WORLD COMET RESEARCH GROUP

International Journal of Modern Research in Science & Engineering
Vol. 4, No. 1, 2021
Doi. 10.67228/30716357/IJMRSE-2021PI9F1M
PP. 01-14

Original Article

Design and Development of a High-Efficiency Solar Thermal Collector

Rahul Mehta[1], Priya Kapoor[2]

[1]*Senior Software Engineer, Wipro Ltd., India.*

[2]*Business Analyst, Accenture, India.*

Received: 12-03-2020 Revised: 12-25-2020 Accepted: 01-01-2021 Published: 01-03-2021

ABSTRACT

Due to its capability to effectively convert solar radiation into useful thermal energy with a high efficiency and low environmental impact, solar thermal energy has become a very important element in sustainable energy systems. Solar thermal collectors are one of the several solar thermal technologies that are important to the performance of the systems, their reliability, and economic viability. In this paper, the design and development of a high-efficiency solar thermal collector will be discussed in an attempt to enhance the thermal performance besides reducing heat losses when these collectors are irradiated in various operating conditions. The design of the proposed collector includes an optimized absorber plate design, selective surface coating, better insulation design, and better heat transfer fluid flow design. An entire framework of thermal modeling, which is built on energy balance equations, is designed to forecast collector performance. The methodology involves the choice of material, optical analysis, thermal analysis, computational analysis and experimental analysis under standard test conditions. Efficiency indicators that include instantaneous efficiency, useful heat gain, and general heat loss coefficient among others are measured and also compared with other conventional flat-plate collectors. The findings indicate that the thermal efficiency is greatly enhanced especially when the temperature range is in the medium-to-high band, and the proposed design can therefore be utilized in domestic water heating, industrial process heating, and solar-assisted power generation. It was concluded in the study that design optimization on component level in addition to better heat transfer mechanisms can significantly improve solar thermal collector efficiency and longtime operation.

KEYWORDS

Solar Thermal Collector, Renewable Energy, Absorber Plate, Thermal Efficiency, Heat Transfer, Selective Coating.

Copyright © WCRG The Author(s) This article is distributed under a Creative Commons Attribution-Share A like 4.0 International License.

ISSN: 3071-6357
PP: 01-14.

1. INTRODUCTION

1.1. Background

The intense development of the global energy demand, as well as the increasing worries about climate change, greenhouse gasses, and the slowly fading fossil fuel deposits, have compounded the quest to find sustainable and environmentally-friendly energies. Solar energy is one of the different renewable energy products that can be utilized because of its huge supply, environmental friendliness and sustainability over time. It is therefore important to harness solar energy to minimize reliance on the conventional fossil-related energy systems and reduce their environmental health effects. Solar thermal technologies in this context have attracted considerable interest because they offer a direct and efficient method of converting incident solar radiation into usable thermal energy with a host of application such as domestic water heating, space heating, industrial process heat as well as solar-assisted cooling systems. The core of any solar thermal system is the solar thermal collector which plays the role of absorbing incident solar radiation and transforming the obtained energy into useable thermal energy. Despite the success that has been achieved in designing and developing solar collectors in the last few decades, the conventional flat-plate and evacuated tube solar collectors still have a number of technical constraints. Such difficulties are high thermal losses through conduction, convection, and radiation, narrow operating temperature limits and so they are limited in applicability, the materials and coatings used deteriorate significantly under extended outdoor operation, and poor heat transfer between the absorber surface and working fluid. These restrictions undermine the general efficiency of any given system and impede widespread implementation of the solar thermal technologies especially in the high-temperature and industry sectors. Supply of better geometry-based and more sophisticated materials perished with improved heat transfer are therefore, big motivational factors to devise better design solar thermal collectors to counter these deficiencies, thus elevating performances, resiliency, and usable viability. High-efficiency solar thermal collectors play a crucial role in both civil and residential applications due to their high efficiency, typically leading to reduced installation and maintenance expenses at the facility, along with decreased fuel costs.

1.2. Importance of High-Efficiency Solar Thermal Collectors

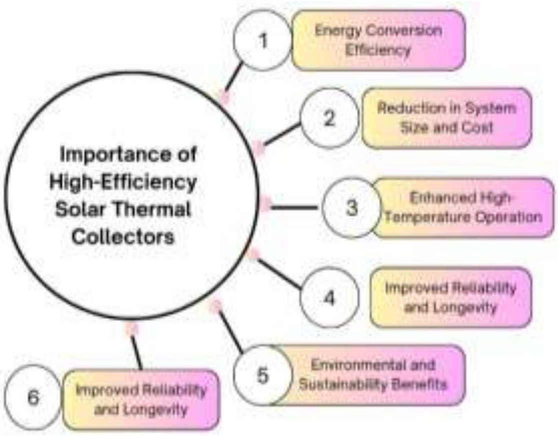

Fig 1 - Importance of High-Efficiency Solar Thermal Collectors

ISSN: 3071-6357
PP: 01-14.

1.2.1 Energy Conversion Efficiency

The high-efficiency solar thermal collectors are important in ensuring that the incident solar radiations are converted to useful thermal energy. Efficiency guarantees better use of the available solar resource and wastage is minimized and system output improved. This comes in especially handy in areas where solar access is limited or at times where the irradiance is low and can still be able to achieve a good thermal performance despite the sun being low.

1.2.2. Reduction in System Size and Cost

Increased efficiency is directly proportional to a smaller area of collectors needed to satisfy a specific thermal demand. This results in small system construction, less use of material and reduces cost of installation. Lower collector sizes are also beneficial in small domestic and commercial uses that need to be integrated with existing buildings and infrastructures, where solar thermal system is more cost effective and conveniently implemented.

1.2.3. Enhanced High-Temperature Operation

The collectors of high efficiency can be effectively used in high temperatures because of decreased thermal losses and enhanced heat movement by means. This increases their use beyond low temperature applications like water heating to medium and high temperature applications in the heating of industrial processes, absorption refrigeration and solar-assisted power generation

1.2.4. Improved Reliability and Longevity

High-efficiency collectors imply the usage of advanced materials, selective coatings, and optimization of thermal insulation which improve the performance stability in terms of durability and long-term support. The ability to reduce thermal stresses and minimize heat losses decreases the risk of degradation of materials and secure the steady performance of materials during the long time of functioning and save maintenance costs.

1.2.5. Environmental and Sustainability Benefits

Using high-efficiency solar thermal technologies, much less solar energy is needed to boost thermal performance resulting in a substantial reduction in the use of fossil fuels and related greenhouse emissions. Their mass adoption not only underpins the idea of global sustainability, but they also encourage the use of clean energy and also lead to long term energy security.

1.2.6. Economic and Industrial Relevance

Economically, the high-efficiency collectors take shorter payback periods and enhance the period of return. With some of the world on the industrial and commercial sectors that demand large amounts of energy, efficient solar thermal systems would result in huge operational cost savings, and competitiveness in addition to funding sustainable development programs.

ISSN: 3071-6357
PP: 01-14.

1.3. Design and Development of a High-Efficiency Solar Thermal Collector

The design and development of a high efficiency solar thermal collector aims at maximizing the amount of solar energy acceptance and reducing the thermal losses and maximizing the heat transfer to the working fluid. High production efficiency means that it is a process that needs a methodical approach that incorporates the use of sophisticated materials, effective geometry configuration, and proper thermal management interventions. Absorber plate is a vital constituent in this process, as it is the one that is in close contact with incoming solar radiation. High-thermal-conductivity surfaces made of copper or aluminum, together with selectively coated surfaces with high solar absorptivity and low thermal emissivity, enhance the capture and retention of energy much higher. Such finishes make such absorbers effective despite high temperature, as they minimize the radiative heat losses. It is also important that the heat transfer mechanism between the absorber plate and the working fluid is optimized. Through appropriate attachment of riser tubes to absorber surface, thermal contact resistance to the absorber surface is reduced and evenly absorb heat. Elaborate flow plans are implemented i.e. hybrid parallel-serpentine plans to equalize the pressure drop, residence time, and temperature distribution across the collector. This leads to a better heat removal factor and a better thermal performance. Proper efficacy of transfer of energy and consistency of operation is also brought by the selection of right working fluid and control of mass flow rate. The other significant consideration of high-efficiency collector design is to reduce thermal loss. Low-iron tempered glass increases the optical transmittance and high-density insulation in the rear and side of the collector reduces the conductive and convective losses. Structural design and sealing are also meant to help minimize the loss of edges and shelter the internal components against deterioration by the environment. Moreover, the collector casing is also designed to deliver mechanical strength, resistance to corrosion and durable nature to an outdoor operational environment. The analysis modeling and the validation of the development process are assisted by the experiment. The performance trends can be predicted through thermal energy balance and optical efficiency models and are used to optimize the design. The validity of these models is checked by experimental testing under controlled conditions which prove the efficiency of the offered design. Comprehensively, the integrated design and development approach is able to guarantee that the high-efficiency solar thermal collector meets high performance, dependability as well as appropriateness of both domestic, commercial and industrial thermal use.

2. *LITERATURE SURVEY*

2.1. Evolution of Solar Thermal Collector Design

The early solar thermal collectors were using simple flat-plate configurations comprised of blackened metallic absorption plates that were mounted underneath the covers of simple transparent glasses to capture sunlight. Although these early systems proved the fundamental possibility of solar thermal energy conversion, they had serious issues with heat losses and low lifespan. In the decades, the collector design has been developed to include the good glazing material, better absorber design, enhanced insulations, and production methods. Modern solar thermal collectors are appropriate in large quantities of domestic and industrial use due to the introduction of evacuated tube collectors, selective surface coating, and modular design which has greatly contributed to thermal efficiency and reliability in operation.

2.2. Absorber Plate Materials and Coatings

The plate used to absorb the light has a very important role when it comes to the thermal performance of a solar collector since it is the one that will transfer the incident solar radiation into useful heat. Copper and aluminum are highly preferred due to high thermal conductivity which drugs quick transfer of heat to the working fluid. Along with base materials, it is also noted that selective surface coating has been widely researched. These coatings are designed to have a large solar absorptivity (α) and small thermal emissivity (ε) hence the maximum energy absorption and the least radiative heat losses. When the elective surfaces are used to replace the traditional black paint surfaces, literature records significant efficiency improvements.

2.3. Heat Transfer Enhancement Techniques

Solar thermal research has been concentrated on increasing the heat transfer between the working fluid and the absorber plate. Methods to enhance the effective heat transfer of a fluid include the use of finned absorber plates, which enhance the effective heat transfer surface, and also turbulence promoters, which break up laminar flow and raise the convective heat transfer coefficient. Different tube designs such as serpentines and parallel flow types have been investigated in order to enhance uniform temperature and heat removal. In more recent times nanofluid-based working fluids i.e. in which nanoparticles are suspended in a traditional fluid have been used with some success in further improving thermal conductivity and overall collector performance although stability and cost issues still exist.

2.4. Thermal Loss Reduction Strategies

The conduction and convection of heat, as well as radiations to atmosphere are the major thermal sources of solar collectors. In a bid to reduce such losses, scientists have explored various design and material based approaches. The covers on the solar use low-iron glass to enhance solar transmittance as well as minimizing the reflective losses. Multi-layer insulation and sophisticated backing material assist in reducing conductive heat leakages especially when operating at very high temperatures. Other studies indicate that there is application of vacuum gaps or inert gas filling between covers in order to reduce convective losses. Also close design to minimise edge and frame loss has been found to lead to observable increased efficiency in the entire collector.

2.5. Performance Modeling and Testing Standards

Valid performance analysis of solar thermal collectors depends on standard test and model innovation. Globally accepted standards, including ISO (ISO 9806) and ASHRAE-based standards, give the same approach to calculating collector performance, heat loss coefficients, and incidence angle modifiers. Through these standards, the comparison of various collector designs becomes reliable as well as providing repeatability on the results of experiments. Such standardized tests make performance models based on them very useful in system simulation, optimization in design and in the prediction of energy yield over long-term.

3. METHODOLOGY

3.1. Design Configuration

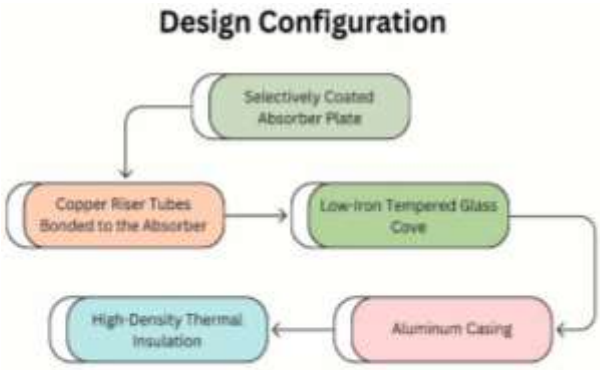

Fig 2 - This Flowchart Represents the Design Configuration

3.1.1. Selectively Coated Absorber Plate

The main element that captures incoming radiation of the sun and converts it to thermal energy is the absorber plate. In the proposed design, the selectively coated plate is an absorber which can accumulate solar energy to the full extent although minimizing the losses through heat. Its coating is selective and has high solar absorptivity but low thermal emissivity, that will promote the heat retention, increase the effectiveness of the collector in its entirety, and enable the system to function at elevated temperatures.

3.1.2. Copper Riser Tubes Bonded to the Absorber

Riser tubes made with copper are bonded well to the absorber plate so as to transfer heat effectively to the working fluid. Copper is chosen because it is of very good thermal conductivity, corrosives as well as being durable in the long term. The electrical connection of the tubes and the absorber plate is maintained properly so as to facilitate lack of any thermal contact resistance, allowing uniformly the extraction of heat and satisfying the thermal characteristics of the collector.

3.1.3. Low-Iron Tempered Glass Cove

A temperate glass cover with low iron is used that prevents the absorber plate and receives a maximum amount of sunlight. The low concentration of iron enhances optical transmittance that guarantees that the solar energy attains the absorber surface. Tempered glass is also useful in thermal stress resistant with high mechanical strength resulting in an improved durability and safety of the collector during changing environmental conditions.

3.1.4. High-Density Thermal Insulation

The back and sides of the collector are thermal insulated with high density to minimize the heat rejection by the conduction and convection. Mineral wool or polyurethane foam are among insulation materials used in the preservation of a higher operating temperature and enhanced energy efficiency. Proper insulation allows the heat captured to be held in the system and it is moved to the working fluid and not to the external environment.

3.1.5. Aluminum Casing

The aluminum casing constitutes the external composition of the solar collector, which supports it and shields the environment. Aluminum is not heavy, non-corrosive, and can be fabricated easily thus it can be used in the outdoors over a long period. The casing also aids in minimizing edge losses and provides internal components with sufficient protection by bringing them together appropriately and screaming them in place, leading to the overall strength and dependability of the collector system.

3.2. Thermal Energy Balance

An energy balance method can also be used to determine the thermal performance of a solar thermal collector and relates the useful heat gain to the amount of absorbed solar energy and the heat losses to the surroundings. The energy gain per m^2 that is actually absorbed by the collector and can be used to gain heat by the working fluid is the useful heat gain of the collector, which is denoted by Qu. It is given as = collector area (Ac) x heat removal factor (FR) x the available energy (net) after subtracting thermal losses. This expression can be boiled down to a single sentence which is: the useful heat gain is proportional to the degree of solar radiations absorbed on the collector surface as well as the efficiency with which this energy is extracted by the circulating fluid. The absorbed solar radiation (S) is the amount of incident solar energy, which is carried through the plate of glass and absorbed into the absorber plate through the selective coating. This is absorbed energy that would be the power input of the collector. Not every energy absorbed is, however, utilized in useful heat, some being set free to the environment in form of conduction, convection, and radiation. All these losses can be captured by the overall heat loss coefficient (UL) that measures the rate of heat loss per unit area per unit temperature difference between the collector and ambient environment. The (Tin -Ta) term is described as the difference between the temperature of the inlet fluid and that of the ambient air. The higher this temperature difference, the higher the thermal losses in which the collector would lose a lot of the heat that would otherwise be utilised. The heat removal factor (FR) expresses the efficiency of which the working fluid can take the heat off of the absorber plate. It includes fluid flow rate effect, thermal conductivity of material and in the collector heat transfer effects. On the whole, this thermal energy balance equation gives a useful representation of the behavior of collectors. It indicates an interaction of the absorbed solar energy and a loss of heat, as well as fluid extraction of heat, and it is a key-tool of analyzing, designing and optimizing solar thermal collectors, under changing operating and environmental conditions.

3.3. Optical Efficiency

One parameter that defines the efficiency of a solar thermal collector is optical efficiency which is the measure of how efficiently the incoming solar radiation is converted by a solar thermal collector into absorbed energy of the absorber surface. They have absorbed solar radiation, denoted

ISSN: 3071-6357
PP: 01-14.

by S, which is indicated as the product of incident solar radiation (Gt) and collector optical properties, which is the product of transmittance and absorptance (. Simply, this relationship implies that only a small part of the solar energy falling on the collector aperture gets eventually absorbed and can be used to transform into thermal energy.The incident solar radiation (Gt) is a summation of the solar energy per unit surface area of the collector surface. This value is affected by geographical position, time of the day, weather, the tilt and direction facing the collector. Not all of these incident energies make it to the absorber plate though. When the solar radiations are passing through the glass cover, some of the light is reflected and absorbed by the glass cover and the rest is transmitted. Transmittance (τ) of the glass cover quantifies the proportion of the incident radiation that manages to go through the glazing and to the surface of the absorber. Low-iron glass with high quality is usually employed to get the maximum transmittance and to reduce optical losses. As soon as the radiation which is sent through arrives at the plate of the absorber, the magnitude of the absorber depends on the absorptance (al) of the absorber surface which has to absorb the radiation that comes across instead of reflecting it. Absorber surfaces are selectively coated to be able to attain a high level of absorptance at the solar spectrum with the result that a large portion of the radiated radiation is transformed into heat. The product (τa) is thus the aggregate optical performance of the collector system, which is a combined effect of the properties of the glazing and the absorber surface. Probably, in practice, optical efficiency is a direct measure of thermal efficiency of the collector, especially in bright sun conditions. Efficiency of the optical can be improved significantly by improving the product of glazing materials, surface, and cleanliness of collectors. Therefore, the optical efficiency formulation would form a basic foundation on determining and optimizing the design of a solar collector since it would give the upper limit of the probable energy input that can be used as useful heat prior to the potential losses due to heat loss.

3.4. Flow Arrangement Optimization

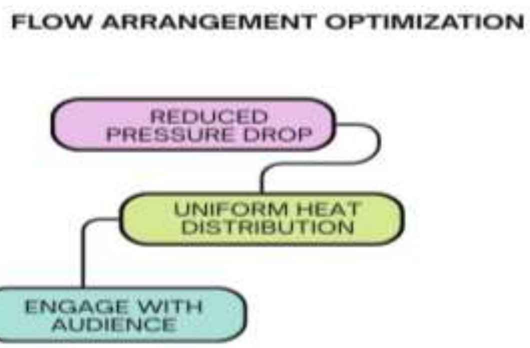

Fig 3 - This Flowchart Represents the Flow Arrangement Optimization

3.4.1. Reduced Pressure Drop

The parallel-serpentine hybrid flow design has been developed in order to reduce the total pressure drop inside the solar collector. This is byetained by permitting the working fluid to pass through a variety of parallel routes through counterbalanced serpentine intersections, such that the hydraulic resistance is lower than in fully serpentine designs. Reduced pressure difference reduces the amount of power required to operate the pumps, thereby increasing the efficiency of the system and less the energy used in its operation especially in forced circulation systems.

3.4.2. Uniform Heat Distribution

This mixed flow pattern encourages the distribution of heat to be smoother in distribution all over the absorber plate. Parallel flow sections aids in the even distribution of the fluid, to avoid a localized cause of overheating and temperatures grading as is the case when using a single-path serpentine structure. Even heat distribution leads to a higher thermal stability, minimization of thermal stresses on the investigator plate, and higher durability and reliability of the collector, on the whole.

3.4.3. Improved Heat Removal Efficiency

The parallel and serpentine flow is designed to increase the efficiency of heat removal since residence time and flow uniformity are balanced. The serpentine-shaped sections provide higher fluid contact time with the absorber surface that is being heated, and the parallel-channels provide the ability to efficiently extract the heat of various parts of the collector. The design of this flow stream enhances it to cool faster by ratio of heat and can afford more proportion of the absorbed solar energy to be utilized and provide higher useful heat output under the fluctuating operating circumstances.

3.5. Experimental Procedure

Solar thermal collector experimental assessment would be at steady-state operation conditions in order to obtain valid and repeatable output measures. The steady-state conditions are created with a constant rate of mass flux of the working fluid, constant solar irradiance, as well as almost constant ambient temperature throughout a given test period. The system can be given a time before data collection that would enable the system to establish thermal equilibrium to reduce variations in the inlet and outlet temperature. There is a necessity of this stabilization period so that the measured thermal parameters reflect well the exact operating behavior of the collector. The rate at which the mass of the working fluid should move is measured by a calibrated flow control valve and was continuously measured with a flow meter to ensure that one maintains the same hydraulic conditions in the experiment. The amount of the sun radiation falling on the collector surface is gauged by a pyranometer placed in the same plane as the collector so that the gathered solar radiation can be reflected in the pyranometer. The ambient temperature is measured by shielded temperature sensors that are not exposed to direct sunlight in order to sidestep the error of measurement that could have occurred during radiative heating. Calibrated thermocouples or resistance temperature detectors (RTDs) are used to measure the temperature at inlet and outlet of the collector and are installed carefully in order to ensure that they are in good thermal contact with the fluid. These measurements are important in finding out the increase in temperature of the working fluid and, hence, the amount of helpful heat collected by the collector. All sensor outputs are attached to a data acquisition system which measures readings at specific times such that under steady-state conditions, time averaged values can be calculated. The data obtained undergoes calculations that help in measuring important performance parameters that include useful heat gain, instant efficiency and heat loss coefficients. Uncertainty analysis of an experiment is also carried out to determine the reliability of the experimental results. The effectiveness of the proposed solar thermal collector would be effectively evaluated through studying of experimental methodology in the form of a controlled and systematic experimental procedure that would be compared with the accepted standards of testing and theoretical expectations.

4. RESULTS AND DISCUSSION

4.1. Thermal Efficiency Analysis

Thermal efficiency of a CdTe Thermal efficiency guarantees thermal neutrality in a high-power CdTe system through minimization of the circulating cooling system volume and the amount of circulating water.A major parameter of solar thermal collector performance is thermal efficiency, which is expressed as the degree to which incident solar energy is effectively turned into useful heat. Used in this research, the collector efficiency, denoted by eta, is a ratio of the useful heat gain (Qu) to the total solar energy received on the collector aperture area (AcGt). Normally speaking, this phrase is the measure of the efficiency that the collector has in taking the solar radiation present and using it to increase the temperature of the working fluid. The greater the efficiency value, the improved conversion of energy and reduced losses of heat in general.The useful heat gain (Qu) is calculated through the experimental results of the mass flow rate and between the temperature of the inlet and outflow of the collector. An measured pyranometer (calibrated) was used to measure incident solar radiation (Gt) and it was also maintained constant during the tests,whereas the collector area (Ac) is not effective in these tests. When these parameters are added together, the instantaneous thermal efficiency of the collector then is computed under various operating conditions. This method is capable of making a direct comparison to the proposed design and the traditional flat-plate solar collector.According to the results of the experiment, it was established that the proposed collector can have a high thermal efficiency, especially when operating at high temperatures. A number of design additions such as adoption of selectively coated plate acts as an absorber, better flow arrangement as well as good thermal insulation contributed to this. The conventional flat plate collectors usually lose much of their efficiency, at higher temperatures of the inlet fluids, as more heat is conducted to the surroundings. Contrarily, the designed one has a higher heat retention and effective heat removal, which minimizes the effects of heat losses.Moreover, flow arrangement will be optimized with respect to having an even temperature field over the absorber, which results in a greater heat transfer factor and better overall energy transfer to the working fluid. This causes the efficiency curve of the proposed collector to be slower in decreasing with an increase in the temperature difference between the ambient air and the collector. These results confirm that the proposed design has a better thermal performer and can be used in any application that needs high operating temperature than other conventional flat-plate solar thermal collectors.

4.2. Heat Loss Coefficient Evaluation

The overall heat loss coefficient is also a sensitive parameter which defines the degree of thermal losses of a solar thermal collector to the surrounding. It considers summative heat losses owing to the conduction across the insulation and casing, rightward diffusion of heat to the surrounding air, and radiations of the absolvers and cover surfaces. The overall heat loss coefficient is found to be reduced dramatically in the current study due to the better design of insulation system and the selectively coated absolver surface. A reduced heat loss factor is a direct plus to an improved thermal efficiency level, especially in elevated operating temperatures.Students should employ the use of high-density thermal insulation in the rear and side walls to the collector so that the conductive heat losses are minimized significantly. The insulation is used to prevent heat loss through the collector structure to ensure higher energy is absorbed by the absorbers and that the energy lost to the environment is minimized. Moreover, close sealing and structural design minimizes edge loss which can be an insignificant factor to overall heat loss in traditional flat-plate collectors, but can be of significant contribution.The selectively coated absorber surface also cuts the radiative heat emission to a minimum and thus adds further thermal losses reduction. Although the coating has a high absorptivity of the solar spectrum, it also has low emissivity of the infrared spectrum. Such a selective mechanism highly suppresses radiative heat loss of the absorber particularly when it is hot in operation.In turn, differences in temperature between the absorber and the ambient medium use a smaller influence on the total heat loss coefficient.It has been experimentally observed that the combined effect of selective coating and enhanced insulation would result in a more stable thermal performance at a wide range of operating conditions. The proposed design shows a significantly reduced efficiency drop rate over increase in temperature difference than conventional collectors having typical black coatings and intermediate levels of insulation. This decrease in the total heat loss coefficient supports the efficiency of the developed thermal loss mitigation measures and shows the applicability of the proposed collector in situations when there is a need to operate the heat collector under high temperature conditions.

4.3. Comparative Performance Assessment

Table 1: Comparative Performance Assessment

Parameter	Conventional Collector	Proposed Collector
Peak Efficiency (%)	55	72
Heat Loss Coefficient (W/m²K)	6.5	4.2
Operating Temperature (°C)	60	90

4.3.1. Peak Efficiency (%)

It was found that the proposed collector has a much greater peak efficiency of 72 versus 55 in the proposed flat-plate collector. This enhancement shows that the proposed design is more efficient in transforming incident solar radiation to the utility of thermal energy. This improvement in efficiency can be explained by the engagement of a selectively coated absorber plate, streamlined flow configuration and less thermal loss. Increased peak efficiency also means that performance will be good during a time of high solar irradiance resulting in an increase in energy output throughout the time of operation.

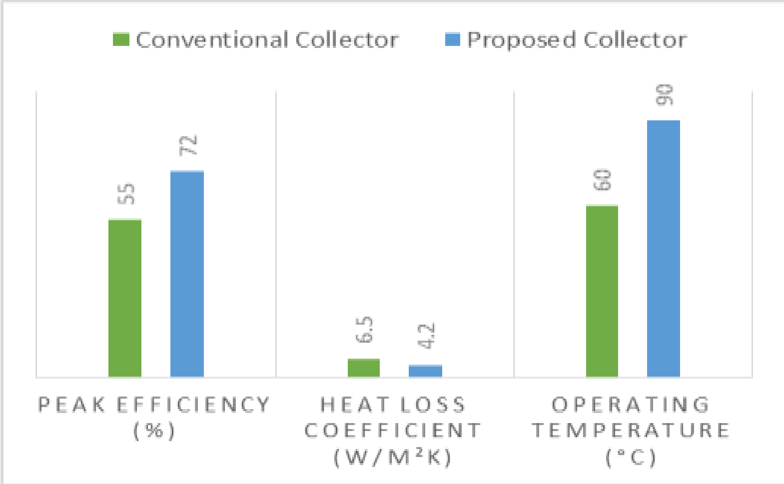

Fig 4 - Comparative Performance Assessment

4.3.2. Heat Loss Coefficient (W/m²K)

It is seen that; the proposed collector has a significant decrease in the overall heat loss coefficient; its value is 4.2 W/m 2K against that of the conventional collector 6.5 W/m 2K. This reduced heat loss coefficient represents the performance of better insulation materials, better sealing and selective surface finish, in reducing heat losses through conductive, convective, and radiative means. The lower heat loss enables the collector to store the absorbed energy better particularly during high temperature polarites between the collector and the ambient surroundings.

4.3.3. Operating Temperature (°C)

The highest operating temperature of the suggested collector is up to 90 ° C, compared to the conventional collector which is normally restricted to about 60 Degree Celsius. This increased operating temperature capability proves the appropriateness of the proposed design to the applications that need medium-temperature heat, like the heating of industrial processes or the absorption cooling system, etc. None of the thermal stability should be underestimated because the low heat loss coefficient and high heat removal efficiency mainly result in the high-temperature stability of operation without severe performance reduction.

4.4. Discussion

The results of the change in thermal efficiency of the proposed solar collector could be mostly explained by the combined actions of the improved absorber design, improvement in thermal losses, and the enhancement in heat transfers. The plate with pre-selected coating and acts as one of the main factors in enhancing the quantity of solar radiation that is converted to useful thermal energy. With a high solar absorptivity and low thermal emissivity, the absorber manages to realize a high degree of incident radiations capture and reduce heat losses through radiations, especially where high operating temperatures are considered. This cherry picking gives the collector the possibility to keep higher absorber temperatures without a respective increase in heat dissipation to the surrounds.Decreased thermal usages also play a part in the improvement of the final performance. Conductive and convective heat losses are highly restricted by using thicker thermal insulation on the rear and sides of the collector. There is also the use of a low-iron glass cover which enhances optical transmittance and minimizes theReflection losses. These features of the design reduce the total heat loss coefficient, thereby letting the collector store more of the absorbed energy. This is particularly critical at high inlet fluid temperatures where the actual efficacy of conventional collectors usually declines very rapidly.Enhanced performance of the collector is also improved because of improved heat transfer mechanisms. The parallelserpentine hybrid flow arrangement is optimized to provide parameter balance of heat extraction throughout the absorber surface and minimize local figures of temperature variation.

The bonding between the copper riser tubes and the absorber plate is done efficiently in order to create minimal thermal contact resistance with the objective of enabling heat transfer to the working fluid to increase. Consequently, there is an enhancement in heat removal factor giving rise to increase in useful heat gain under equal amount of solar input.The combination of these effects actually produces a collector which does not only have a higher peak efficiency but more importantly has a stable performer in the broadest range of operating conditions. By and large, the findings show that innovative incorporation of superior materials, thermal loss reduction measures, and optimized flow design can enhance the functionality of flat-plate solar thermal collector to a great extent, which makes them viable in applications of elevated temperatures and more challenging applications.

5. CONCLUSION

This paper has managed to present the design and development of a high-efficiency solar thermal collector as well as its entire performance assessment with high thermal and optical parameters. The proposed collector delivers high thermal-efficient performance over a massive enhancement over thermal efficiency of traditional flat-plate solar collectors through the integration of an optimized absorber geometry, selectively coated absorber surface, and enhanced thermal insulation. All of these design improvements, in turn, allow the solar radiation to be better absorbed, heat losses to be lower, and the heat transfer to the working fluid easier, leading to the better performance of the whole system.This is due to the optimized absorber geometry which is complemented by an efficient bonding of copper riser tubes and is such that uniform heat distribution and efficient heat removal can be achieved throughout the collector surface. Selective surface coverings of high absorptivity and low emissivity are important in achieving maximum energy benefit and reducing currently radiative loss, especially in the operating conditions of high temperatures. Also, the inclusion of high density of insulation materials and a well-formed casing system can greatly eliminate conductive and convective heat loss and as a consequence, the heat loss coefficient will be lowered and the reliability of the collector under different weather conditions will increase.An overall thermal energy balance model was created in order to forecast the performance of the collector in various operating conditions. The model takes into consideration the optical efficiency, mechanisms of heat loss, and fluid heat removal properties which give a realistic account of the behavior of the collector. The results of experimental studies carried out in steady-state through the control conditions indicate a high level of correlation with the determined trends, which confirms the validity and validity of using the created thermal model. The correlation of the results of theory and experiment verifies the strength of the design approach taken in this paper.The enhanced performances and ability to operate in a high temperature allow the proposed collector to be used in a broad spectrum of applications such as domestic water heating, commercial space heating and industrial process heat generation. It can also be used in higher temperature applications and consequently its potential is expanded to more complex uses like absorption cooling and solar-assisted industrial systems.The future studies can be aimed at analyzing long-term durability and reliability of the selective coatings and insulation materials in the case of the outdoor long-term exposure. More open measures can be performed by use of nanofluid-containing working fluids, which will be combined with the others to enhance the nature of the heat transfer. Moreover, the field implementation and techno-economic assessment are suggested to undertake on a large-scale field and test the feasibility of commercial implementation and also to determine the viability of the experimental system of solar thermal collector in reality.

REFERENCES

[1] Duffie, J. A., & Beckman, W. A. (2013). Solar Engineering of Thermal Processes (4th ed.). John Wiley & Sons.
[2] Kalogirou, S. A. (2004). Solar thermal collectors and applications. Progress in Energy and Combustion Science, 30(3), 231–295.
[3] Garg, H. P., & Prakash, J. (2000). Solar Energy: Fundamentals and Applications. Tata McGraw-Hill.
[4] Sukhatme, S. P., & Nayak, J. K. (2017). Solar Energy: Principles of Thermal Collection and Storage (3rd ed.). McGraw-Hill Education.
[5] Hottel, H. C., & Woertz, B. B. (1942). Performance of flat-plate solar-heat collectors. Transactions of the ASME, 64, 91–104.
[6] Selvakumar, P., Somasundaram, P., & Thirumalai, R. (2014). Performance analysis of flat plate solar collector using nanofluids. Energy Conversion and Management, 88, 372–381.
[7] Saidur, R., Leong, K. Y., & Mohammad, H. A. (2011). A review on applications and challenges of nanofluids. Renewable and Sustainable Energy Reviews, 15(3), 1646–1668.
[8] Tiwari, G. N., & Sahota, L. (2017). Advanced Solar-Distillation Systems. Springer.
[9] Tripanagnostopoulos, Y., Souliotis, M., &Nousia, T. (2000). Solar collectors with colored absorbers. Solar Energy, 68(4), 343–356.
[10] Kumar, S., & Mullick, S. C. (2010). Wind heat transfer coefficient in solar collectors. Solar Energy, 84(6), 956–963.
[11] Zambolin, E., & Del Col, D. (2010). Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors. Solar Energy, 84(8), 1382–1396.
[12] Chow, T. T. (2010). A review on photovoltaic/thermal hybrid solar technology. Applied Energy, 87(2), 365–379.
[13] Herrando, M., Markides, C. N., &Hellgardt, K. (2014). A UK-based assessment of hybrid PV and solar-thermal systems. Applied Energy, 122, 288–309.
[14] International Organization for Standardization (2017). ISO 9806: Solar Energy Solar Thermal Collectors Test Methods. Geneva, Switzerland.
[15] ASHRAE (2020). ASHRAE Handbook—HVAC Systems and Equipment. American Society of Heating, Refrigerating and Air-Conditioning Engineers.