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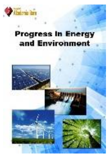

Review Article

# Evacuated tube solar air collectors: A review of design configurations, simulation works, and applications

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Nabila Sulaiman*,[1], Sany Izan Ihsan[1], Syed Noh Syed Abu Bakar[1], Zafri Azran Abdul Majid[2], Zairul Azrul Zakaria[1]

[1] Department of Mechanical Engineering, Kulliyyah of Engineering, International Islamic University Malaysia (IIUM), Gombak, 53100 Kuala Lumpur, Malaysia
[2] Department of Audiology and Speech-Language Pathology, Kulliyyah of Allied Health Science, International Islamic University Malaysia (IIUM), 25200 Kuantan, Pahang, Malaysia
* **Correspondence email:** nabilaiium@gmail.com

## Abstract

One of the primary components of solar energy utilization systems is evacuated tube solar air collectors (ETSACs). The irradiance is absorbed by these collectors, which is then transformed into thermal energy at the absorbing surface before being transmitted to the air passing through the collectors. This type of collector outperforms flat plate collectors in terms of reducing heat loss through conduction and convection and also during cloudy days; thus, ETSACs are the most preferred collectors to be applied for space heating, crop drying, and industrial applications. This review focuses on a summary of design configurations, simulation works, and applications of ETSACs in order to understand the influence of the thermal performance of ETSACs so that these collectors can be applied more effectively. Studies on the use of nanofluids as thermal performance enhancers and phase change materials as thermal storage media can be considered to enhance the thermal performance of ETSACs.

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## 1 Introduction

Climate change and global warming have been environmental concerns since the 19th century [1]. Both issues can put lives at risk and affect human health in various ways, resulting in illness and death from increasingly frequent extreme weather events [2]. It is inevitable because the climate is changing faster than nature can adapt [3]. Many renewable energy sources have been proposed, such as wind energy, hydro-turbine energy, and geothermal energy, and the most popular is solar energy because it is inexhaustible, free, and abundantly available, as well as environmentally friendly [4]. As the rate of solar energy falling on the Earth's surface is 120 × 105 W, the amount of energy received by the Earth from the sun in a single day can supply all of the world's energy needs for more than 20 years [5]. In addition, solar energy has a small impact on the environment. The benefits of solar energy are favorable in several ways, such as ease of usage or harvest, less overall costs, and versatility [6].

Solar radiation can be converted into thermal energy using various solar conversion devices. A solar collector is used to collect solar radiation in the solar thermal energy conversion system, which converts solar radiation into heat [7]. Heat energy is one of the options to meet the energy requirements of many applications in the process industries. Hence, a solar thermal energy system is one of the interesting possibilities for producing thermal energy for heat processing applications. For small-scale applications like space heating, cooling, water heating, heat for process industries, and power production, there is a significant opportunity to use solar thermal energy systems instead of conventional energy sources [8].

A solar collector is the primary component of solar conversion devices, which transform photons into thermal energy in any solar system [9]. The incoming solar energy is absorbed by heat exchangers called solar collectors, which then convert the solar energy into heat before transferring it to the working fluid [10]. There are two types of solar collectors: concentrating and non-concentrating. Concentrating collectors obtain solar radiation by reflection or refraction using mirrors or lenses and can be divided into non-imaging and imaging categories, depending on whether the image of the sun is focused at the receiver or not, whereas non-concentrating collectors use the same area for intercepting and absorbing solar radiation, are fixed in place, and do not track the sun [11]. An evacuated tube solar collector, which is used in most applications due to its high efficiency, is one of the solar collectors that is permanently set in place and does not track the sun [12].

Evacuated tube solar collectors (ETSCs) are straightforward devices that absorb the sun's energy and transmit heat to a working fluid, such as air, water, or other working fluids [13]. It has been demonstrated that a selective surface and a better convection suppressor may work well together to perform satisfactorily at temperatures higher than 50 °C [14]. A thermal energy storage tank or a load receives the solar energy captured during the day, at night, or during overcast days via the solar working fluid.

Additionally, compared to flat plate collectors, evacuated tube collectors have a greater capacity to capture solar energy [15]. This is due to the compressed vacuum that the two glass envelopes around it, which at high operating temperatures, significantly reduces conductive and convective heat loss [16]. Moreover, the use of efficient selective coating material on the inner tube absorber surface with a unique selective coating, such as aluminum-nickel, has better solar heat absorption and negligible heat reflective qualities [17]. Despite their principal use in solar collector components for commercial solar water heaters, one-ended evacuated tubes have recently been used as solar air heaters in suggested arrangements [18].

A thorough literature assessment is undertaken in this review article to summarize studies on evacuated tube solar air collectors (ETSACs). Subsequently, a comparison and evaluation of thermal performance in terms of design configurations, simulation works, and applications are presented in this paper. It may be beneficial in determining their current state of the art, any gaps in the knowledge base, and ways to enhance ETSAC performance. As listed in Table 1, several reviews on ETSCs have previously been published. This study of design configurations, simulation efforts, and implementations of ETSACs will bring new values and information to those already present.

**Table 1** Objectives of review papers related to evacuated tube solar collectors.

| Review Papers | Objectives of Review Papers |
|---|---|
| Strategies to improve the thermal performance of heat pipe solar collectors in solar systems: A review [10] | Summary of all the anticipated strategies to enhance the thermal efficiency of different industrial, domestic, and innovative heat pipe solar collector systems. |
| Applications of evacuated tubes collector to harness the solar energy: A review [19] | Evacuated tube collectors are used for many different applications, including solar water heating, solar drying, solar air heating, and solar desalination, and they have been shown to be the most effective equipment for solar thermal applications. |
| A comprehensive study on the progressive development and applications of solar air heaters [20] | A thorough analysis of the literature on the development of solar thermal air heating systems, as well as their history, foundations, and most recent advancements. |
| Solar-thermal driven drying technologies for large-scale industrial applications: State of the art, gaps, and opportunities [21] | Guidance for future research and innovation on large-scale industrial solar thermal-driven drying technologies by defining the state of the art, gaps, and opportunities. |
| Global advancement on experimental and thermal analysis of evacuated tube collector with and without heat pipe systems and possible applications [22] | A discourse of the advancement, various types of evacuated tube collectors, and their low/medium temperature applications. |

| | |
|---|---|
| Review of thermal performance and efficiency in evacuated tube solar collector with various nanofluids [23] | A summary of recent studies on the effectiveness of ETSCs utilizing different nanofluids. |
| A thermodynamic review of solar air heaters [24] | The advancements of aspects for solar air heating systems since 1877 up to now, with the cutting-edge of some novel patents of solar air heaters. |
| An up-to-date review on evacuated tube solar collectors [25] | A review of detailed study of ETSCs having heat pipe and direct flow. |
| Performance investigation of evacuated tube solar heating system: A review [26] | A summary of the research work on evacuated tube solar heating systems, as well as their use and applicability for different solar thermal engineering systems that have been studied by different researchers. |
| Development on evacuated tube solar collectors: A review of the last decade results of using nanofluids [27] | Effects of nanofluids on the performance of ETSCs. |

## 2 Overview of evacuated tube solar air collectors

Evacuated tube solar air collectors are one of the solar collectors for air heating and do not need particular attention to temperatures below 0 °C. Heat may be applied to air at any temperature without causing high pressures or leaking in air collectors, and also without causing any harm. When compared to evacuated tube solar water heaters, ETSACs offer the advantages of less leakage [20], inexpensive cost [24], simple construction [28], and less corrosion [29]. As they use less material, ETSACs are quite popular among all heating systems, especially in space heating and food and crop drying [30]. Furthermore, as air is directly employed as a working fluid, the number of system components required is reduced.

However, low heat transfer capacity and thermal conductivity [31], low convective heat transfer coefficient, and substantial heat loss to the environment [32] between the absorber plate and fluid moving in the tube result in the poor thermal efficiency of ETSACs [20]. By enhancing the heat transfer rate, ETSACs can be more efficient in solar energy utilization systems and thermal efficiency [29] and can be regarded as an environmentally benign product as they can prevent 73 kg/month of carbon dioxide ($CO_2$) from entering the atmosphere [33].

As a result, researchers have endeavored to learn more about ETSACs. The efficiency of solar air heaters like ETSACs can be greatly increased by making changes to the design and construction [34], using heat transfer enhancement devices like vortex generators [35–37], adding roughness to the absorber plate [38–42], using phase change materials (PCMs) [43–47], and using nanofluids [48–52].

Absorber and collector are the two main parts of an ETSAC. The absorber will take heat from the collector and become heated as solar radiation hits the surface of the collector tube. Each evacuated tube is made up of two concentric glass tubes constructed of borosilicate glass. The outer tube is transparent for a little reflection, and there is a vacuum of 5 × 102 Pa between the tubes. Aluminum-nickel/aluminium (Al-Ni/Al) coating is installed to the inner tube to improve solar radiation absorption [17]. The tube will receive warm air to be applied as an energy source. Fig. 1 shows the scholarly works overtime for ETSACs from 2003 until 2023 accessed from lens.org on 28th March 2023. The pattern of the demand for ETSACs is still growing and there is potential for further exploration.

## 3 Design configurations of evacuated tube solar air collectors

Previous research has shown that design configurations have a significant impact on the thermal performance of ETSACs, which can be categorized into the geometry of the absorber, modification of flow passages, number of passes, and external aid based on the studies conducted.

### 3.1 Geometry

Much research has been conducted on the design of ETSACs. Kim and Seo [53] evaluated the effectiveness of solar collectors with four different shapes of absorber tubes. The four models of different absorber shapes are as follows: Model I with two strip-type fins attached on the opposite sides of the circular tube surface, where the fins are wide enough to be tightly fitted inside the glass evacuated tube, Model II with circular fins inside the U-tube absorber and two copper tubes are welded on both sides of copper circular fins, Model III with two copper tubes welded on both sides of the wide copper plate and are connected with the U-tube absorber, and Model IV with a rectangular duct used for the U-tube absorber and two copper tubes are welded on both sides of the inner surface of the rectangular duct. By comparing with the numerical model of a single standard collector tube for validation, Model III resulted in the highest efficiency when the incidence angle was small. However, higher efficiency could be observed for Model II when the incidence angle of solar irradiation increased. Furthermore, the diffuse irradiation and shadow effect caused by the subsequent tube must also be considered to have a more accurate performance assessment. Model III performed the best across the board for all ranges of incidence angles. An assessment of the thermal performance of various collector tube center distances was carried out to explore the effect of center distance on thermal performance. As a result, as the diameter of the collector was constant, the center distance increased, and fewer collector tubes were fitted. Consequently, the absorbing area shrunk significantly, and the thermal performance worsened.

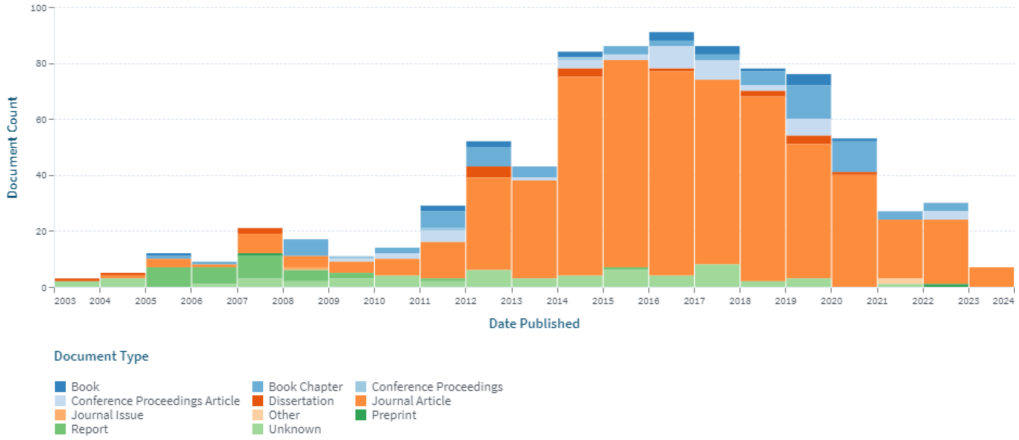


**Fig. 1** Scholarly works overtime for evacuated tube solar air collectors.

Supankanok et al. [54] modified the inner structure of the evacuated tube to enhance heat transfer from copper heat pipe to aluminum fins by adding stainless steel scrubbers to the evacuated tube's surface area for heat conduction, where the efficiency increased by 34.96%.

Kumar et al. [55] investigated the thermal performance of one-ended ETSACs experimentally throughout the winter season at NIT Kurukshetra, India. The maximum temperature difference between the outlet air and the inlet air at a solar intensity of 904 W/m2 was found to be 72.7 ℃ with a flow rate of 5.06 kg/h and length of 0.83 m. In this experiment, evacuated tubes were used to produce hot air corresponding to different lengths of directional aluminum tubes without using any intermediate fluid.

Naik et al. [56] evaluated the performance of U-type evacuated tube solar collectors using different working fluids of aqueous lithium chloride solution (LiCl-$H_2O$), water, and air via mathematical modeling. The results showed that collector length, working fluid flow rate, and solar intensity have a major impact on collector performance. Nevertheless, when compared to air and LiCl-$H_2O$ solution in this test of various working fluids, the results indicated that water has the maximum quantity of heat energy absorption capability.

Ataee and Ameri [57] modeled all-glass evacuated solar collector tubes with coaxial fluid conduit for T-type and H-type models with forced convection flow using air and $CO_2$ as working fluids. The effects due to changes in the properties and design parameters (i.e., mass flow rate, solar radiation intensity, inlet temperature, ambient temperature, optical efficiency, and length of the delivery tube and absorber tube) on the air and $CO_2$ temperature distribution in the tube collector were investigated. The outcome showed that the H-type model outperformed the T-type model in terms of output flow temperature and energy efficiency for both air and $CO_2$ as working fluids.

Paradis et al. [58] analyzed how environmental and operational factors affect the performance of the evacuated glass tube with open ends based on the developed thermal and experimental models. They compared the simulation model with the experimental model for validation purposes and discovered that the primary factor determining the performance of solar air heaters is the mass flow rate of air. When the air flow rate increased by more than 10 m3/h during the investigation, a turbulent effect was produced, resulting in an increased heat transfer coefficient. Subsequently, as the air flow rate increased to 40 $m^3$/h, the thermal efficiency remained constant at 70% while convective and radiative heat losses decreased.

Dabra et al. [59] evaluated the effect of tilt angles on the thermal performance of all-glass ETSACs experimentally. The set-up consists of a header with 15 evacuated glass tubes, each with one end placed on a platform that can be adjusted, connected to a heat exchanger, and exposed to the sun for 8 hours. The tests determined that a 30° tilt angle of collectors with a reflector performed better thermally than either a 45° tilt angle with or without reflector. Furthermore, the thermosyphon phenomenon within the evacuated tubes did not improve by increasing the collector tilt angle.

A solar air heater with integrated collector storage employing evacuated tubes as solar absorbers and paraffin as a thermal storage medium was proposed by Wang et al. [60]. In the proposed system, flat lap joint-type micro-heat pipe arrays act as heat conductors, transferring either the heat from the thermal storage tank or the solar energy absorbed by the evacuated tubes to the air flow channel. According to the findings, the charging and discharging efficiency (i.e., thermal storage and released efficiency) were 67.5% and 98.5%, respectively. When the air flow rate was 240 m3/h and the input temperature was 15 °C, the highest mean extraction power was 1,268.8 W.

Through experiment and numerical modeling, Wang et al. [61] developed a unique transparent-vacuum glass tube solar air collector consisting of micro-heat pipe arrays (MHPA), selective absorption films, and transparent-vacuum glass tubes. The collector's pressure loss was less than 20 Pa, and its average efficiency could reach 82.7%.

### 3.2 Modification of flow passages

Mehla and Yadav [62] compared and analyzed the performance of standard, copper coil, and circular fin headers of one-ended evacuated tubes coupled with latent heat storage device of PCMs of acetamide with air as its working fluid experimentally. Over the course of 16 h, the thermal performance of the ETSACs was assessed for both daytime and nighttime. Solar radiation serves as the heat source during the day, while the PCM serves as the heat source at night. When compared to a standard solar evacuated tube collector, they discovered that the outlet temperature in an ETSAC employing circular fins and copper coil performed better.

Liang [63] proposed experimental research on the all-glass ETSACs inserted with metal pipes. The results showed that small changes in flow rate could affect the temperature and pressure of the tubes.

Abu Hamed and Alkharabsheh [64] developed new evacuated tube solar air heaters with different configurations of copper tube: without fins neither coils attached to the copper tube, with copper coil spiraled on the copper tube, and with aluminium fins attached to the copper tube. The configurations were tested experimentally to find the best configuration with the highest thermal performance at different flow rates of 0.6, 0.9, and 1.25 m3/min. The heat transmission between the fluid and the copper tube heat exchanger is improved by the two separate high thermal conductivity metal fins and coils of the evacuated tube solar heating systems. The system with aluminium fins attached was found to have the greatest air temperature differences at the lowest flow rate and the greatest performance at the maximum flow rate.

Singh and Vardhan [65] evaluated an evacuated tube collector solar air heater equipped with helical coil inserts (ETC-HI). The heater consists of 20 evacuated tubes with the air mass flow rates ranging from 100 to 1,000 kg/h under the solar thermal simulator at indoor conditions. When compared to a basic ETC solar air heater, the optimized ETC-HI's maximum thermal efficiency was found to be 70.9%. Even with increased pressure losses, the effective efficiency of the ETC-HI was higher than that of a standard ETC solar air heater. The ETC-HI achieved the highest possible effective efficiency of 69.93%, whereas the effective efficiency of simple ETC solar air heaters was 64.43%.

Kumar et al. [66] conducted an experimental investigation on the thermal performance of an ETSAC with inserted baffles (ETSACIB) and discovered that inserting baffle configurations could increase thermal efficiency. The baffle length has a beneficial effect on thermal efficiency and temperature rise.

The energy and exergy behavior of an evacuated tube with inserted baffles solar air collector (ETIBSAC) with various design configurations of twisted tape was also examined by Kumar et al. [37] by analytical method. They discovered that loose-fit perforated twisted tape (LFPTT) performed better than other twisted tape designs in terms of energy efficacy. The findings demonstrated that the ETIBSAC with LFPTT generates maximum effective thermal and energy efficiencies at lower air flow rates, with the suggested insertion of twisted tape enhancing the thermal performance of the system.

### 3.3 Number of passes

A solar air heater with 40 evacuated tubes used for heating was assessed by Yadav and Bajpai [67]. The outer glass tube is 1,500 mm long, with an outside diameter of 47 mm and a diameter of 37 mm for its absorber tube. Light rays can flow through the transparent outer tube with minimum reflection due to its transparency and a unique selective coating of Al-Ni/Al that has outstanding solar radiation absorption and low reflection qualities for the inner tube. The amount of water in the experimental setup is 108 L, which serves as a heat-collecting medium, capturing the solar heat directed toward the tubes. The air passing through the header pipe receives this heat by conduction and natural convection. This set-up has an evacuated tube header and water-filled tubes, and due to thermosyphon circulation, this water heats up as it passes through the tubes and enters the header. The header receives this heat, which has a pipe that conducts heat from the header to the air flow in it. In this study, the experiment was conducted to determine which air flow is more effective and the effect of solar radiation intensity and air flow rate on the air's outlet temperature over time. Based on the results, downflow configurations are more efficient than upflow conditions at all flow rates because the former experienced fewer losses and demonstrated higher thermal performance. A temperature of 60 ℃ or more is achievable in downward flow. There are smaller differences of temperature at the upper and lower heads in downflow configurations than upflow configurations.

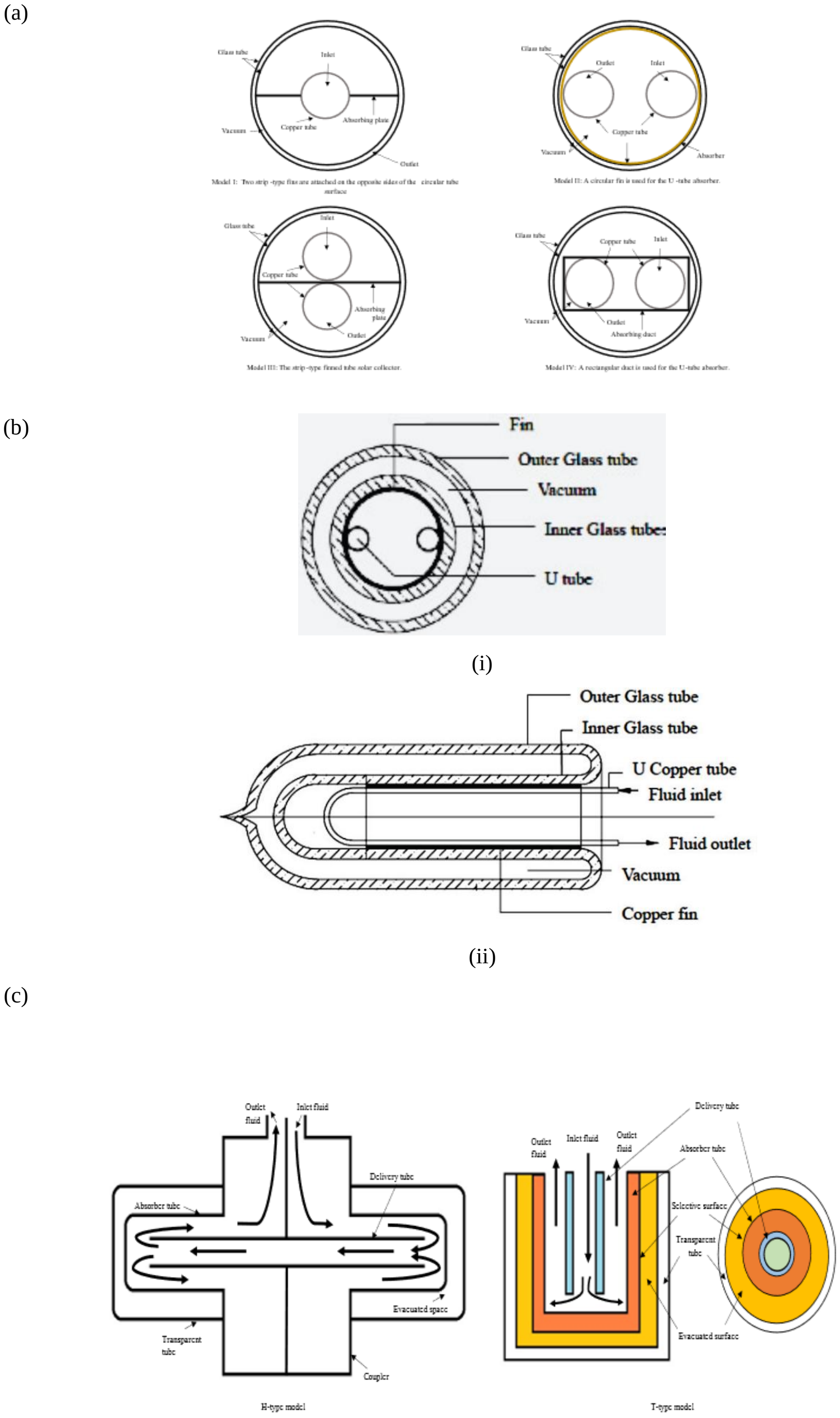
Recently, Zakaria et al. [68] proposed an improved evacuated tube design known as the evacuated glass-thermal absorber tube collector (EGATC) that outperformed the heat pipe evacuated tube collector in terms of temperature differences and output temperature. The inner and outer absorbers are the two components that made up the thermal absorber. The outer absorber is made of a larger diameter pipe closed by one side end cap, while the inner absorber is made of a small diameter pipe coupled with fins. Both heat absorbers are incorporated inside the evacuated glass. With the system's double pass flow and preheating flow at the inner absorber, the revolutionary thermal absorber design produces a high cumulative temperature at the output temperature [69].

### 3.4 External aid

Bakry et al. [70] investigated an experimentally simple one-ended evacuated tube solar collector with a small unit cell for air heating at low constant flow rates. One of these unit cells has a single-axis parabolic concentrator (SPC) that tracks the sun's rays built into it to increase the temperature. It shows that a large solar air heater may be built using the examined unit-cell's performance characteristics and have a significant improvement over flat plate solar air heaters.

Wang et al. [71] carried out an experimental study of a set of evacuated tube solar high and moderate temperature air heaters with a streamlined compound parabolic concentrator (CPC) and a U-shaped copper tube heat exchanger. It consists of a high-pressure air compressor and a large pressure container, which provides a steady air flow with a steady initial temperature throughout the test process, and 30 linked collecting units which are comprised of four parts: an all-glass evacuated tube absorber, a simplified CPC, a concentric copper tube heat exchanger, and a stainless-steel screen mesh layer. The findings showed that the current solar air collector, even during the winter, has exceptional high-temperature collecting capability. At noon, the air temperature at the collector outflow may surpass 160 °C for 3 h, and on bright days, the highest temperature may reach 230 °C. The observed thermal efficiency at 70 °C for the air reached a value of 0.52. At an air temperature of 150 °C, thermal efficiency achieved a value of 0.35, while the thermal efficiency of only 0.21 was recorded at 220 °C.

Zhang et al. [72] developed an experimental setup to examine the thermal performance of an ETC with a heat shield (ETC-HS) at temperatures over 100 °C and to compare it to the performance of an ETC without a heat shield (ETC-NHS). Direct-flow coaxial evacuated tube solar collectors with and without heat shields were investigated for their ability to extract heat. It is clear from the findings that a heat shield is a practical and cost-effective tool for limiting heat loss from an evacuated tube. Due to the heat shield's covering effect, it was found that the ETC-HS had superior thermal performance, reduced heat loss, and higher optical efficiency when compared to the ETC-NHS. Fig. 2 shows a compilation of various designs of ETSACs while Table 2 presents a summary of ETSAC designs and corresponding parameters affecting thermal performance in this paper.



Model I: Two strip -type fins are attached on the opposite sides of the circular tube surface

Model II: A circular fin is used for the U -tube absorber.

Model III: The strip -type finned tube solar collector.

Model IV: A rectangular duct is used for the U-tube absorber.

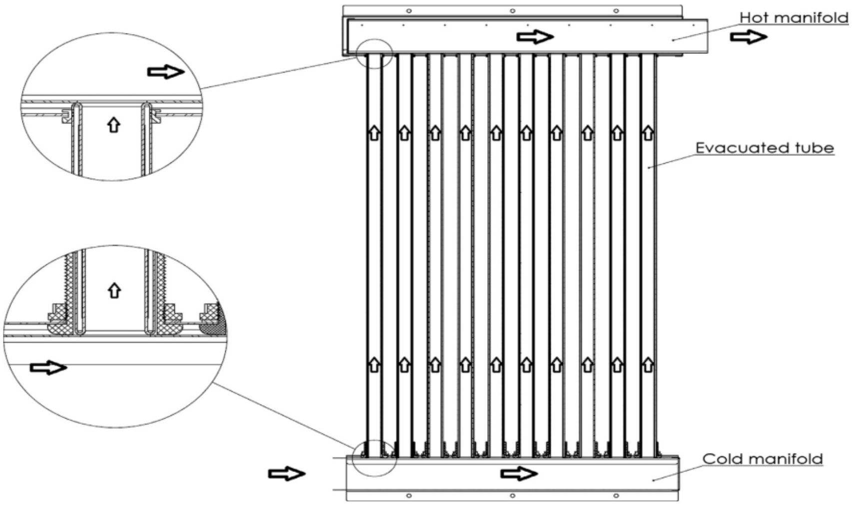
(i)

(ii)

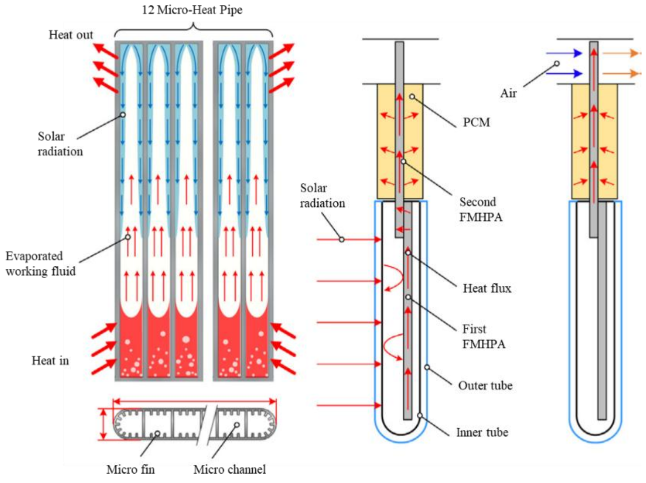
H-type model

T-type model

(d)

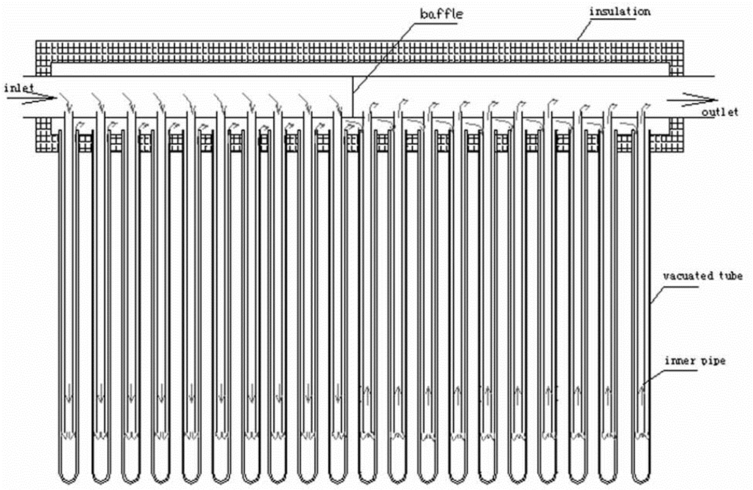

Hot manifold
Evacuated tube
Cold manifold

(e)


12 Micro-Heat Pipe
Heat out
Solar radiation
Evaporated working fluid
Heat in
Micro fin
Micro channel
Air
PCM
Second FMHPA
Solar radiation
Heat flux
First FMHPA
Outer tube
Inner tube

(i) (ii)

(f)


baffle
insulation
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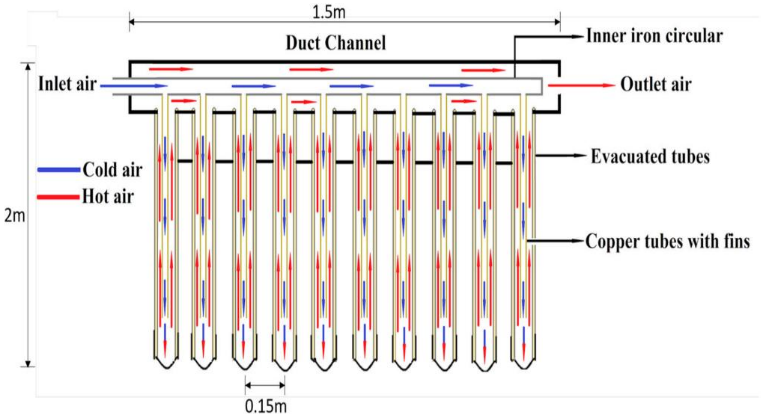
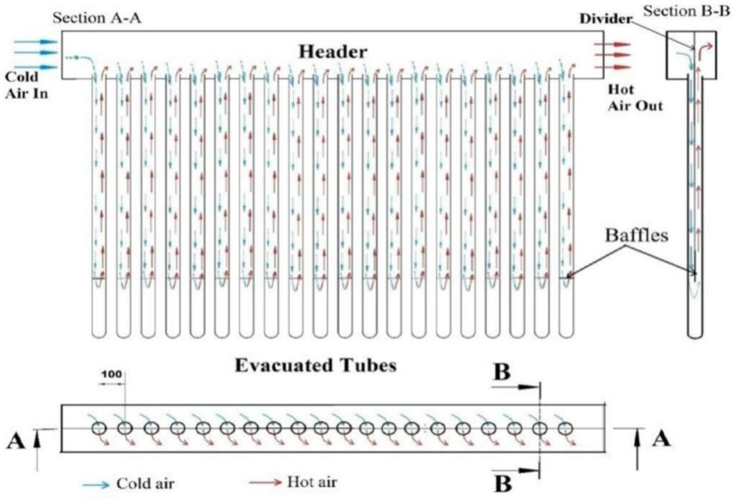
outlet
vacuated tube
inner pipe

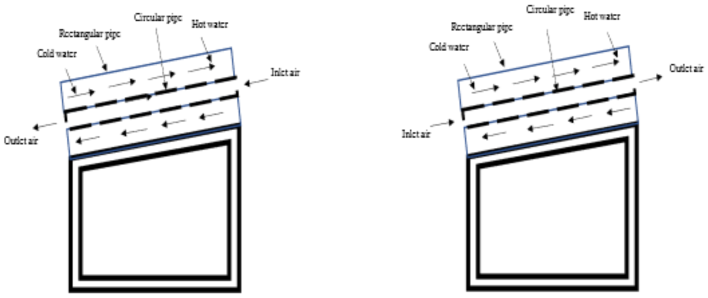
(g)



(h)



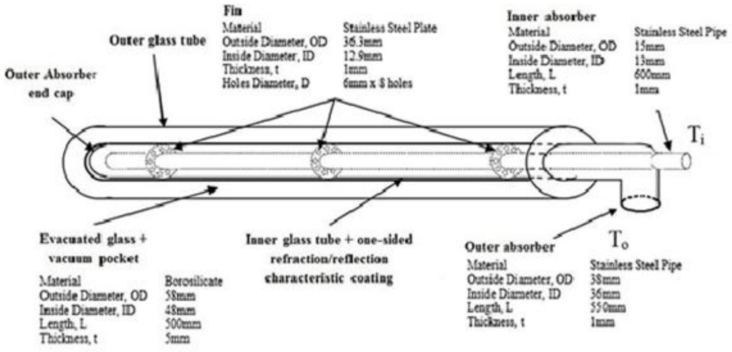
(i)



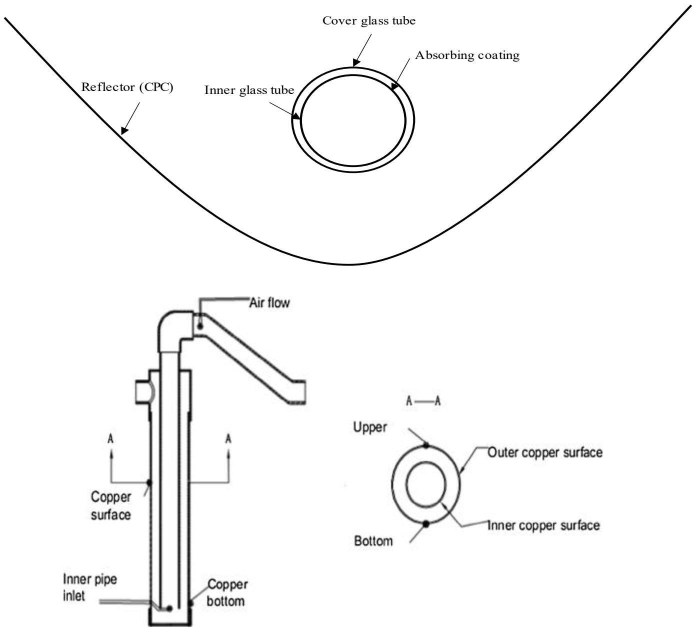
Schematic of a header with down-flow of air

Schematic of a header with up-flow of air

(j)



(k)



(l)

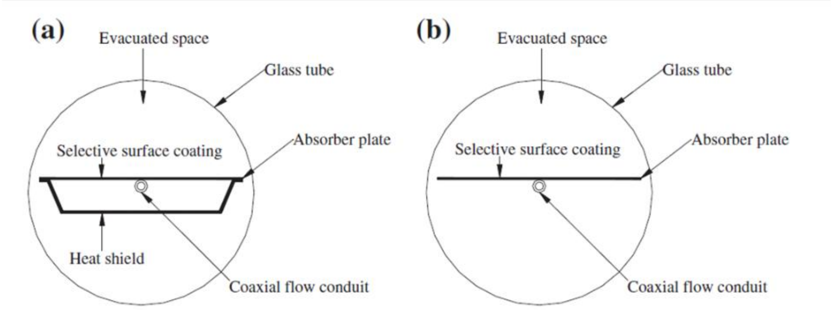


**Fig. 2** Various designs of ETSACs: **(a)** shapes of absorber tubes by Kim and Seo [53]; **(b)** schematic of the U-type evacuated tube solar collector by Naik et al. [56] for (i) cross-section and (ii) illustration; **(c)** schematic diagram of H-type & T-type models by Ataee and Ameri [57]; **(d)** schematic view of the solar evacuated tube collector [58]; **(e)** Working principles of the (i) evacuated tube-integrated collector storage solar heater and (ii) flat micro-HP arrays by Wang et al. [60]; **(f)** schematic of the all-glass ETSACs by Liang [63]; **(g)** schematic diagram of the evacuated tube solar heaters by Abu Hamed and Alkharabsheh [64]; **(h)** arrangements for the flow of air in the experimental setup by Kumar et al. [66]; **(i)** schematic designs for the head of evacuated tubes by Yadav and Bajpai [67]; **(j)** EGATC construction by Zakaria et al. [68]; **(k)** additional reflector for a U-shaped copper tube heat exchanger by Wang et al. [71]; and **(l)** cross-sections of evacuated tubes (a) with and (b) without a heat shield by Zhang et al. [72].

**Table 2** Summary of ETSAC designs and corresponding design parameters.

| Authors | Main Findings | Design Parameters Affecting Thermal Performance |
|---|---|---|
| Kim and Seo [53] | • Different shapes of absorber tubes give different performances.<br>• Various arrangements of collector tubes affect thermal performance.<br>• Incidence angle, beam irradiation, diffuse irradiation, and shadow also influence thermal performance. | • The shape of the absorber tube<br>• Collector tube arrangement<br>• Incidence angle of solar irradiation<br>• Total irradiation<br>• Solar energy utilization |
| Supankanok et al. [54] | • Adding stainless-steel scrubbers to the evacuated tube's interior structure modifies how aluminum fins connect to the copper heat pipe, enhancing the heat transfer. | • Inner structure of evacuated tube |
| Kumar et al. [55] | • Thermal performance of one-ended ETSAC without using any intermediate fluid. | • Different lengths of directional aluminum tubes |

| | | |
|---|---|---|
| Naik et al. [56] | • Water has the highest amount of heat energy absorption compared to air and LiCl-$H_2O$ solution in U-type evacuated tube solar collectors | • Collector length<br>• Working fluid flow rate<br>• Solar radiation intensity |
| Ataee and Ameri [57] | • For the H-type model, the outlet flow temperature and exergy efficiency for both air and $CO_2$ as working fluids are greater than the T-type model in coaxial fluid conduit design. | • Coaxial fluid conduit types |
| Paradis et al. [58] | • A turbulent effect was produced when the air flow rate was raised more than 10 $m^3/h$; consequently, the heat transfer coefficient increased. | • Air mass flow rate |
| Dabra et al. [59] | • The effect of tilt angles on the thermal performance of all-glass ETSACs. | • Tilt angle |
| Wang et al. [60] | • The charging and discharging efficiency (i.e., thermal storage and released efficiency) were 67.5% and 98.5%, respectively. When the air flow rate was 240 $m^3/h$ and the input temperature was 15 °C, the highest mean extraction power was 1,268.8 W. | • Lap joint-type flat MHPA serves as heat conductors |
| Wang et al. [61] | • The collector's pressure loss was less than 20 Pa, and its average efficiency could reach 82.7% for MHPA. | • MHPA<br>• Selective absorption films |
| Mehla and Yadav [62] | • When compared to a standard solar evacuated tube collector, the outlet temperature in an ETSAC utilizing circular fins and copper coil performed better. | • Additional circular fins and copper coil |
| Liang [63] | • Experimental research on the all-glass ETSACs inserted with metal pipes. | • Air flow rate |
| Abu Hamed and Alkharabsheh [64] | • At both the lowest flow rate and the maximum flow rate, the system with aluminum fins had the greatest air temperature differential and the greatest efficiency designed absorber. | • Metal fins and copper coil |
| Singh and Vardhan [65] | • Effective efficiency for the ETC-HI was superior to the simple ETC solar air heater. | • Helical coil inserts |
| Kumar et al. [66] | • Thermal efficiency could be obtained with inserted baffle arrangements. | • Baffle length |
| Kumar et al. [37] | • In terms of energy efficiency, LFPTT outperformed other twisted tape designs in terms of thermal performance. | • Twisted tape inserts |
| Yadav and Bajpai [67] | • Due to lower losses in downflow conditions, downflow arrangement is more efficient than upflow arrangement at all flow rates. | • Intensity of solar radiation<br>• Air flow rate |
| Zakaria et al. [68][69] | • EGATC outperformed HP-ETC in terms of temperature difference and outlet temperature. | • Double pass flow for the system<br>• Preheating flow at the inner absorber |
| Bakry et al. [70] | • The performance parameters of unit cells with SPC showed remarkable enhancement. | • Additional single-axis sun rays-tracking parabolic concentrator. |
| Wang et al. [71] | • ETSAC demonstrated exceptional solar gathering performance with CPC. | • Additional CPC – metal heat exchanger<br>• U-shaped copper tube heat exchanger |
| Zhang et al. [72] | • A heat shield is an effective and economical device for reducing heat loss from an evacuated tube. | • Heat shield |

The studies of ETSAC designs focused on the enhancement of thermal performance. Subsequently, based on the summary, it can be concluded that most of the thermal performance of ETSACs is influenced by the air mass flow rate. This parameter depends on the shape and type of absorber tubes, the arrangement of collector tubes, and the inclusion of additional fins, coils, and inserts, which are the main factors affecting the area of collector tubes. Increasing the area for heat absorption will increase the rate of heat transfer from the absorber to the air. Other than that, the thermal performance of ETSACs can be improved by the use of absorber materials [73], internal heat transfer components, integrated systems of energy storage, heat transfer surface area [74], incidence angle and intensity of solar radiation, and organizations, as well as the optimal inlet temperature through optimization for preheating conditions [75] because the efficiency of solar collectors in capturing solar energy and converting solar radiation into thermal energy is predominantly vital [76].

However, more efforts and studies are needed to incorporate design modifications and changes of evacuated tube absorbers as they will offer efficiency gains in terms of thermal performance. In order to obtain more details on the thermal performance of ETSACs, simulation works have been conducted by researchers to enhance understanding. Another performance improvement is by implementing numerous design modifications utilizing computational fluid dynamics (CFD) [77].

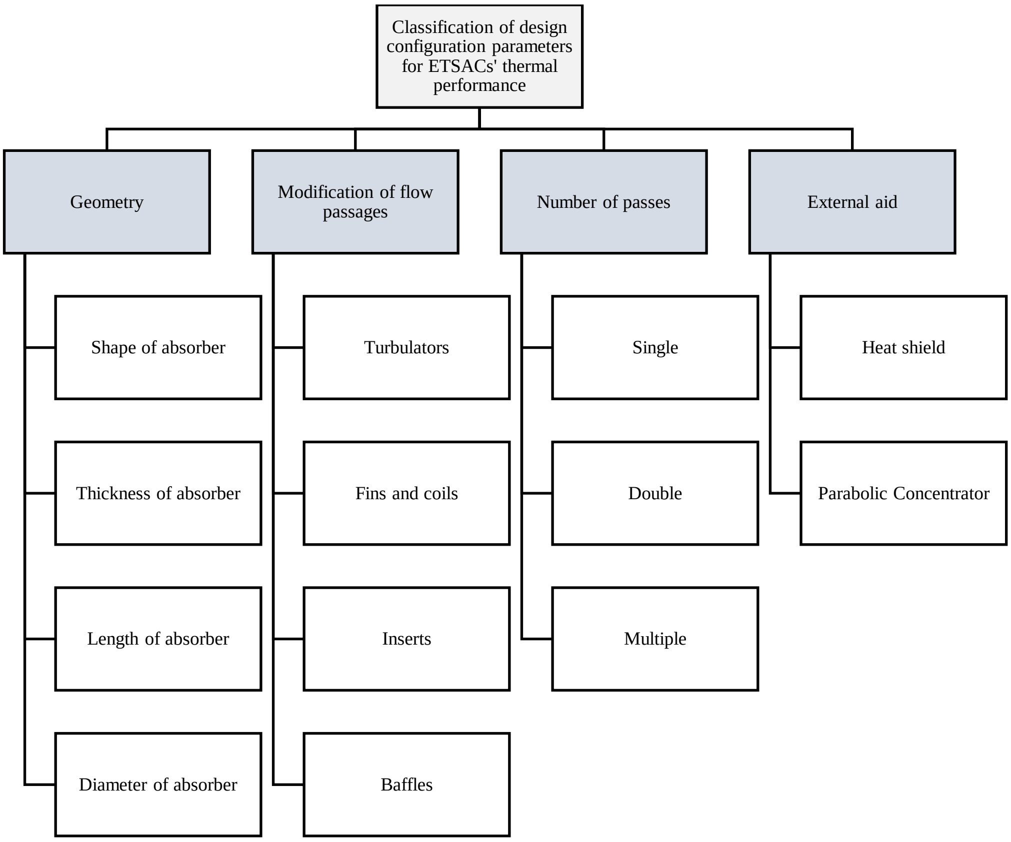


**Fig. 3** Classification of design configuration parameters for thermal performance of ETSACs.

## 4 Simulation works of evacuated tube solar collectors

In both commercial applications and scholarly research projects, CFD is a potent tool for the study of fluid flow through dryers and thermal design. Numerous studies have addressed modeling and numerical studies of the heat and flow processes in ETSCs for water and air heating.

### *4.1 Simulation works for water heating*

Hayek [77] performed CFD-based numerical prediction of the overall performance of ETSCs. A standard evacuated tube design can be significantly improved by making small adjustments, such as placing the junction at a slightly lower level than the standard one, according to the results of an investigation of a typical water-in-glass element with its tank portion and different design variations.

Beeker [78] carried out fluid simulation of the manifold to study the heat transfer at the manifold and to increase the accuracy of the ETSC model of water heating. A parametric study was performed to investigate the influence of adding propylene glycol to the working fluid and the effect of reducing the condenser and manifold diameters. Based on the outcome, adding propylene glycol substantially decreased the heat transfer efficiency at the manifold, and reducing both diameters by 10 mm resulted in a small increase in heat transfer.

Yazdi et al. [51] used Gambit software to evaluate the thermal performance of nanofluid flow within an evacuated tube solar collector and ANSYS Fluent to model the features of heat transfer for nanofluid flow with 1%, 3%, and 5% volumes. According to the numerical analysis, it was demonstrated that the collector's performance was improved when compared to pure water fluid. The findings indicated that increasing the volume percentage of nanoparticles greatly increases the collector's efficiency.

Sato et al. [79] evaluated the behavior of the fluid within a modified evacuated tube solar collector using numerical analysis in order to assess the model's potential for improvement. They learned that a thermosyphon mechanism was used to run the double-ended evacuated tube. The thermal storage tank's water stagnation issues from the simulation were resolved by changing the shape, which was then tested using a newer tube.

An innovative, straight-through evacuated tube collector made entirely of glass was examined by Du et al. [80] using thermal performance modeling and performance prediction. This collector uses water as its heat transfer medium. The prediction accuracy of the artificial neural network (ANN) models improved significantly compared to CFD approaches by integrating the thermal simulation model with the ANN models and utilizing the modeled collector output as one of the input models.

Ahmed et al. [81] used CFD to investigate how to improve heat transfer and the fluid flow characteristics of the laminar flow of water through a tube with helical screw tape. According to the findings of the simulation, compared to a simple tube, the heat transfer rate for heating water rose by 1.34–2.6 of Nusselt numbers.

The pressure losses for splitting and combining fluid flow across a tee junction of an evacuated tube solar collector manifold were calculated using CFD by Badar et al. [82]. Then, a theoretical model based on successive approximations was used to predict the isothermal and non-isothermal flow distribution in the laminar range through a collector composed of 60 parallel vacuum tubes linked in reverse (U-configuration) and parallel (Z-configuration) flow arrangements. The outcomes are quite consistent with the experimental findings for U-configuration that are currently available.

Aggarwal et al. [83] reviewed the application of CFD for the optimization of various thermal enhancement techniques used in ETSCs. They covered the CFD usage in geometrical modifications for thermal performance enhancement of ETSCs for water heating, heat transfer augmentation, comparison of experiments and simulations, and various techniques for reducing heat losses on ETSC performance.

### *4.2 Simulation works for air heating*

For air heating applications, Iranmanesh et al. [84] examined the performance of a solar cabinet drying system equipped with a heat pipe ETSC and a thermal storage system while using PCM. Using CFD modeling to evaluate performance, they discovered that the PCM increased the input thermal energy by approximately 1.72% and 5.12% for the air flow rates of 0.025 and 0.05 kg/s, respectively, but an excessive increase in the air flow rate (up to 0.05 kg/s) decreased the input thermal energy. The system with the PCM at 200 g of apple slices and an air flow rate of 0.025 kg/s achieved the highest total drying efficiency of 39.9%, and by utilizing CFD modeling, it was also demonstrated that there was a strong agreement between the simulated and experimental data for the storage system and the dryer.

The thermohydraulic performance of a rib-roughened solar evacuated tube collector for air heating was examined by Singla et al. [85] utilizing CFD. Half of the absorber tube was heated uniformly with 1,000 W/m2 using roughness geometry parameters of relative roughness pitch (P/e) of the order 6–12 and Reynolds number varying from 2,500 to 8,000. This shows that applying rib roughness in a solar evacuated tube collector is advantageous compared to using a plain tube.

The simulation by using MATLAB of Ataee and Ameri [57] for the H-type and T-type evacuated tube collectors showed that utilizing a selective coating absorber tube raises the outlet temperature of the collection tube for both models of CO2 and air as working fluids, while thermal conductivity and emissivity changes do not influence the delivery tube. By validating the results with Kim & Seo [53], the findings demonstrated that increasing the solar radiation intensity, collector tube length, and optical efficiency leads to an increase in the exergy efficiency, whereas increasing the mass flow rate and ambient temperature leads to a reduction in the exergy efficiency. Increasing the mass flow rate leads to a decrease in the outlet temperature of the collector tube, whereas increasing the solar radiation, collector tube inlet temperature, optical efficiency, and collector tube length leads to an increase in the outlet temperature.

Paradis et al. [58] developed a transient thermal model for a single evacuated tube with open ends with air as its working fluid. They used MATLAB to solve the first-order differential equations for each control volume with a fully explicit scheme using a fourth-order Runge-Kutta algorithm. The results show a good agreement between the simulation and experimental measurements with a root mean square error of 0.50 K on the outlet air flow temperature, Tout. Table 3 presents a summary of simulation works for ETSCs.

**Table 3** Summary of simulation works for ETSCs.

| Author | Working Fluids | Software Used | Main Findings |
|---|---|---|---|
| Hayek [77] | Water | ANSYS | Changing the location of a junction to a slightly lower level than the standard one improved the performance. |
| Beeker [78] | Water | ANSYS | Adding propylene glycol substantially decreased the heat transfer efficiency at the manifold and reducing both diameters by 10 mm resulted in a small increase of heat transfer. |
| Yazdi et al. [51] | Water | ANSYS Fluent | Increasing the volume proportion of nanoparticles increased the collector's efficiency substantially, based on the numerical study. |
| Sato et al. [79] | Water | ANSYS CFX | The simulation's issues with water stagnation inside the thermal storage tank were resolved by changing the shape with additional two open ends on a thermosiphon system. |
| Du et al. [80] | Water | ANSYS and ANN | • Improved prediction accuracy of ANN models.<br>• Prediction of the CFD model alone resulted in the lowest accuracy compared to ANN models. |
| Ahmed et al. [81] | Water | ANSYS | In comparison to the plain tube, the simulation's findings revealed an increase in the heat transfer rate, measured in terms of Nusselt numbers of 1.34–2.6 when a helical screw tape insert was applied. |
| Badar et al. [82] | Water | Gambit | The results agree with U-configuration for junction losses. |
| Aggarwal et al. [83] | Water | ANSYS | A review of CFD applications in evaluating the performance of ETSCs. |
| Iranmanesh et al. [84] | Air | ANSYS Fluent | The performance of a solar cabinet drying system equipped with ETSCs simulated, developed, and showed a good agreement with experimental results. |
| Singla et al. [85] | Air | ANSYS | A solar evacuated tube collector has an advantage over a plain tube when rib roughness is applied. |
| Ataee and Amari [57] | Air and $CO_2$ | MATLAB | The h-type model outperformed the T-type model in performance for both air and $CO_2$. |
| Paradis et al. [58] | Air | MATLAB | The fluid mass flow rate, ambient temperature, solar radiation, and wind speed were varied, and a good agreement between the simulation and experimental measurements was achieved by its root mean square error of 0.50 K on the outlet air flow temperature. |

Based on the summary, very few studies of simulation works have been carried out to evaluate the thermal performance of ETSACs. Most of the studies used water as the working fluid to be simulated in ETSCs for the evaluation of thermal performance and heat transfer characteristics. Hence, there are still gaps in studying the thermal performance of ETSACs using simulation. Moreover, most of the simulation works used CFD modeling to investigate the fluid flow, temperature, and velocity distribution within the tubes and to enhance thermal performance. Parametric studies can also be conducted through these simulation works to evaluate the thermal performance of ETSCs, and the thermal performance of EGATCs can be studied through simulation as no simulation study on this topic has been developed yet.

Computational fluid dynamics modeling and simulation can accurately predict product quality in relation to drying conditions like the air flow, heat transfer, and mass transfer characteristics of solar dryers [87]; provide a reliable method to predict and design solar dryers; and minimize postharvest loss and maximize the quality of dried fruits and vegetables. Fig. 4 shows the classification of simulation works for ETSCs.

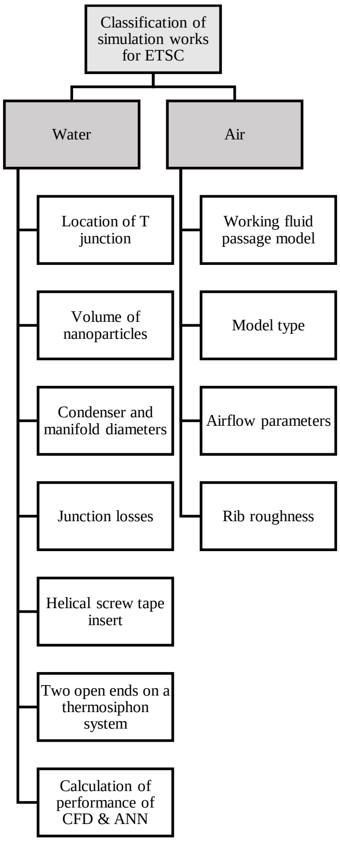


**Fig. 4** Classification of simulation works for ETSCs.

## 5 Application of evacuated tube solar air collectors

Evacuated tube solar air collectors are extensively used for applications that require direct use of hot air, such as industrial [26], space heating, and drying [22] as the absorption of solar radiation energy by a thermal collector reduces the moisture content through a fluid flow [88]. A recent study of ETSAC based on a novel hybrid active greenhouse solar dryer conducted by Singh and Gaur [88] reported that the drying time was reduced by 47.36%, 61.90%, and 34.09% for tomato, bottle gourd, and ginger, respectively, compared to a conventional dryer. They developed a drying bed using hot water from ETSCs, which is delivered to the copper tubes of the heat exchanger and then radiates heat into the surrounding air and the crop surface that encounters it.

The application of ETSACs in fruit and crop drying enhanced drying performance, as determined by Mahesh et al. [89]. They conducted experiments on fruit and vegetable samples, such as pineapple, apple, banana, guava, beans, brinjal, carrot, lady finger, and potato to be dried by ETSACs and open sun drying. The results showed that the solar dryer and open sun drying efficiencies fluctuated in the range of 55%–78%.

Singh et al. [90] compared the performance of flat plate and evacuated tube-type tunnel dryers and found that the thermal efficiency of the ETSAC was 14.96%, 20.01%, and 13.48% at an air velocity of 0.7 m/s with a duration of 5 h 45 min for drying of fenugreek leaves, curry leaves, and coriander, respectively. The performance of the ETSAC is better than the flat plate type tunnel dryer at the same air velocity and duration.

Veeramanipriya and Umayal Sundari [91] presented a prototype hybrid photovoltaic thermal (PV-T) solar dryer assisted with an evacuated tube collector for drying cassava slices. The ETSAC was developed and integrated with external sources by a PV panel for continuous drying after the sunshine hour of cassava, and it managed to reduce the moisture content from 91.5% to 10.67% (weight basis). Nevertheless, there are limited studies on evacuated tube collectors supported by hybrid PVT solar dryers.

Malakar et al. [92] examined the thermal performance of an evacuated tube solar dryer (ETSD) with and without a load of beetroot slices for drying by analyzing the drying kinetics, mass transfer phenomena, color changes, and retention of bioactive compounds of beetroot slices in the ETSD and open sun drying. From the results, the average drying rate was found to be 8.5 g water/g dry solid·h and 7.94 g water/g dry solid·h. The initial moisture level was 84.05%, which decreased to 9.25% and 13.56% using the ETSD and sun drying, respectively.

Using an ETSD with and without thermal energy storage, Dutta et al. [93] studied the thermal performance of the dryer, drying parameters, and quality attributes of pretreated (control, peeled, and cured sample) turmeric slices. With two pretreatments — curing at 100 °C for 45 min and peeled fresh turmeric — they compared the performance of evacuated solar dryers with (ETDP) and without PCMs (ETD). According to the research, turmeric samples were dried from an initial moisture content of 84.6% (weight basis) to a final moisture content of between 13% and 8.8% (weight basis). The cured turmeric samples dried using the ETDP retained the highest curcumin content, while the cured samples dried using the ETD dried fastest.

Rajagopal et al. [94] studied the performance of a forced convection solar dryer fabricated with an evacuated tube collector, a drying chamber, and a blower to dry copra. The initial moisture content of copra ranged from 51.7% to 52.3%, and the final moisture content was about 7%–8% by using this method, and less time was required than the natural convection solar dryer to attain the equilibrium moisture content.

Hosseinzadeh et al. [95] investigated the performance of a portable evacuated tube solar cooker as a direct solar cooker and discovered that solar radiation is the most effective parameter for the thermal power of a solar cooker whereas absolute pressure is the most effective parameter of an evacuated tube solar cooker. Table 4 presents a summary of applications for ETSACs.

**Table 4** Summary of applications for evacuated tube solar air collectors

| Authors | Applications | Main findings |
|---|---|---|
| Singh and Gaur [88] | Tomato, bottle gourd, and ginger | Drying time was reduced by 47.36%, 61.90%, and 34.09% for tomato, bottle gourd, and ginger, respectively, compared to a conventional dryer. |
| Mahesh et al. [89] | Pineapple, apple, banana, guava, beans, brinjal, carrot, lady finger, and potato | The corresponding solar dryer efficiency and open sun drying efficiency varied in the range of 55%–78%. |
| Singh et al. [90] | Fenugreek leaves, curry leaves, and coriander | The ETSAC performance results were 14.96%, 20.01%, and 13.48% at an air velocity of 0.7 m/s with a duration of 5 h 45 min for drying of fenugreek leaves, curry leaves, and coriander, respectively, better than the performance of a flat plate dryer. |
| Veeramanipriya & Umayal Sundari [91] | Cassava | The ETSAC was developed and integrated with external sources by a PV panel for continuous drying after the sunshine hour of cassava and managed to reduce the moisture content from 91.5% to 10.67% (weight basis). |
| Malakar et al. [92] | Beetroot | The initial moisture content of 84.05% was reduced to 9.25% and 13.56% for the ETSD and sun drying, respectively. |
| Dutta et al. [93] | Turmeric | The initial moisture content of the turmeric samples was 84.6% (weight basis), with a final moisture content of 13%–8.8% (weight basis). The cured turmeric samples dried using the ETDP had the highest curcumin content (7.49%, AA: 65.92%, TPC: |

| | | |
|---|---|---|
| | | 22.38 mg GAE/g, and b*: 58.63), while the cured turmeric samples dried using the ETD dried fastest. |
| Rajagopal et al. [94] | Copra | The initial moisture content of copra ranged from 51.7% to 52.3%, and the final moisture content was about 7%–8% using forced convection. |
| Hosseinzadeh et al. [95] | Solar cooker | • Solar radiation is the most effective parameter for the thermal power of a solar cooker.<br>• Absolute pressure is the most effective parameter of an evacuated tube solar cooker. |

From these studies, it can be observed that ETSACs have a significant impact in saving time with their efficiency to perform better in crop and vegetable drying than flat plate collectors and conventional dryers before and after sunshine hours. The thermal performance of ETSACs influences the drying time of agricultural products and solar cooker applications. It can reduce 50% of the total time in solar drying applications and also reduce the cost of the existing system [19]. Furthermore, it helps in maintaining the quality of drying products compared to open sun drying, such as physical and chemical composition [91] and its colors, average phenolic content, antioxidant capacity, and betalain pigment retention [92]. There are various designs and applications of ETSACs for drying agriculture products, such as a PV-T solar dryer aided with an ETC, using thermal energy storage of PCMs, and comparing the performance of ETSACs with and without load. Thus, there is a need to explore the thermal performance of EGATC to improve its performance, hence contributing to the enhancement of crop drying performance. Fig. 5 shows the types of ETSAC applications.

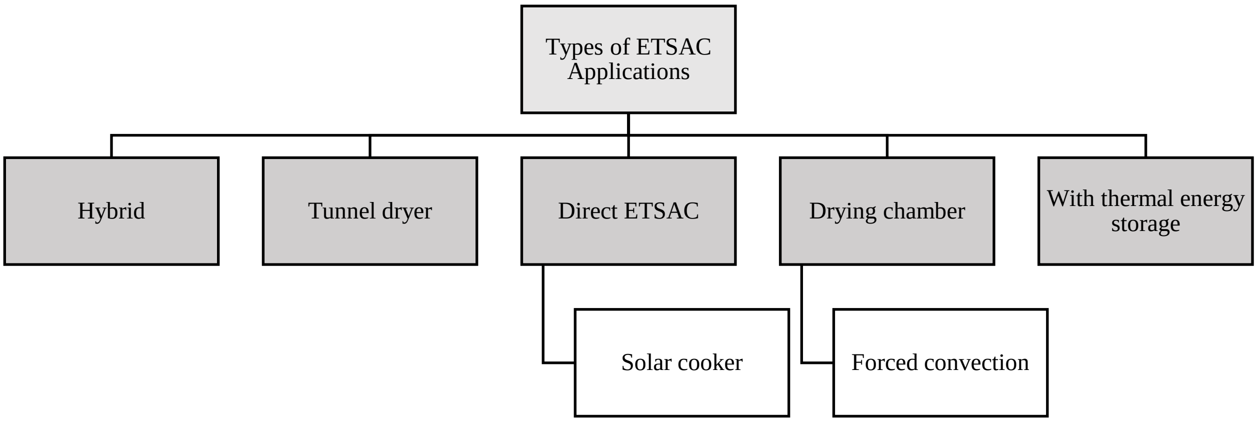


**Fig. 5** Types of ETSAC applications.

Moreover, the thermal performance of ETSACs can also be enhanced by applying thermal storage, such as PCMs, which have been conducted by Elbrashy et al. [30], Kalidasan et al. [43], Mehla and Yadav [96], Vedanarayanan et al. [97], and Dhaou et al. [98], where this approach can maximize the possibility of ETSAC applications in space heating and also crop and fruit drying. In addition, PCMs have been extensively employed to overcome the two main problems caused by the intermittent nature of solar radiation: reducing energy fluctuations and storing solar thermal energy during the day and releasing it in the absence of sunlight [46].

Other than that, the use of nanofluids as a thermal enhancement method in ETSCs, which have been reviewed by Olfian et al. [27] and Kumar et al. [52], discovered that most of the researchers work on water as a working fluid, and only a few used nanofluids as a working fluid in their experiments. There is a potential for using nanofluids in ETSACs, which can be further explored as only a few studies have been conducted in this area, such as by Chamsa-ard et al. [50], Gorjian et al. [99], and Sadeghi [100].

## 6 Conclusions and future recommendations

Based on the ongoing studies related to enhancing the thermal performance of ETSACs, it can be observed that ETSACs are in higher demand than ever. The supply of hot air using solar energy is the primary environmental advantage of installing ETSACs. Moreover, ETSACs are widely used for various purposes, including drying items in the agricultural and industrial sectors, as well as supplying heat for buildings. As a result, they play an essential role in solar thermal systems.

Recent studies on the design of ETSACs in improving thermal performance involve additional features, such as fins, twisted tape, and helical inserts, which are proven to perform better than conventional ETSACs. Furthermore, CFD offers a huge potential to study the thermal performance of ETSACs to help in understanding the thermal performance of ETSACs better, especially in air heating applications as most ETSAC applications, which are space heating, solar cooking, and agricultural drying, have ongoing demand recently. Nevertheless, studies of the use of nanofluids as thermal performance enhancers and PCMs as thermal storage media can be considered for enhancing the thermal performance of ETSACs. Lastly, EGATC as one of the ETSACs, which will contribute to solar thermal applications, can be explored through numerical simulations for enhancing its thermal performance.

## Declaration of Conflict of Interest

The authors declared that there is no conflict of interest with any other party on the publication of the current work.

## ORCID

Nabila Sulaiman https://orcid.org/0000-0002-1982-7038
Sany Izan Ihsan https://orcid.org/0000-0002-5171-6338
Syed Noh Syed Abu Bakar https://orcid.org/0000-0003-2097-2176
Zairul Azrul Zakaria https://orcid.org/0000-0001-8281-7599

## References

[1] M.J. Ring, D. Lindner, E.F. Cross, M.E. Schlesinger, Causes of the global warming observed since the 19th century, Atmospheric and Climate Sciences 2 (2012) 401–415. https://doi.org/10.4236/acs.2012.24035.

[2] P. A. Owusu, S. Asumadu-Sarkodie, A review of renewable energy sources, sustainability issues and climate change mitigation, Cogent Engineering 3 (2016) 1167990. https://doi.org/10.1080/23311916.2016.1167990.

[3] A. Suman, Role of renewable energy technologies in climate change adaptation and mitigation: A brief review from Nepal, Renewable and Sustainable Energy Reviews 151 (2021), 111524. https://doi.org/10.1016/j.rser.2021.111524.

[4] R. Kumar, R. Arya, N. Diwakar, S. Daniel, Investigating the different process parameters and their effects of solar energy, International Journal for Research Trends and Innovation 4 (2019) 1–5.

[5] M.H. Ahmadi, M. Ghazvini, M. Sadeghzadeh, M.A. Nazari, R. Kumar, A. Naeimi, T. Ming, Solar power technology for electricity generation: A critical review, Energy Science & Engineering 6 (2018) 340–361. https://doi.org/10.1002/ese3.239.

[6] F.M. Guangul, G.T. Chala, Solar energy as renewable energy source: SWOT analysis, 2019 4th MEC International Conference on Big Data and Smart City (ICBDSC) (2019) 1–5. https://doi.org/10.1109/ICBDSC.2019.8645580.

[7] L. Kumar, M. Hasanuzzaman, N.A. Rahim, Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review, Energy Conversion and Management 195 (2019) 885–908. https://doi.org/10.1016/j.enconman.2019.05.081.

[8] K. Ravi Kumar, N.V.V. Krishna Chaitanya, N. Sendhil Kumar, Solar thermal energy technologies and its applications for process heating and power generation – A review, Journal of Cleaner Production 282 (2021) 125296. https://doi.org/10.1016/j.jclepro.2020.125296.

[9] Q. Li, W. Gao, W. Lin, T. Liu, Y. Zhang, X. Ding, X. Huang, W. Liu, Experiment and simulation study on convective heat transfer of all-glass evacuated tube solar collector, Renewable Energy 152 (2020) 1129–1139. https://doi.org/10.1016/j.renene.2020.01.089.

[10] A. Shafieian, M. Khiadani, A. Nosrati, Strategies to improve the thermal performance of heat pipe solar collectors in solar systems: A review, Energy Conversion and Management 183 (2019) 307–331. https://doi.org/10.1016/j.enconman.2018.12.115.

[11] S.A. Kalogirou, Solar thermal collectors and applications, Progress in Energy and Combustion Science 30 (2004) 231–295. https://doi.org/10.1016/j.pecs.2004.02.001.

[12] S.E. Zubriski, K.J. Dick, Measurement of the efficiency of evacuated tube solar collectors under various operating conditions, Journal of Green Building 7 (2012) 114–130. https://doi.org/10.3992/jgb.7.3.114.

[13] B. Window, Heat extraction from single ended glass absorber tubes, Solar Energy 31 (1983) 159–166. https://doi.org/10.1016/0038-092X(83)90077-4.

[14] S. Kalogirou, The potential of solar industrial process heat applications, Applied Energy 76 (2003) 337–361. https://doi.org/10.1016/S0306-2619(02)00176-9.

[15] P. Olczak, D. Matuszewska, J. Zabagło, The comparison of solar energy gaining effectiveness between flat plate collectors and evacuated tube collectors with heat pipe: Case study, Energies 13 (2020), https://doi.org/10.3390/en13071829.

[16] A. Dubey, A. Arora, Enhancement of heat transfer in solar parabolic trough air heater: An experimental study, in: International Conference of Advance Research and Innovation, 2020, pp. 54–57. http://dx.doi.org/10.2139/ssrn.3560009.

[17] M.A. Alghoul, M.Y. Sulaiman, B.Z. Azmi, M. Abd Wahab, Review of materials for solar thermal collectors, Anti-Corrosion Methods and Materials 52 (2005) 199–206. https://doi.org/10.1108/00035590510603210.

[18] A. Kumar, S. Kumar, U. Nagar, A. Yadav, Experimental study of thermal performance of one-ended evacuated tubes for producing hot air, Journal of Solar Energy 2013 (2013) 524715. https://doi.org/10.1155/2013/524715.

[19] D. Mevada et al., Applications of evacuated tubes collector to harness the solar energy: a review, International Journal of Ambient Energy 43 (2022) 344–361. https://doi.org/10.1080/01430750.2019.1636886.

[20] V. Goel, V.S. Hans, S. Singh, R. Kumar, S.K. Pathak, M. Singla, S. Bhattacharyya, E. Almatrafi, R.S. Gill, A comprehensive study on the progressive development and applications of solar air heaters, Solar Energy 229 (2021) 112–147. https://doi.org/10.1016/j.solener.2021.07.040.

[21] I. Kamfa, J. Fluch, R. Bartali, D. Baker, Solar-thermal driven drying technologies for large-scale industrial applications: State of the art, gaps, and opportunities, International Journal of Energy Research 44 (2020) 9864–9888. https://doi.org/10.1002/er.5622.

[22] K. Chopra, V.V. Tyagi, A.K. Pandey, A. Sari, Global advancement on experimental and thermal analysis of evacuated tube collector with and without heat pipe systems and possible applications, Applied Energy 228 (2018) 351–389. https://doi.org/10.1016/j.apenergy.2018.06.067.

[23] H. Kim, J. Kim, H. Cho, Review of thermal performance and efficiency in evacuated tube solar collector with various Nanofluids, International Journal of Air-Conditioning and Refrigeration 25(2) (2017) 1730001. https://doi.org/10.1142/S2010132517300014.

[24] A. Saxena and A.A. El-sebaii, A thermodynamic review of solar air heaters, Renewable and Sustainable Energy Reviews 43 (2015) 863–890. https://doi.org/10.1016/j.rser.2014.11.059.

[25] A. Kumar, Z. Said, and E. Bellos, An up-to-date review on evacuated tube solar collectors, Journal of Thermal Analysis and Calorimetry 145 (2021) 2873–2889. https://doi.org/10.1007/s10973-020-09953-9.

[26] A. Sharma and G. Saxena, Performance investigation of evacuated tube solar heating system: A review, Journal of Alternate Energy Sources and Technologies 9 (2018) 15–26. https://doi.org/10.37591/joaest.v9i3.1249.

[27] H. Olfian, S. Soheil, M. Ajarostaghi, M. Ebrahimnataj, Development on evacuated tube solar collectors: A review of the last decade results of using nanofluids, Solar Energy 211 (2020) 265–282. https://doi.org/10.1016/j.solener.2020.09.056.

[28] M.A.J. Al-Neama, Performance enhancement of solar air collectors applied for drying processes, Doctoral dissertation, Szent István University, Gödöllő, Hungary, 2018.

[29] V.C. Parashottambhai, Investigations on evacuated glass tube, Doctoral dissertation, Gujarat Technological University Ahmedabad, 2022.

[30] A. Elbrashy, F. Aboutaleb, M. El-Fakharany, F.A. Essa, Experimental study of solar air heater performance with evacuated tubes connected in series and involving nano-copper oxide/paraffin wax as thermal storage enhancer, Environmental Science and Pollution Research 30 (2023) 4603–4616. https://doi.org/10.1007/s11356-022-22462-6.

[31] A. Fudholi, K. Sopian, M.H. Ruslan, M.A. Alghoul, M.Y. Sulaiman, Review of solar dryers for agricultural and marine products, Renewable and Sustainable Energy Reviews 14 (2010) 1–30. https://doi.org/10.1016/j.rser.2009.07.032.

[32] E. Vengadesan, R. Senthil, A review on recent developments in thermal performance enhancement methods of flat plate solar air collector, Renewable and Sustainable Energy Reviews 134 (2020) 110315. https://doi.org/10.1016/j.rser.2020.110315.

[33] A. Abi Mathew, V. Thangavel, A novel thermal storage integrated evacuated tube heat pipe solar air heater: Energy, exergy, economic and environmental impact analysis, Solar Energy, 220 (2021) 828–842. https://doi.org/10.1016/j.solener.2021.03.057.

[34] A.E. Kabeel, M.H. Hamed, Z.M. Omara, A.W. Kandeal, Solar air heaters: Design configurations, improvement methods and applications – A detailed review, Renewable and Sustainable Energy Reviews 70 (2017) 1189–1206. https://doi.org/10.1016/j.rser.2016.12.021.

[35] S. Chamoli, R. Lu, D. Xu, P. Yu, Thermal performance improvement of a solar air heater fitted with winglet vortex generators, Solar Energy 159 (2017) 966–983, 2018, https://doi.org/10.1016/j.solener.2017.11.046.

[36] S. Rashidi, M. Hossein Kashefi, F. Hormozi, Potential applications of inserts in solar thermal energy systems – A review to identify the gaps and frontier challenges, Solar Energy 171 (2018) 929–952. https://doi.org/10.1016/j.solener.2018.07.017.

[37] A.V. Kumar, T.V Arjunan, D. Seenivasan, R. Venkatramanan, S. Vijayan, M. Matheswaran, Influence of twisted tape inserts on energy and exergy performance of an evacuated Tube-based solar air collector, Solar Energy 225 (2021) 892–904. https://doi.org/10.1016/j.solener.2021.07.074.

[38] B.N. Prasad, J.S. Saini, Effect of artificial roughness on heat transfer and friction factor in a solar air heater, Solar Energy 41 (1988) 555–560. https://doi.org/10.1016/0038-092X(88)90058-8.

[39] N.K. Pandey, V.K. Bajpai, Experimental investigation of heat transfer and friction characteristics of arc-shaped roughness elements having central gaps on the absorber plate of solar air heater, Journal of Solar Energy Engineering 138 (2016) 1–8. https://doi.org/10.1115/1.4033402.

[40] R.S. Gill, V.S. Hans, R.P. Singh, Optimization of artificial roughness parameters in a solar air heater duct roughened with hybrid ribs, Applied Thermal Engineering 191 (2021) 116871. https://doi.org/10.1016/j.applthermaleng.2021.116871.

[41] A.K. Raj, C.N. Vinay, M. Srinivas, S. Jayaraj, Experimental investigation on solar thermal air heater with a combination of roughness elements for heat transfer improvement, Journal of Thermal Analysis and Calorimetry 146 (2021) 1453–1464. https://doi.org/10.1007/s10973-020-10097-z.

[42] M.A. Aravindh A. Sreekumar, Efficiency enhancement in solar air heaters by modification of absorber plate-a review, International Journal of Green Energy 13 (2016) 1209–1223. https://doi.org/10.1080/15435075.2016.1183207.

[43] B. Kalidasan, A.K. Pandey, S. Shahabuddin, M. Samykano, M. Thirugnanasambandam, R. Saidur, Phase change materials integrated solar thermal energy systems: Global trends and current practices in experimental approaches, Journal of Energy Storage 27 (2020) 101118. https://doi.org/10.1016/j.est.2019.101118.

[44] F. Abdalla, P. Tuohy, D. Evans, P. Blackwell, A review of integrated phase change materials for evacuated tube solar collector system, in: International Conference on Energy Research, 2018, pp. 379–390.

[45] F.S. Javadi, H.S.C. Metselaar, P. Ganesan, Performance improvement of solar thermal systems integrated with phase change materials (PCM), a review, Solar Energy 206 (2020) 330–352. https://doi.org/10.1016/j.solener.2020.05.106.

[46] M. Aramesh, B. Shabani, On the integration of phase change materials with evacuated tube solar thermal collectors, Renewable and Sustainable Energy Reviews 132 (2020) 110135. https://doi.org/10.1016/j.rser.2020.110135.

[47] M.A. Essa, I.Y. Rofaiel, M.A. Ahmed, Experimental and theoretical analysis for the performance of evacuated tube collector integrated with helical finned heat pipes using PCM energy storage, Energy, 206 (2020) 118166. https://doi.org/10.1016/j.energy.2020.118166.

[48] H. Tyagi, P. Phelan, R. Prasher, Predicted efficiency of a Low-temperature Nanofluid-based direct absorption solar collector, Journal of Solar Energy Engineering 131 (2009) 041004. https://doi.org/10.1115/1.3197562.

[49] S. Iranmanesh, H.C. Ong, B.C. Ang, E. Sadeghinezhad, A. Esmaeilzadeh, M. Mehrali, Thermal performance enhancement of an evacuated tube solar collector using graphene nanoplatelets nanofluid, Journal of Cleaner Production 162 (2017) 121–129. https://doi.org/10.1016/j.jclepro.2017.05.175.

[50] W. Chamsa-ard, S. Brundavanam, C.C. Fung, D. Fawcett, G. Poinern, Nanofluid types, their synthesis, properties and incorporation in direct solar thermal collectors: A review, Nanomaterials, 7 (2017) 131. https://doi.org/10.3390/nano7060131.

[51] M.H. Yazdi, E. Solomin, A. Fudholi, G. Divandari, K. Sopian, P.L. Chong, Thermal performance of nanofluid flow inside evacuated tube solar collector, International Journal of Heat and Technology 39 (2021) 1262–1270. https://doi.org/10.18280/ijht.390424.

[52] A. Kumar, A. Kumar, Z. Said, A comprehensive review analysis on advances of evacuated tube solar collector using nanofluids and PCM, Sustainable Energy Technologies and Assessments 47 (2021) 101417. https://doi.org/10.1016/j.seta.2021.101417.

[53] Y. Kim, T. Seo, Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube, Renewable Energy 32 (2007) 772–795. https://doi.org/10.1016/J.RENENE.2006.03.016.

[54] R. Supankanok, S. Sriwong, P. Ponpo, W. Wu, W. Chandra-Ambhorn, A. Anantpinijwatna, Modification of a solar thermal collector to promote heat transfer inside an evacuated tube solar thermal absorber, Applied Sciences 11 (2021) 4100. https://doi.org/10.3390/app11094100.

[55] A. Kumar, S. Kumar, A. Yadav, Thermal performance analysis of evacuated tubes solar air collector in Indian climate conditions, International Journal of Ambient Energy 37 (2016) 162–171. https://doi.org/10.1080/01430750.2014.915884.

[56] B.K. Naik, A. Varshney, P. Muthukumar, C. Somayaji, Modelling and performance analysis of U type evacuated tube solar collector using different working fluids, Energy Procedia 90 (2016) 227–237. https://doi.org/10.1016/j.egypro.2016.11.189.

[57] S. Ataee, M. Ameri, Energy and exergy analysis of all-glass evacuated solar collector tubes with coaxial fluid conduit, Solar Energy 118 (2015) 575–591. https://doi.org/10.1016/j.solener.2015.06.019.

[58] P.-L. Paradis, D.R. Rousse, S. Hallé, L. Lamarche, G. Quesada, Thermal modeling of evacuated tube solar air collectors, Solar Energy 115 (2015) 708–721. https://doi.org/10.1016/j.solener.2015.03.040.

[59] V. Dabra, L. Yadav, A. Yadav, The effect of tilt angle on the performance of evacuated tube solar air collector: experimental analysis, International Journal of Engineering, Science and Technology (2018) 100–110. https://doi.org/10.4314/ijest.v5i4.9.

[60] Z. Wang, Y. Diao, Y. Zhao, C. Chen, L. Liang, T. Wang, Thermal performance of integrated collector storage solar air heater with evacuated tube and lap joint-type flat micro-heat pipe arrays, Applied Energy 261 (2020) 114466. https://doi.org/10.1016/j.apenergy.2019.114466.

[61] T. Wang, Y. Zhao, Y. Diao, R. Ren, Z. Wang, Performance of a new type of solar air collector with transparent-vacuum glass tube based on micro-heat pipe arrays. Energy 177 (2019) 16–28. https://doi.org/10.1016/j.energy.2019.04.059.

[62] N. Mehla, A. Yadav, Experimental analysis of thermal performance of evacuated tube solar air collector with phase change material for sunshine and off-sunshine hours, International Journal of Ambient Energy 38 (2017) 130–145. https://doi.org/10.1080/01430750.2015.1074612.

[63] H. Liang, Experimental research on the all-glass evacuated tube solar air collector, in: Proceedings of ISES World Congress 2007 (Vol. I – Vol. V), Springer, Berlin, Heidelberg, 2008. https://doi.org/10.1007/978-3-540-75997-3_125.

[64] T. Abu Hamed, S. Alkharabsheh, Design and performance analysis of a new evacuated tube solar air heaters equipped with fins and coils, International Journal of Sustainable Energy 39 (2020) 997–1008. https://doi.org/10.1080/14786451.2020.1798446.

[65] I. Singh, S. Vardhan, Experimental investigation of an evacuated tube collector solar air heater with helical inserts, Renew. Energy 163 (2021) 1963–1972. https://doi.org/10.1016/j.renene.2020.10.114.

[66] A.V. Kumar, T.V. Arjunan, D. Seenivasan, R. Venkatramanan, S. Vijayan, Thermal performance of an evacuated tube solar collector with inserted baffles for air heating applications, Solar Energy 215 (2021) 131–143. https://doi.org/10.1016/j.solener.2020.12.037.

[67] A. Yadav, V.K. Bajpai, An experimental study on evacuated tube solar collector for heating of air in India, World Academy of Science, Engineering and Technology 79 (2011) 81–86. https://doi.org/10.5281/zenodo.1083537.

[68] Z.A. Zakaria, Z.A.A. Majid, M.A. Harun, A.F. Ismail, S.I. Ihsan, K. Sopian, A. Abdul Razak, A.F. Sharol, Investigation on the thermal performance of Evacuated Glass-Thermal Absorber Tube Collector (EGATC) for air heating application, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 79 (2021) 48–64. https://doi.org/10.37934/arfmts.79.2.4864.

[69] Z.A. Zakaria, Z.A.A. Majid, M.A. Harun, A.F. Ismail, S.I. Ihsan, K. Sopian, A. Abdul Razak, A.F. Sharol, Experimental investigation of integrated energy storage on the thermal performance enhancement of Evacuated Glass-Thermal Absorber Tube Collector (EGATC) for Air Heating Application, Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 96(1) (2022) 137–152.

https://doi.org/10.37934/arfmts.96.1.137152.

[70] A.I. Bakry, Y.A.F. El-Samadouny, S.A. El-Agouz, A.M. Alshrombably, K.S. Abdelfatah, M.A. Said, Performance of the one-ended evacuated tubes as medium temperature solar air heaters at low flow rates, Sustainable Energy Technologies and Assessments 30 (2018) 174–182. https://doi.org/10.1016/j.seta.2018.10.002.

[71] P.Y. Wang, H.Y. Guan, Z.H. Liu, G.S. Wang, F. Zhao, H.S. Xiao, High temperature collecting performance of a new all-glass evacuated tubular solar air heater with U-shaped tube heat exchanger, Energy Conversion and Management 77 (2014) 315–323. https://doi.org/10.1016/j.enconman.2013.08.019.

[72] X. Zhang, S. You, H. Ge, Y. Gao, W. Xu, M. Wang, M., T. H., X. Zheng, Thermal performance of direct-flow coaxial evacuated-tube solar collectors with and without a heat shield, Energy Conversion and Management 84 (2014) 80–87. https://doi.org/10.1016/j.enconman.2014.04.014.

[73] A.A. Razak, Z.A.A. Majid, M.H. Ruslan, K. Sopian, Thermal performance analysis of staging effect of solar thermal absorber with cross design, Malaysian Journal of Analytical Sciences19 (2015) 1264–1273.

[74] G. Martínez-Rodríguez, A.L. Fuentes-Silva, M. Picón-Núñez, Solar thermal networks operating with evacuated-tube collectors, Energy 146 (2018) 26–33. https://doi.org/10.1016/j.energy.2017.04.165.

[75] M. Picón-Núñez, G. Martínez-Rodríguez, A.L. Fuentes-Silva, Targeting and design of evacuated-tube solar collector networks, Chemical Engineering Transactions 52 (2016) 859–864. https://doi.org/10.3303/CET1652144.

[76] A.P. Singh, O.P. Singh, Performance enhancement of a curved solar air heater using CFD, Solar Energy, 174 (2018) 556–569. https://doi.org/10.1016/j.solener.2018.09.053.

[77] M. Hayek, Investigation of evacuated-tube solar collectors performance using computational fluid dynamics, in: 2009 International Conference on Advances in Computational Tools for Engineering Applications, Beirut, Lebanon, 2009, pp. 240-244. https://doi.org/10.1109/ACTEA.2009.5227901.

[78] S. Beekers, Efficiency of an evacuated tube solar collector under varying operating conditions and configurations, Master's thesis, Eindhoven University of Technology, Eindhoven, Netherlands, 2021.

[79] A.I. Sato, V.L. Scalon, A. Padilha, Numerical analysis of a modified evacuated tubes solar collector, in: International Conference on Renewable Energies and Power Quality, 2012, pp. 384–389. https://doi.org/10.24084/repqj10.322

[80] B. Du, P.D. Lund, J. Wang, Combining CFD and artificial neural network techniques to predict the thermal performance of all-glass straight evacuated tube solar collector, Energy 220 (2021) 119713. https://doi.org/10.1016/j.energy.2020.119713.

[81] K. Ahmed, O. Le, I. Andri, A. Pina, J. Fournier, CFD study of heat transfer enhancement and fluid flow characteristics of laminar flow through tube with helical screw tape insert, Energy Procedia 160 (2019) 699–706. https://doi.org/10.1016/j.egypro.2019.02.190.

[82] A.W. Badar, R. Buchholz, Y. Lou, F. Ziegler, CFD based analysis of flow distribution in a coaxial vacuum tube solar collector with laminar flow conditions, International Journal of Energy and Environmental Engineering 3 (2012) 24. https://doi.org/10.1186/2251-6832-3-24.

[83] S. Aggarwal, R. Kumar, S. Kumar, M. Bhatnagar, P. Kumar, Computational fluid dynamics based analysis for optimization of various thermal enhancement techniques used in evacuated tubes solar collectors: A review, Materials Today Proceeding 46 (2021) 8700–8707. https://doi.org/10.1016/j.matpr.2021.04.021.

[84] M. Iranmanesh, H. Samimi Akhijahani, M.S. Barghi Jahromi, CFD modeling and evaluation the performance of a solar cabinet dryer equipped with evacuated tube solar collector and thermal storage system, Renewable Energy 145 (2020) 1192–1213. https://doi.org/10.1016/j.renene.2019.06.038.

[85] M. Singla, V.S. Hans, S. Singh, CFD analysis of rib roughened solar evacuated tube collector for air heating, Renewable Energy 183 (2022) 78–89. https://doi.org/10.1016/j.renene.2021.10.055.

[86] B. Du, P.D. Lund, J. Wang, M. Kolhe, E. Hu, Comparative study of modelling the thermal efficiency of a novel straight through evacuated tube collector with MLR, SVR, BP and RBF methods, Sustainable Energy Technologies and Assessments 44 (2021) 101029. https://doi.org/10.1016/j.seta.2021.101029.

[87] J. Hu, G. Zhang, Performance improvement of solar air collector based on airflow reorganization: A review, Applied Thermal Engineering 155 (2019) 592–611. https://doi.org/10.1016/j.applthermaleng.2019.04.021.

[88] P. Singh, M.K. Gaur, Environmental and economic analysis of novel hybrid active greenhouse solar dryer with evacuated tube solar collector, Sustainable Energy Technologies and Assessments 47 (2021) 101428. https://doi.org/10.1016/j.seta.2021.101428.

[89] A. Mahesh, C.E. Sooriamoorthi, A.K. Kumaraguru, Performance study of solar vacuum tubes type dryer Performance study of solar vacuum tubes type dryer, Journal of Renewable and Sustainable Energy 4 (2012) 063121. https://doi.org/10.1063/1.4767934.

[90] S. Singh, R.S. Gill, V.S. Hans, M. Singh, A novel active-mode indirect solar dryer for agricultural products: Experimental evaluation and economic feasibility, Energy 222 (2021) 119956. https://doi.org/10.1016/j.energy.2021.119956.

[91] E. Veeramanipriya, A.R. Umayal Sundari, Performance evaluation of hybrid photovoltaic thermal (PVT) solar dryer for drying of cassava, Solar Energy 215 (2021) 240–251. https://doi.org/10.1016/j.solener.2020.12.027.

[92] S. Malakar, M. Alam, V.K. Arora, Evacuated tube solar and sun drying of beetroot slices: Comparative assessment of thermal performance, drying kinetics, and quality analysis, Solar Energy 233 (2022) 246–258. https://doi.org/10.1016/j.solener.2022.01.029.

[93] C. Dutta, D.K. Yadav, V.K. Arora, S. Malakar, Drying characteristics and quality analysis of pre-treated turmeric (Curcuma longa) using evacuated tube solar dryer with and without thermal energy storage, Solar Energy 251 (2023) 392–403. https://doi.org/10.1016/j.solener.2023.01.032.

[94] T. Rajagopal, S. Sivakumar, R. Manivel, Development of solar dryer incorporated with evacuated tube collector, International Journal of Innovative Research in Science, Engineering and Technology 3 (2014) 2655–2658.

[95] M. Hosseinzadeh, A. Faezian, S.M. Mirzababaee, H. Zamani, Parametric analysis and optimization of a portable evacuated tube solar cooker, Energy 194 (2020) 116816. https://doi.org/10.1016/j.energy.2019.116816.

[96] N. Mehla A. Yadav, Thermal analysis on charging and discharging behaviour of a phase change material-based evacuated tube solar air collector, Indoor Built Environment 27 (2018) 156–172. https://doi.org/10.1177/1420326X16667626.

[97] V. Vedanarayanan, J. Dilli Srinivasan, K. Arulvendhan, P. Thirusenthil Kumaran, R. Selvakumar, T. Maridurai, M. Sudhakar, S. Al Obaid, S. Alfarraj, M.M. Raj, Performance development and evaluation of solar air collector with novel phase change material, International Journal of Photoenergy 2022 (2022) 3787141. https://doi.org/10.1155/2022/3787141.

[98] M.H. Dhaou, S. Mellouli, F. Alresheedi, Y. El-Ghoul, Numerical assessment of an innovative design of an evacuated tube solar collector incorporated with pcm embedded metal foam/plate fins, Sustainability (Switzerland) 13(19) (2021) 10632. https://doi.org/10.3390/su131910632.

[99] S. Gorjian, H. Ebadi, F. Calise, A. Shukla, C. Ingrao, A review on recent advancements in performance enhancement techniques for low-temperature solar collectors, Energy Conversion and Management 222 (2020) 113246. https://doi.org/10.1016/j.enconman.2020.113246.

[100] G. Sadeghi, M. Najafzadeh, M. Ameri, Thermal characteristics of evacuated tube solar collectors with coil inside: An experimental study and evolutionary algorithms, Renewable Energy 151 (2020) 575–588. https://doi.org/10.1016/j.renene.2019.11.050.