ultrasonic process. The result of the experiment showed that, the efficiency of the solar collector can be increased more by employing CeO_2- water nano-fluid instead of just water, as the changes in removed energy parameter, vary from 30.61-191.8% and in absorbed energy parameter[10] from 3.51-10.74%.

Sharafeldin *et al.*[11] did an experimental study on the effects of using WO_3-water nano-fluid on the efficiency of a flat plate solar collectors and they also investigated the thermal performance of the collector using these nano-fluids at various mass flux rates and volume fractions. The result elucidated, the efficiency of the solar collectors can be improved by the addition of WO_3 nano-particles to water depending on mass flow rate, concentration and the reduced temperature parameter. Based on the comparison of the 3 mass flux rates and volume fractions, it is found that at a mass flux rate of 0.0195 kg sec^{-1} m^2 and a volume fraction of 0.0666%, an efficiency of 71.87% can be achieved with a 13.48% increase in absorbed energy parameter.

In order to improve the performance of the solar energy collectors, a reflector was introduced. It was observed that the collector efficiency and heat transfer rate depend on solar radiation. The collector efficiency, without reflector was about 51% but this can be maximized by 10% to an efficiency of 61% by mounting a glass to prevent the radiation emitted by the absorber plate from escaping and using a reflector to concentrate the solar heat on the collector[12].

During optimization, it is advisable to use the LiB-H_2O nano-fluid as working fluids at a generator temperature of 75.64°C and evaporating temperature of 7.5°C to get a system COP of 0.3995 and an exergetic efficiency of 0.01976. The optimization process was responsible for the higher exergetic improvement[13].

According to Sokhansefat *et al.*[14], weather conditions and inlet fluid temperature affects the performance of flat plate collectors more than evacuated tube collectors and based on their study, putting both collectors to be in cold climates results to be profitable and economic. But, it was found that, applying evacuated tube collector in cold climate was more profitable than FPC because it had shorter payback period with an NPV of $1981 in 15 years. Therefore, ETC was more preferred for selection of cold climate design.

The return on investment was calculated for both evacuated tube and flat plate collectors taking both the equipment and operation costs of a non-solar collector system into consideration and for the flat plate, the return on investment was found to be 9 years whereas, for the evacuated tube collector it was about 11 years. Even though flat plate collectors had lower costs and return on investments, further research had to be made on them regarding the installation and maintenance costs[15].

Based on a study made by Abuska and Sevik[16], the annual revenue of fuel consumption saving using flat plate collectors was found to be 59.4-76.1 $/year and the payback period was 4.3-4.6 years. It is possible to decrease the payback period, improve the operational efficiency and usage of SAC in heat generation systems by integrating PV panel to FPC's. The environmental-economic costs were found to be between 4.5 and 5.77 $ per year.

Parabolic trough collector: Parabolic trough collectors are long, trough-shaped reflector of parabolic cross-section with a slope controlled by the rim angle which focus the reflected sunlight radiation on to the receiver tube (heat pipe). The receiver was positioned at the focus of the length of the trough to absorb most of the energy focused onto it and it transfers this heat to the working fluid which gets heated to a higher temperature when pumped through the receiver tube to accept the heat absorbed by it. The receiver can be made of black-coated steel or copper tubing, insulated by a protective glass cover enclosing a vacuum layer to reduce heat loss to the surrounding. To increase efficiency, anti-reflective coating can be used on the outer glass surface. Most parabolic troughs always have a tracking system and they were mounted on structural supports that would allow them to track the sun from east to west direction during the day time. The supports for parabolic trough can be made of steel, aluminium or other material with higher strength[17].

Increasing the pitch angle of parabolic trough collector does not significantly affect the collector frequency and for many models the mode shapes are greatly similar. This goes to show that pitch angle slightly affect the frequency and mode shape of the trough solar collector[18].

Jin *et al.*[19] proposed a unifying method of analyzing parabolic trough collectors with different dimensions using similarity principle and dimensional analysis by deriving six dimensionless numbers to ensure the similarity between the scaled and prototype models. The results showed that there was a great correlation between the key parameters of different kinds of parabolic trough collectors and also indicated the relative independence of solar thermal system performances on dimensions.

Every different collectors operate under different operating conditions, so incorporating these different collectors together can be used for wider applications working under any condition. Combing flat plate collectors with parabolic trough collectors in series can give industry process temperatures ranging from low (T<100°C) to high (T>250°C)[20].

In 2013, during a test made in Denmark, the feasibility of parabolic trough collectors in large scale solar heating plants for district heating had been validated in the pilot thirsted plant and the results showed that in solar district heating plants, parabolic trough collector can also be used operating at temperatures ranging[21] from 85-95°C.

Even though storage tank volume can greatly directly affect the exergy output of a solar thermal system, it will be safe to say it affects both the thermal output and the exergetic output of the parabolic trough solar collectors since study showed higher storage tank volume can lead to higher thermal output and to lower exergetic outputs because of the decrease in the temperature level for greater storage tanks. The reason for this can be the direct and proportional relationship between the mean storage tank temperature and the storage tank volume[22].

Bellas and Lidorikis[23] found that, by using an optimized low-absorbing TCO it is possible to increase the efficiency of the collector. Here, the coating can produce excellent spectral selectivity with high transparency in the solar spectrum and high reflectance in the IR. During the work, the gain had been found to be between 5 and 10% for low-index NCs and 9.5-21% for high-index NC and this value greatly depend on the concentration ratio.

For parabolic trough collectors, the increase in the heat transfer development and absorption of solar intensity in the receiver tube can be achieved by using nano-fluids as a heat transfer fluid. Out of several heat transfer fluids CuO/water and Cu/therminol VP-1 nano-fluids have standout to be the best nano-fluid as compared to other nano-fluids. On the economic aspects, using these nano-fluids had disadvantages as they are expensive to purchase increasing the total investment cost. The concentration ratio of the nano-particle in the heat transfer fluid should be optimized for a best transfer enhancement in the receiver tube of the parabolic trough collectors[24].

The beam solar radiation directly affected the thermal efficiency of the collector. When comparing the different working fluids of the collector it was evident that Al_2O_3 nano-fluid had high heat transfer rate compared to SiC nano-fluid but, CuO nano-fluid had a higher heat transfer rate compared to Al_2O_3 [25-27].

For a wide field of solar panels, the exergetic analysis indicated that a continuous outpouring of the solar radiation will cause the exergy in the heat transfer fluid circulating through the parabolic trough collectors. In the daytime, the increase in the exergy was substantial and it was the main exergy contribution compared to the auxiliary heater exergy, which becomes low at night[28].

Guo *et al.*[29] performed a parametric analysis of parabolic trough collectors for various receiver diameters, inlet temperatures, ambient temperatures, incident angles and wind velocities. In every analysis, only one parameter was examined parametrically, while all the others had been kept constant. According to their results, there is optimum mass flow rate exergetically in every case and they stated the need of reducing the high optical losses, is one way to improve PTC's exergetically.

Based on a test performed to study the thermal performance of PTC's, the daily average efficiencies in summer and winter had been found to be of 63 and 40%, respectively. In addition to this, results of experiments on the effect of the cosine loss showed that, adopting the rotatable axis tracking increased the daily average collector efficiency by 5.0% and reduced the daily average cosine loss by 10.3% compared with north-south axis tracking[30].

Su *et al.*[31] compared the results between a ray tracing model and the commercial optical software and based on the results, the ray tracing model was validated to be true. Showing each ray can be traced by the PTC model, the incident angle can be calculated when the solar ray entered the absorber tube. The thermal efficiency can also be found by using the reflection, the transmittance and the absorption at different incident angle for each ray tracing. Thus, the solar absorption of the receiver tube depends on the angle of incidence.

Murtuza *et al.*[32] did an experiment that lasted for 12 months and after measuring the average temperatures of both inlet water and outlet water they concluded that, temperatures ranging from 80-103°C can be achieved between February and May. After calculating the Reynold number with different kinds of flows such as 0.4, 0.8 and 1.2 LPM, it was possible to know the flow pattern in the absorber tube which showed, higher temperatures were obtained in the March, April and May with laminar flow based on the plots of surface temperature, outlet temperature and thermal efficiency versus Reynolds number of the 12 months.

The two key elements in the cost management in the parabolic trough solar concentrators are the projection of solar collectors on the market and the assessment and cost management in the design, operation and construction of these collectors[33].

There are many ways to reduce the cost that was used to construct parabolic trough systems one of which included the increment of land area. This was, compared with the cost at 2.8 ha the cost for a PTC field can be cut by about 46% at 10 ha and by about 72% at 160 ha. The economic or the cost analysis can be recognised in the labour cost, receiver cost, collector cost, structural system costs and these were used to cut the specific cost by 75%. At places where the cost per unit area of the solar field was minimal, it was advised to use parabolic trough collectors for large scale concentrated solar power applications[34].

Evacuated tube collector: Evacuated tubes contain two glass tubes made of borosilicate where the inner and outer glass tubes are separated by vacuum space. The vacuum plays the role of an insulator to block the short wave radiation from escaping and this has proven to be the best methods to trap radiation. It was also used to direct the radiant energy incident inside the tube without a huge heat loss. The evacuated glass tubes were filled with water and placed in open tank and the hot water will start to rise up while the cold water sinks into the glass tubes since the density of the hot water was lighter than cold water. By the thermo-siphon principle which was based on natural convection, the water heats up on a cyclic repetition. The heat transfer fluid near the surface started to evaporate instantly as the solar radiation was incident on the collector of the outer glass and the short radiation was incident on the inner tube consisted of the heat pipe where the radiation falls on the external surface of the heat. At the evaporator region, a vapour will be created which absorbed latent heat of vaporization then the vapour traveled to the condenser region where the vapour condense by giving up the heat to the manifold where the heat was exchanged with cold fluid passing through the manifold[35].

Evacuated tube collectors was preferably used for high temperature applications such as desalination of sea water, air conditioning, refrigeration and industrial heating processes since their performance was better than that of flat plate collectors[36].

Evacuated tube solar collectors (ETC) were the most widely used type of collectors because they had a high-working temperature and thermal efficiency compared to other collectors such as flat plate solar collectors. Several configurations exist for evacuated tube collector. The simplest one uses a flat plate with a flow arrangement of tubes attached to an evacuated glass cylinder. The efficiency of evacuated tube collector can be increased by using a heat pipe as the absorbing element in the collector tube. The heat was transferred through the heat pipe having a small temperature difference of fluid between the heat input and output. The heat pipe consisted of a closed container integrated with a capillary device then charged with a working fluid suitable for the operating conditions. The incoming fluid was first absorbed from the tubes and then it vaporized in the pipe[37].

Nie *et al.*[38] stated that, higher thermal efficiencies can be achieved for the evacuated tube solar collectors by reducing the temperature below zero than that of working under common conditions. For temperatures below zero, the thermal efficiencies increased as the reduced temperature decreased and the growth rate of the thermal efficiency will decreased slowly. The growth rate of the thermal efficiency was higher for lower solar irradiances which were the higher sensitivity to the mass flow rate and the solar irradiance changes.

Abd-Elhady *et al.*[39] did two sets of experiments to study the impact of oil and foamed metals on the performance of evacuated tubes, one with an artificial sun under constant solar irradiance and another under the real sun. The result had proved to show, adding thermal oil improved the rate of heat transfer from the inner surface of the tube to the heat pipe as the bulb temperature increased by 15%, i.e., from 166-191°C due to filling the evacuated tube with the thermal oil.

A two part experiment, one for the evacuated tube collector/storage (ETC/S) with a Compound Parabolic Concentrator (CPC) and one without a compound parabolic concentrator were conducted by Felinski and Sekret[40] to measure the heating medium flow rate and solar radiation intensity using a flow meter and pyrometer. They found that, for the first 80 min, the paraffin's temperature increased steadily for the evacuated tube collector/storage with a compound parabolic concentrator and without it but soon, the CPC showed to had an effect on the rise of the temperature causing the temperature of the paraffin to rise more rapidly. The main reason for this was the fact that the CPC will direct more solar radiation on the surface of the evacuated tube.

After conducting an investigation on 2 m^2 concrete absorber plate solar water heater, Sable[41] stated that, during months of September, January and April average water temperature of 150 L of water collected per day was found to be 62, 59 and 69°C, respectively at a water flow rate of 30 lph. Thus, with this capacity of the evacuated tube solar water heater, it is possible to fulfil the demand of hot water for various purposes in most weather conditions mostly for normal weather days and partially for cloudy days.

From the thermal standpoint, the ambient conditions selected for the design will determine the number of solar collectors required to attain the targeted performance from the system. Larger collector areas can be used to compensate for certain deficiencies such as lower inlet temperatures and a lower solar radiation intensities[42].

Iranmanesh *et al*.[43] experimentally investigated the effect of graphene nano-platelets/distilled water nano-fluid on the thermal performance of evacuated tube solar collector water heaters. They introduced graphene nano-platelets to improve the efficiency of evacuated tube solar collectors and tested them with 3 different volumetric flow rates (0.5, 0.1 and 1.5 L min^{-1}). Graphene nano-platelets had high thermal conductivity which can increased up to 27.6%. The results from the experiment indicated that, due to their high thermal properties, employing graphene nano-platelets can increase thermal efficiency of these systems up to 35.8-90.7% depending on their flow rates.

To increase the outlet temperature of the working fluid it's recommended to lower the mass flow rate of the fluid and use optimum length of collector. The net heat energy gain at high solar intensity was highly affected by change in the ambient temperature. Based on the study, water had proven to be the best heat energy absorber fluid compared to air and $LiCl$-H_2O solution[44].

Bellos *et al*.[45] investigated the continuous carbon nanotube sheet from forests as a selective coatings in evacuated tube collectors and these have proven to be the most appropriate solar selective coating for evacuated tube collector water heaters with a wide operational spectral range. For CNT coatings, the highest optical absorption, comes from the tallest forest, the highest sheet area density, larger CNT diameter and higher number of CNT walls.

The characteristics and the performance of different types of evacuated tube collectors for solar water heating systems was investigated by Martinez *et al*.[3]. They evaluated the system feasibility by calculating the payback time. They determined the operating temperature of the system to be 50°C which is good enough for domestic purposes and their cost analysis showed that the solar water heater using an ETSC was more cost effective than the electric water heater.

Based on the economic analysis Sable[41] performed on a roof integrated concrete solar collectors, evacuated tube collectors had been found to have a short payback period, meaning the investment cost can be recovered with in a short period of time. Along with environmental benefits of reduction in green-house gasses and air pollutants, replacing the conventional energy sources with solar water heating systems can be a good protection from future fuel shortages and price rise.

CONCLUSION

Applications and processes include the use of phase change materials either in the collection or storage of thermal energy, heating, solar cooling, drying, domestic co-generation, solar assisted heat pumps and others. Here, the utilization of solar thermal collector's specifically focused on solar water heaters which undertake the conversion of solar energy into thermal energy (heating). Nano-fluids are suggested to be used in solar water heater systems as a working fluid to enhance the system's energy harvesting potential and to improve the collector efficiency in solar water heating systems. Various nano-fluids such as CuO-water, CeO_2-water WO_3-water LiB-water, Al_2O_3, SiC and graphene nano-platelets have been suggested. Further recommendations have been made to increase the performance of solar water heater systems which includes the selection of optimum mass flow rate, coatings and the usage of SWH components such as reflector and heat pipes. Solar water heating systems have also been proven to have good economical and environmental benefits. Solar thermal system performances are relatively independent on dimensions but, the exergy analyses have proven to be the best method to evaluate and compare possible configurations of these systems. At the moment, there is a lack of studies that brings these 3 solar collectors altogether to discuss and compare based on their performance and economic aspects.

SIGNIFICANCE OF THE STUDY

The main significance of this project is to provide anyone person who is interested in using solar water heating technologies, with the necessary information required to select the most appropriate solar collector system form the thermal and economical standpoint. This will help in the proper selection and employment of SWHs to solve a problem that our community faces regarding the shortage of energy and rise of energy cost.

REFERENCES

1. Kalogirou, S.A., 2004. Solar thermal collectors and applications. Prog. Energy Combust. Sci., 30: 231-295.

2. Tian, Y. and C.Y. Zhao, 2013. A review of solar collectors and thermal energy storage in solar thermal applications. Applied Energy, 104: 538-553.
3. Martinez, P.M., V.A. Pozdin, A. Papadimitratos, W. Holmes, F. Hassanipour and A.A. Zakhidov, 2017. Dual use of carbon nanotube selective coatings in evacuated tube solar collectors. Carbon, 119: 133-141.
4. Kalogirou, S.A., S. Karellas, K. Braimakis, C. Stanciu and V. Badescu, 2016. Exergy analysis of solar thermal collectors and processes. Prog. Energy Combust. Sci., 56: 106-137.
5. Felinski, P. and R. Sekret, 2017. Effect of PCM application inside an evacuated tube collector on the thermal performance of a domestic hot water system. Energy Buildings, 152: 558-567.
6. Kalogirou, S.A., S. Karellas, V. Badescu and K. Braimakis, 2016. Exergy analysis on solar thermal systems: A better understanding of their sustainability. Renewable Energy, 85: 1328-1333.
7. Sint, N.K.C., I.A. Choudhury, H.H. Masjuki and H. Aoyama, 2017. Theoretical analysis to determine the efficiency of a CuO-water nanofluid based-flat plate solar collector for domestic solar water heating system in Myanmar. Solar Energy, 155: 608-619.
8. Chandraprabu, V., G. Sankaranarayanan, S. Iniyan and S. Suresh, 2013. Performance of CuO/water nanofluid as outer fluid in the tube in tube condensing unit of air conditioner: Experimental study. J. Nanofluids, 2: 213-220.
9. Genc, A.M., M.A. Ezan and A. Turgut, 2018. Thermal performance of a nanofluid-based flat plate solar collector: A transient numerical study. Applied Thermal Eng., 130: 395-407.
10. Sharafeldin, M.A. and G. Grof, 2018. Experimental investigation of flat plate solar collector using CeO_2-water nanofluid. Energy Conversion Manage., 155: 32-41.
11. Sharafeldin, M.A., G. Grof and O. Mahian, 2017. Experimental study on the performance of a flat-plate collector using WO_3/Water nanofluids. Energy, 141: 2436-2444.
12. Bhowmik, H. and R. Amin, 2017. Efficiency improvement of flat plate solar collector using reflector. Energy Rep., 3: 119-123.
13. Bellos, E. and C. Tzivanidis, 2018. Performance analysis and optimization of an absorption chiller driven by nanofluid based solar flat plate collector. J. Cleaner Prod., 174: 256-272.
14. Sokhansefat, T., A. Kasaeian, K. Rahmani, A.H. Heidari, F. Aghakhani and O. Mahian, 2018. Thermoeconomic and environmental analysis of solar flat plate and evacuated tube collectors in cold climatic conditions. Renewable Energy, 115: 501-508.
15. Najera-Trejo, M., I.R. Martin-Dominguez and J.A. Escobedo-Bretado, 2016. Economic feasibility of flat plate vs evacuated tube solar collectors in a combisystem. Energy Procedia, 91: 477-485.
16. Abuska, M. and S. Sevik, 2017. Energy, exergy, economic and environmental (4E) analyses of flat-plate and V-groove solar air collectors based on aluminium and copper. Solar Energy, 158: 259-277.
17. Hafez, A.Z., A.M. Attia, H.S. Eltwab, A.O. ElKousy and A.A. Afifi *et al*., 2018. Design analysis of solar parabolic trough thermal collectors. Renewable Sustainable Energy Rev., 82: 1215-1260.
18. Zou, Q., Z. Li and H. Wu, 2017. Modal analysis of trough solar collector. Solar Energy, 141: 81-90.
19. Jin, J., Y. Ling and Y. Hao, 2017. Similarity analysis of parabolic-trough solar collectors. Applied Energy, 204: 958-965.
20. Tian, Z., B. Perers, S. Furbo and J. Fan, 2018. Analysis and validation of a quasi-dynamic model for a solar collector field with flat plate collectors and parabolic trough collectors in series for district heating. Energy, 142: 130-138.
21. Perers, B., S. Furbo and J. Dragsted, 2013. Thermal performance of concentrating tracking solar collectors. DTU Civil Engineering Report R-292, August 2013.
22. Bellos, E., C. Tzivanidis and V. Belessiotis, 2017. Daily performance of parabolic trough solar collectors. Solar Energy, 158: 663-678.
23. Bellas, D.V. and E. Lidorikis, 2017. Design of high-temperature solar-selective coatings for application in solar collectors. Solar Energy Mater. Solar Cells, 170: 102-113.
24. Kumaresan, G., P. Sudhakar, R. Santosh and R. Velraj, 2017. Experimental and numerical studies of thermal performance enhancement in the receiver part of solar parabolic trough collectors. Renewable Sustainable Energy Rev., 77: 1363-1374.
25. Marefati, M., M. Mehrpooya and M.B. Shafii, 2018. Optical and thermal analysis of a parabolic trough solar collector for production of thermal energy in different climates in Iran with comparison between the conventional nanofluids. J. Cleaner Prod., 175: 294-313.
26. Chandraprabu, V., G. Sankaranarayanan, S. Iniyan, S. Suresh and V. Siva, 2013. Heat transfer enhancement performance of Al_2O_3/water nanofluid in condensing unit of air conditioner: Experimental study. Int. Rev. Mech. Eng., 7: 686-691.
27. Chandraprabu, V., G. Sankaranarayanan, S. Iniyan and S. Suresh, 2014. Heat transfer enhancement characteristics of Al_2O_3/water and CuO/water nanofluids in a tube in tube condenser fitted with an air conditioning system-An experimental comparison. J. Thermal Sci. Eng. Applic., Vol. 6, No. 4. 10.1115/1.4027396.
28. El Ghazzani, B., D.M. Plaza, R.A. El Cadi, A. Ihlal, B. Abnay and K. Bouabid, 2017. Thermal plant based on parabolic trough collectors for industrial process heat generation in Morocco. Renewable Energy, 113: 1261-1275.

29. Guo, J., X. Huai and Z. Liu, 2016. Performance investigation of parabolic trough solar receiver. Applied Thermal Eng., 95: 357-364.
30. Qu, W., R. Wang, H. Hong, J. Sun and H. Jin, 2017. Test of a solar parabolic trough collector with rotatable axis tracking. Applied Energy, 207: 7-17.
31. Su, Z., S. Gu and K. Vafai, 2017. Modeling and simulation of ray tracing for compound parabolic thermal solar collector. Int. Commun. Heat Mass Transfer, 87: 169-174.
32. Murtuza, S.A., H.V. Byregowda and M. Imran, 2017. Experimental and simulation studies of parabolic trough collector design for obtaining solar energy. Resour. Efficient Technol., 3: 414-421.
33. Conrado, L.S., A. Rodriguez-Pulido and G. Calderon, 2017. Thermal performance of parabolic trough solar collectors. Renewable Sustainable Energy Rev., 67: 1345-1359.
34. Mokheimer, E.M., Y.N. Dabwan, M.A. Habib, S.A. Said and F.A. Al-Sulaiman, 2014. Techno-economic performance analysis of parabolic trough collector in Dhahran, Saudi Arabia. Energy Conversion Manage., 86: 622-633.
35. Kumar, S.S., K.M. Kumar and S.S. Kumar, 2017. Design of evacuated tube solar collector with heat pipe. Mater. Today: Proc., 4: 12641-12646.
36. Budihardjo, I., G.L. Morrison and M. Behnia, 2003. Development of TRNSYS models for predicting the performance of water-in-glass evacuated tube solar water heaters in Australia. Proceedings of the ANZSES Annual Conference, November 26-29, 2003, Melbourne, Australia.
37. Ghoneim, A.A., H.M. Shabana, M.S. Shaaban and A.M. Mohammedein, 2016. Performance analysis of evacuated tube collector in hot climate. Eur. Int. J. Sci. Technol., 5: 8-20.
38. Nie, X., L. Zhao, S. Deng and X. Lin, 2017. Experimental study on thermal performance of U-type evacuated glass tubular solar collector with low inlet temperature. Solar Energy, 150: 192-201.
39. Abd-Elhady, M.S., M. Nasreldin and M.N. Elsheikh, 2017. Improving the performance of evacuated tube heat pipe collectors using oil and foamed metals. Ain Shams Eng. J. 10.1016/j.asej.2017.10.001.
40. Felinski, P. and R. Sekret, 2017. Effect of a low cost parabolic reflector on the charging efficiency of an evacuated tube collector/storage system with a PCM. Solar Energy, 144: 758-766.
41. Sable, A., 2017. Experimental and economic analysis of concrete absorber collector solar water heater with use of dimpled tube. Resour.-Efficient Technol., 3: 483-490.
42. Martinez-Rodriguez, G., A.L. Fuentes-Silva and M. Picon-Nunez, 2018. Solar thermal networks operating with evacuated-tube collectors. Energy, 146: 26-33.
43. Iranmanesh, S., H.C. Ong, B.C. Ang, E. Sadeghinezhad, A. Esmaeilzadeh and M. Mehrali, 2017. Thermal performance enhancement of an evacuated tube solar collector using graphene nanoplatelets nanofluid. J. Cleaner Prod., 162: 121-129.
44. Naik, B.K., A. Varshney, P. Muthukumar and C. Somayaji, 2016. Modelling and performance analysis of U type evacuated tube solar collector using different working fluids. Energy Procedia, 90: 227-237.
45. Bellos, E., C. Tzivanidis, K.A. Antonopoulos and G. Gkinis, 2016. Thermal enhancement of solar parabolic trough collectors by using nanofluids and converging-diverging absorber tube. Renewable Energy, 94: 213-222.