CHAPTER 2

SOLAR THERMAL SYSTEMS WITH FLAT PLATE REFLECTOR - LITERATURE REVIEW

2.1 Overview

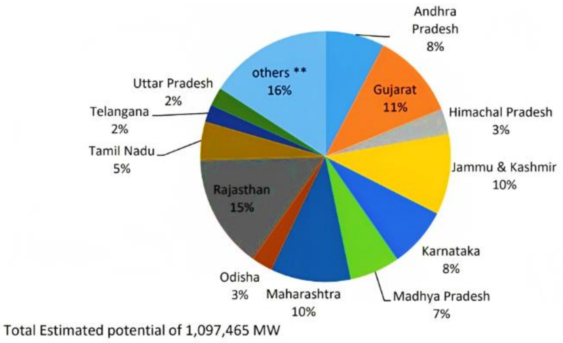
The present chapter begins by discussing the importance of RESs for a nation's development. It then looks at the drawbacks of using NRESs excessively. A brief summary of solar energy availability and possible remedies is given. After that, the chapter explores several STS applications for diverse use cases while pointing out the system's current flaws. Additionally, the use of STS with FPTRs for various applications are investigated in detail, with a focus on the challenges that are currently present with the solar system evaluation techniques already in use. The discussion extends to the availability of various numerical tools for analysing STS with FPTRs, drawing insights from recent literature. The chapter addresses the shortcomings identified in the current literature regarding grid refinement processes and discusses potential methods for rectification. The research gaps identified through a comprehensive literature survey are outlined, leading to the delineation of the objectives of the current study at the chapter's end.

2.2 The need of solar thermal system

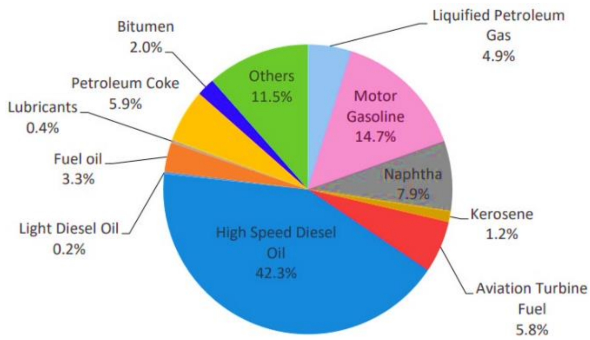
Energy is crucial for a nation's development as deriving from either RESs or NRESs. As a developing nation, India has significant energy needs for its development, including industries and household applications. Table 2.1 provides information from the year 1980 to 2020 regarding key energy and economic indicators that play a vital role in India's progress. It is evident that as India's GDP increased, energy consumption also rose at the same rate. Furthermore, there is a noticeable surge in coal and oil consumption, as indicated in Table 2.1. A detailed explanation of India's projected energy usage till the year 2020 is shown in Fig. 2.1. It gives in depth information on the patterns, trends, and percentages of energy consumption in the nation's different sectors or sources during the period of time. Table 2.2 shows the potential for RES in 2020, 2025, and 2030. From the table, it is observed that there is a gradual increase in the potential for solar energy. The state-level potential for producing energy from RES is shown in Fig. 2.1(a). When compared to other states, Gujarat and Rajasthan exhibit the highest levels of engagement. Nonetheless, the states of Telangana, Odisha, and Uttar Pradesh exhibit extremely low potential for producing renewable energy, highlighting the real void in which these sources require development. The output of petroleum products by type for the 2019–20 fiscal year is shown in Fig. 2.1(b). The installed capacity by year and energy produced from various sources are shown in Figs. 2.1(c) and 2.1(d), respectively.

Table 2.1 Critical energy and economic metrics in India. (“India Energy Outlook,” 2021)

#	Indicator	Indicator participation in (%) year wise			
		1980	1990	2000	2020
1.	GDP per capita	5.2	3.2	6.4	7.2
2.	Energy demand per capita	13	18	25	32
3.	Oil demand per capita	18	13	18	30
4.	Coal demand per capita	13	21	38	60
5.	Residential energy use	21	19	32	41
6.	Steel and cement use	19	13	28	40
7.	Car ownership	13	2	5	18
8.	CO_2 emissions per capita	2	16	21	39



(a)



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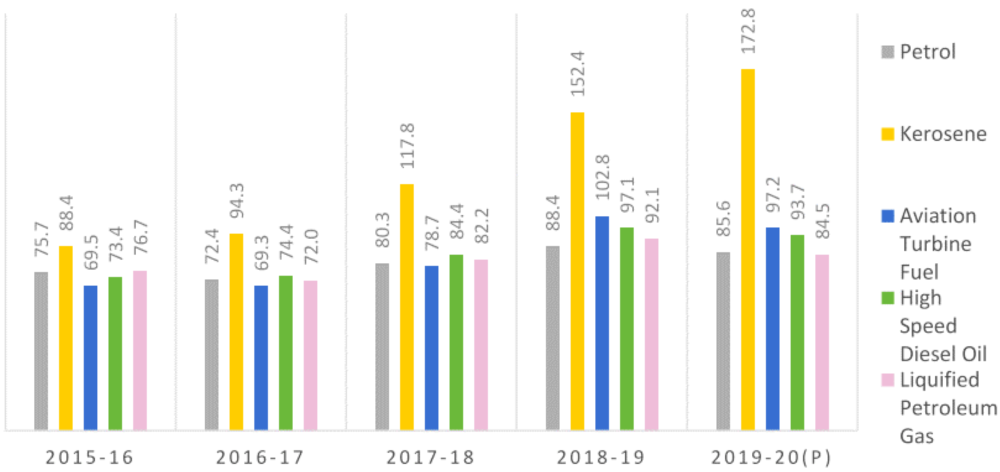

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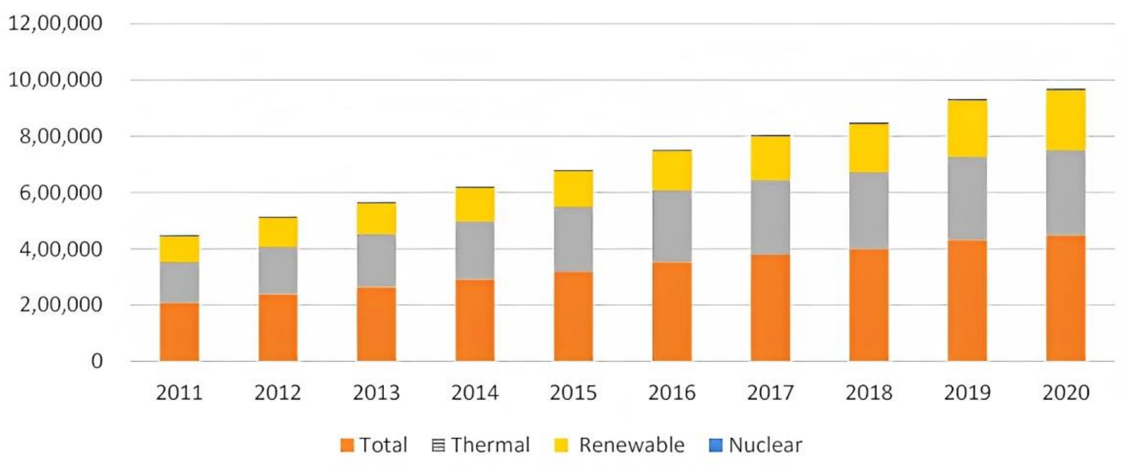


(d)

Fig. 2.1 Specifics of India's energy usage, (a) estimated potential of renewable energy as of march 31, 2020, (b) production of petroleum products by type of product (c) yearly wholesale price indices of selected energy commodities, and (d) yearly and state-wide installed capacity of generation of electricity in MW (Sharma Naresh Kumar, R Savithri, 2021)

Table 2.2 Possible potential of renewable energy in India (Sharma Naresh Kumar, R Savithri, 2021)

#	Types of RES	Possible potential (%)	Projected potential (%)	Projected potential (%)
		2020	**2020 – 25**	**2020 – 30**
1.	Solar energy	53.2	58.6	62.3
2.	Wind power energy	19.5	20.3	12.3
3.	Geothermal energy	13.5	15.3	10.2
4.	Hydro power energy	10.9	8.6	12.3
5.	Biomass power energy	1.3	1.1	0.7
6.	Tidal power energy	1.2	1.2	1.3
7.	Cogeneration bagasse energy	0.5	0.8	0.9
8.	Others energy	0.6	0.2	0.2

The energy consumption by the different sector is presented in Table 2.3 and it is observed that there is exponential energy consumption in the industrial section can be observed. Investigation reveals a notable decline in energy consumption within both the domestic and agricultural sectors. However the commercial section is outperform the all sector and shows sudden growth in energy requirement in upcoming years. Besides, according to the literature, it has been observed that the excessive utilization of NRES poses significant adverse effects on a nation (A. Patel et al., 2016). Table 2.3 presents the energy consumption across different sectors for the years 2019, 2020, and 2025 (projected) for the Indian continent. The data shows exponential energy consumption in the industrial sector, while the domestic and agriculture sectors exhibit poor energy consumption. However, the commercial sector outperforms all other sectors, displaying a sudden growth in energy requirements in the upcoming years. It is also observed that the excessive utilization of NRES poses significant detrimental environmental effects on a country and it get damage to the various aspects of the country on a large scale.

Table 2.3 Consumption of energy by sector during 2019 to 2020 of India (Sharma Naresh Kumar, R Savithri, 2021)

#	Sector	Energy consumption (%)	Green gas production (%)	
		2019-2020	2020	2020-25 (Projected)
1.	Industries	42.7	58.3	63.5
2.	Domestic	24.0	16.3	12.3
3.	Agriculture	17.7	12.3	9.6
4.	Commercial	8.0	12.3	19.6
5.	Traction and railways	1.5	0.3	0.3
6.	Others	6.1	1.2	1.1

The need for RES has become increasingly apparent in addressing these issues. Harnessing energy from renewable sources like solar, wind, hydro, and geothermal power offers a sustainable alternative. On the other hand, it comes from natural resources that replenish within a human timescale, making them sustainable and not depleting over time like finite fossil fuels (Manieniyan et al., 2009). This ensures a continuous and reliable energy supply for future generations. Using it reduces dependence on NRES and promoting energy security and reducing geopolitical risks associated with resource availability (Mannhardt et al., 2023). Additionally, transitioning to RES is crucial to mitigate climate change, reduce pollution, and preserve natural resources. Only 9% of India's total power output came from RES by the year 2020, which indicates a low installed capacity. The estimated potential of RES and consumption of electricity sector wise for Indian economic perspective has been depicted in Fig 2.1 (a). The greatest source of RES is the sun and its direct as well as indirect impacts on the globe (solar radiation, wind, falling water, and various plants, i.e. biomass), gravitational forces (tides), and the heat of the earth's core are used to power the system of energy consumption (Bellos, 2019). These resources offer huge energy potential, but they are widely distributed and difficult to access.

Solar energy, in particular, is vital as a primary energy source among the available numerous RES. The sun provides abundant and consistent energy that can be harnessed through solar technologies. By tapping into solar power, nations can significantly cut down on greenhouse gas emissions, combat climate change, and contribute to global environmental sustainability (C.-H. Wang et al., 2022). Solar energy is versatile, with applications ranging from generating electricity through photovoltaic cells to using solar thermal applications for heating and industrial processes. Harnessing solar power not only diversifies the energy mix but also promotes technological innovation and economic growth in the renewable energy sector. Useful from the sun can be harness through solar photovoltaic and STS (Dincer, 2000).

In the following discussion, a brief overview of statistics aims to provide a more quantitative perspective on the comparison between STS and solar photovoltaic. In terms of efficiency, modern solar photovoltaic systems can achieve conversion efficiencies ranging from 9% to 12%, depending on the type of solar photovoltaic cells used (Patel, Jay, 2023). In contrast, STSs typically having higher conversion efficiencies ranging from 18% to 34%, compared to solar photovoltaic cell. These numbers underscore the advantage of STSs in directly converting sunlight into thermal energy with superior efficiency (J. Patel & Patel, 2023). Cost considerations are crucial in the renewable energy landscape. Table 2.4 shows the comparative cost comparison between the solar photovoltaic and STS. This cost has experienced a significant increment over the past decade and observed that solar photovoltaic is more economically challenging (SunShot, 2012). On the other hand, STSs, especially concentrating solar power plants, may entail higher upfront costs. These cost differences highlight the financial aspects that require careful consideration when choosing between the two technologies. It's important to note that the manufacturing phase of solar photovoltaic panels contributes substantially to their environmental impact. In contrast, STSs, with their ability to provide dispatch able power through advanced storage methods, contribute to grid stability and present a competitive environmental profile. These statistics emphasize the quantitative aspects of the solar thermal and solar photovoltaic comparison, offering a data-driven perspective on their efficiency, cost, and environmental implications. As technology continues to advance, these numbers may evolve, underscoring the ongoing importance of research and development in the field of solar energy (Herrando et al., 2023). In the following discussion the ray tracing simulation process is discuss.

Table 2.4 Cost comparison of solar thermal system and solar photovoltaic (Herrando et al., 2023)

#	Technology	Benchmark price (2010) (Rs./W)	Reference price (2021) (Rs./W)
1.	Commercial rooftop photovoltaic	5.00	3.63
2.	Residential rooftop photovoltaic	6.00	4.63
3.	STS	7.20	3.23

2.3 Ray tracing simulation

Ray tracing simulation (RTS) is crucial for advancing or improvising a given solar applications, providing detailed insights into the behavior of sunlight when it interacts with different surfaces and materials. This technique models how light rays travel through the solar energy system, considering reflection, refraction, and absorption. These are key for making solar energy systems more efficient and well-designed. Ray tracing is a basic computational method that simulates the path of light rays in complex settings. It helps analyse the effect of solar radiation on solar energy devices. By showing the sunlight interaction with solar panels, concentrators, or collectors, ray tracing helps improve the design of these devices to capture and use as much energy as possible. Additionally, ray tracing is used for thermal analysis, ensuring visual accuracy, understanding how materials interact with light, and analyzing shadows and shading. This makes it a versatile tool for enhancing solar energy systems.

In the context of FPTR augmented STS the accurately assessing its optical performance is very essential. This is because even a loss of a single ray can significantly impact energy capture, making the analysis of solar reflecting systems' optical performance critical (Georgiou et al., 2013). This kind of analysis helps understand the behavior of solar beam rays after reflection from the reflectors and it helps in optimization of the system's design to maximize sunlight capture to convert it into usable energy. Literature suggests that several theories make the RTS method both easy to implement and accurate (Bellos & Tzivanidis, 2019a). in an investigation the application of RTS is shown to analyze the optical characteristics of a heliostat reflector and a receiver where all the rays getting concentrated is studied for the region of Spain (Cui et al., 2019). Fig. 2.2 illustrates the solar radiation in relation to the dual-axis tracked heliostat. Where, the Solar incidence optic cone center vector ($\overrightarrow{S_s}$) give the information about the altitude angle of the Receiver's global axis and the receiver's rotating axis (R_s). The value of $\overrightarrow{S_s}$ can be calculated with use of Eq. (2.1) and the R_s denotes the solar rotation matrix, and its value is chosen to be [0, 0, 1]. Besides, the Primary reflected optic cone center ($\overrightarrow{t_s}$) and the value of unit vector of the Heliostat global axis ($\overrightarrow{\eta_H}$) are calculated with use of Eq. (2.2) and Eq. (2.3) simultaneously. The results indicate a 12% variation between the numerical results and experimental results. The deviation is high and it stresses the need for an improved testing methodology dedicated for FPTR-based STS.

$$\overrightarrow{S_s} = [0,0,1]R_s = [\cos\alpha_s \cos\gamma_s, \cos\alpha_s \sin\gamma_s, \sin\alpha_s] \quad (2.\ 1)$$

$$\overrightarrow{t_s} = [\cos\alpha_{h2t} \cos\gamma_{h2t}, \cos\alpha_{h2t} \sin\gamma_{h2t}, \sin\alpha_{h2t}] \quad (2.\ 2)$$

$$\overrightarrow{\eta_H} = [\cos\alpha_H \cos\gamma_H, \cos\alpha_H \sin\gamma_H, \sin\alpha_H] \quad (2.\ 3)$$

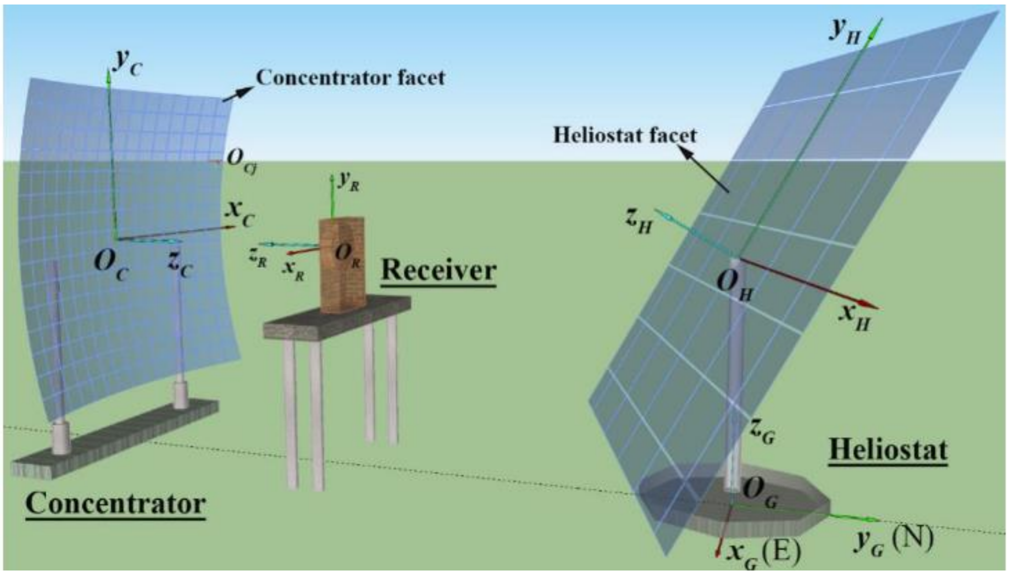


Fig. 2.2 Schematic diagram of the solar furnace and coordinate systems (Cui et al., 2019)

In an another study, researchers had utilized an RTS method to investigate and enhance the performance of the Solar furnace (SF-60) located in Almeria, Spain (Jafrancesco et al., 2014; Pereira et al., 2019). They developed a specific program written in C language that is based on the RTS method. The study noted improvement of around 8% in the value of η_{thr} of numerically constructed models when appropriate assumptions were considered. However, study clearly noted certain limitations of RTS technique, such as the requirement for rigorous statistical analysis and the modeling of complex geometries. Another mathematical approach followed in several literature is to use Monte Carlo optimization method (MCOM) [ref. 1, 2 3 and 4]. The approach can be considered as an improved method compared to RTS, as the method can handle multiple rays simultaneously. Several challenges are addressed and the method is simple to implement when, multiple ray reflection is followed. In this case handling information is easy compared to that in case of RTS. MCOM has not been widely utilized to analyse the STS, although it is simple to implement, the results showed that it is comparatively extensive and computationally demanding due to involvement of complex mathematics. However, it is worth reviewing the available literature on the MCOM and the corresponding lacunae present in it, the summary of the same is followed herein.

In one of the investigation the experimental study of an Octagonal shaped receiver (OSR) of the SF-60 using the MCOM was carried out to understand the optical performance of the system (Pereira et al., 2020). The experiment had been conducted to demonstrate the influence of homogeneous flux distribution on the OSR surface. The actual experimental model of the OSR is as shown in Fig. 2.3 (a) and the corresponding flux distribution profile on the receiver plate is as shown in Fig. 2.3 (b). The findings helps in identifying the fact that it was advisable to use a multi-mirror homogeniser based receiver to avoid radiation losses at the receiver surface. In an another study, the numerical investigation studied the thermal performance of STS to understand and interpret the impact of reflector having spherical and parabolic aperture areas (Jafrancesco et al., 2014). The results indicate that spherical mirrors can achieve higher temperatures, while parabolic reflectors offer a more uniform distribution of sunlight to the receiver. Additionally, the importance of optical factors like focal length, angle of curvature, and reflectivity (ρ) significantly affects the STS's overall performance, as shown in Table 2.5. The comparative discussion of the RTS and MCOM shows that both methods perform well for simulating the STS when detailed information on single rays is not needed. However, for tracking the path of individual solar beam rays and identifying their intersection points on adjacent reflectors, more specific data and detailed analysis is required. In the following discussion the different types of reflectors used with STS are explored.

(a) (b)

Fig. 2.3 (a) Radiation homogenisers with 8 sides, seen from top and (b) Energy flux received at base while using homogeniser is used (Pereira et al., 2020).

Table 2.5 Summary of RTS method and MCOM used for numerical analysis of STS.

Authors	**Method**	**Objective**	**Observation**
(Nandwani, 1988)	RTS	To analyse the optical performance of box type solar oven with use of four booster reflectors.	It is observed that there is 10 % of deviation in the validation results of numerical study with the experimental results.
(C. F. Chen et al., 2010)	RTS	To examine the different geometry to obtain higher value of C with use of heliostat reflectors.	RTS helps in understanding the homogeneous distribution of multiple solar rays on the receiver.
(Chong &	RTS	To analyse the effect of	Using azimuthal alignment, the total

Tan, 2012)		azimuthal alignment system with FPTR on the thermal performance of the STS.	cost of tracking is reduced by 34%, and RTS helps to align the system with the sun.
(Terrón-Hernández et al., 2018)	RTS	To experiment appropriate position of compound parabolic collector to achieve the temperature range from 100 °C to 230 °C for baking application with use of STS.	Validating experimental data with numerical studies presents a significant challenge when RTS is employed as the computational method.
(Yurcheko et al., 2015)	RTS	To perform numerical analysis of non-tracking type compound parabolic collector with heliostat reflector to observed it thermal performance.	Performance to cost is 12 % is more and the peak temperature of the system mount to 146°C .
(Cheng et al., 2014)	MCOM	To numerical analyse the performance of the STS with using CTR under different solar altitude condition.	With use of MCOM the reflecting system efficiency is obtained and it worked efficiently in low solar altitude angle when the value of focal length is 0.47m.
(Petrasch, 2014)	MCOM	To develop open source numerical model for testing cylindrical, spherical and parabolic concentration solar system with FPTR.	The code has been thoroughly validated and tested, showing good agreement with pre-existing code used for benchmarking. However, it is difficult to understand the path followed by the rays using the MCOM method.
(Duan et al., 2020)	MCOM	To develop a numerical model based on MCOM for simulating the radiative flux distribution on the receiver, which reflected by large heliostat field.	A comparative investigation of the various configurations of the heliostat mirror on the field produced the best results for the tool's ultimate performance.
(Zhao et al., 2018)	MCOM	To analyse the performance of solar cooker with FPTR.	MCOM helps to simulate the overall optical behaviour of the STS.
(Nydal, 2014)	MCOM	To investigate the effect of two FPTR on the performance of concentrating type collector used with sensible heat storage	Simulating complex geometric structures numerically is quite challenging when using MCOM.

material.

2.4 Solar thermal system with curved type and flat plate type reflectors

As discussed previously the STS is further divided into two main parts: the SCS and the STS with reflectors. SCS is further classified into concentrating type collector and flat plate type collector. The SCS requires robust construction materials for supporting the structural load of the collector and receiver together, as they both are connected together. The concentrating type collector additionally requires a dual-axis tracking system for better carrying capacity, while the flat plate type collector system do require any dual-axis tracking, although holding and moving it according to the sun can be a challenging task (Tyagi et al., 2021). However, a STS with a reflector is easy to operate and manageable to perform even under critical solar radiation conditions. In addition, the shape of the reflector and its location in the system plays a very crucial role in predicting the optical efficiency (η_{opt}) of the system.(Khullar et al., 2018). Commercially there are mainly two types of solar reflectors available, based on their geometry; (a) CTR and (b) FPTR (Bellos et al., 2020). The schematic representation of the application of CTR and FPTR for concentrating type collector is as shown in Fig. 2.4 and Fig. 2.5, respectively. In Fig. 2.4, it is observed that a parabolic reflector functions as a CTR for the concentrating type collector, directing all rays towards the receiver positioned at the focal point of the concentrating type collector. Continuous tracking is necessary to precisely reflect the solar rays to the focal point. On the other hand, Fig. 2.5 illustrates the use of an FPTR to redirect all incident rays into the system without concentrating them at a focal point. Despite the lack of concentration, the simplicity and ease of maintenance of the FPTR contribute to its popularity. In the following discussion, differences in geometric properties, final applications, maintenance costs, and manufacturing possibilities are explored.

In one of the study solar still with CTR was investigated and aimed at enhancing the efficiency and cost-effectiveness. The results indicated a notable improvement in η_{thr} due to the use of CTR augmented solar still. However, this improvement obtained not without the expense of increased overall system costs, which posed a significant drawback for both commercial and industrial applications (Momeni et al., 2019). The study of solar water heaters with CTR and the analysis of numerical models for solar radiation conditions and shadow conditions have been conducted (Madadi Avargani et al., 2020). However, it has been claimed that system is sensitive and even a minor misalignments in the tracking system can lead to significant losses in the system's thermal performance. Studying the results one can conclude that accurate tracking is crucial for STSs equipped with CTR. In another study, a STS with different CTR having different aperture areas were experimented (Saxena et al., 2022). The results indicated that a curved-shaped apertures may yield superior performance. However, the manufacturing of this particular shape is highly expensive under Indian conditions. This made this system an unfavourable choice for the commercial applications. Furthermore, a few studies have showed the effectiveness of CTR in solar thermal applications (Ciulla et al., 2020; Yılmaz et al., 2020). Due of the significant expenses involved in their construction, tracking, and maintenance, they continue the combined overall cost reaches very high and the system tends to be less appealing, especially in developing world.

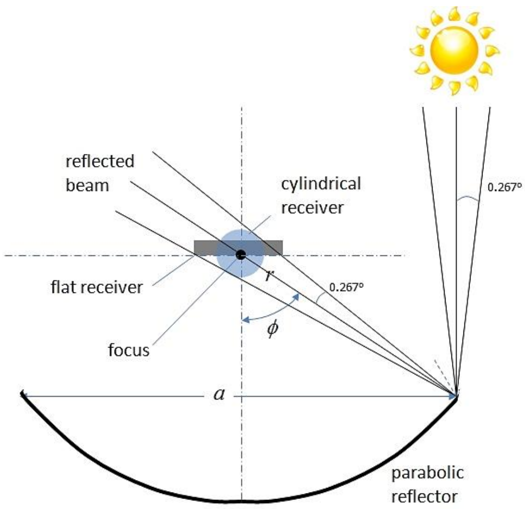


Fig. 2.4 Schematic representation of concentrating type collector with CTR (Tanaka, 2015b)

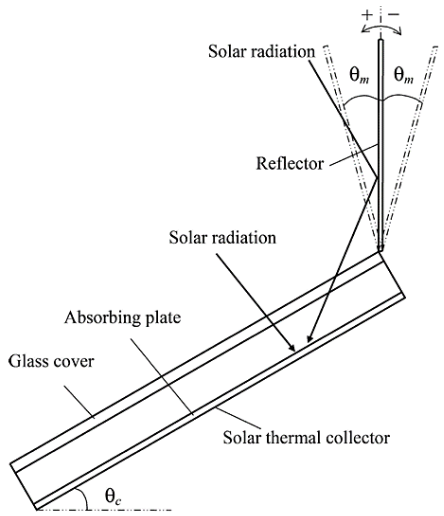


Fig. 2.5 Schematic representation of flat plate type collector with FPTR (Guidara et al., 2017)

On other hand, researchers noted that the STS having FPTRs require minimum maintenance to keep the system in good working condition and additionally the system can also provide better η_{opt} (Aragaw & Adem, 2022). Besides, owing to its simple design and easily accessible components, these systems also require minimal maintenance. Another major advantage is its durability, since FPTRs are made up of tough materials. Therefore, the overall system can survive a variety of weather situations (Wassie et al., 2022). As a flexible option for satisfying hot water and space heating demands, these systems are adaptable and can be implemented into both residential and commercial structures. However, very few literatures had demonstrated the effective way of extracting the solar energy by use of STS using FPTR. Table 2.6 mentions the range of STS applications for heating and cooling. It also presents the approximate temperature range for various applications, providing a better understanding of the achievable temperatures. The following discussion highlights a few important studies related to the impact of FPTRs on solar thermal applications.

Table 2.6 Applications of solar energy in general and their service temperature (Bellos & Tzivanidis, 2018a; Yadav & Banerjee, 2016)

Categories	Applications	Temperature
Heating (50 to 260℃)	Domestic hot water production	~50 ℃
	Space heating applications	50 º to 70 ℃
	Drying applications	50 º to 70 ℃
	Cooking and baking	120º to 260 ℃
Cooling/refrigeration with sorption machines (80 to 150 ℃)	Single-stage machines	80 ℃
	Multistage machines	150 ℃
Industrial heat, for instance, steam production (90 to 400 ℃)	Washing procedures	90 ℃
	Chemicals production	200 ℃
	Methanol reforming	~300 ℃

The influence of angle made between reflector and the horizontal plane (Φ) on the performance of a solar flat plate type collector with two FPTRs were investigated in the '*Ouargla*' area of Algeria (Rachedi et al., 2022). The findings show that the ideal value of Φ for all reflectors in the fully monitored system stays constant at 67° throughout the year. In the Egyptian desert, a research of a similar kind was carried out using a solar flat plate type collector and four FPTRs (Ibrahim & El-Reidy, 1995). This research also lead to the similar conclusion as that of previous one. In an another experimental study a typical solar photovoltaic system with additional flat mirrors were investigated to find out improvement in the performance (Zainulabdeen et al., 2019). The results demonstrated a significant improvement of 22% in the overall efficiency due to the use of these additional reflectors. The thermal performance of a STS can also be enhanced through the incorporation of additional flat mirrors or reflectors in the similar fashion into any system. Following section extensively discusses the performance augmentation of the FPTRs in the value of η_{thr} of a given STSs.

An experimental study conducted to enhance the overall performance of a solar thermal-based water heating system having FPTR, in a conventional water heating systems (Fernández-González et al., 2018). The results demonstrate that the water heating system with a FPTR has shown increase in output temperature by a significant amount of 47°C compared to a conventional system. In an another performance augmentation study in which the focus was to investigate the impact of changes in the angle (Φ) of FPTR on the functionality of solar flat plate type collectors (Qiu et al., 2021). The use of a FPTR in a solar still improves the device's efficiency by reflecting, or more precisely, by directing the additional sun rays back into the system, which would have otherwise been lost or escape out of the system (Ketabchi et al., 2019). Numerical investigation on a solar still supports the argument that the re-reflected rays are key to increase the temperature of the floating salty water in the system. The effectiveness of a solar cooker fitted with a three-sided FPTR was numerically investigated. The study concluded that, compared to a regular solar cooker the improved solar cooker's average value of η_{thr} can be improved by up to 27% (Khan et al., 2022). Moreover, the adapted solar cooker exhibited minimal operating and maintenance costs, and the benefits of it offered outweighed the expenses associated with its modification. Table 2.7 displays the various applications of FPTR in STS, particularly in linear Fresnel reflector applications with FPTR.

Table 2.7 Brief Summary of FPTR used for different STS

Authors	**Objective of study**	**Observation**
(Y. Zhu et al., 2017)	To design and analyse a scalable linear Fresnel reflector with use of multiple flat reflector for residential cooking application.	By use of scalable linear Fresnel reflector, the maximum thermal efficiency is achieved is 64% compared to a simple linear Fresnel reflector system.
(Apaolaza-Pagoaga et al., 2023)	To investigate the effect of partial load on the performance of funnel solar cooker made out of flat reflector.	Overall 11% reduction in the thermal performance of the funnel cooker observed which can be overcome with use of a glass dome type cover fitted over the cooker.
(Wassie et al., 2022)	To predict the effect of flat mirror on the performance of solar cooker.	The cooker with three flat mirrors increased the thermal efficiency by about 35% more than the conventional cooker.
(J. Zhu & Huang, 2014)	To perform numerical ray tracing simulation to predict the performance of linear Fresnel reflector	There is an improvement of 9.3% in the output temperature in case of linear Fresnel reflector used with two plane reflectors.
(Bellos & Tzivanidis, 2018b)	To study the performance of linear Fresnel reflector with nanofluid particles.	The heat transfer coefficient is found to be enhanced close to 30–35% due to combination of nanofluid particles and use of linear Fresnel reflector
(Lin et al., 2013)	To predict the performance of flat plate reflector based solar collector prototype with a modified V-shaped cavity receiver	This hybrid system increased efficiency of 18 % compared to a simple system with highest temperature reaches to 150 ℃.
(Tawfik et al., 2021)	To examine the performance of solar cooker with incorporating flat plate internal reflectors.	The thermal efficiency of cooker with internal reflector is increased to 12% compared to a conventional system.
(Harmim et al., 2013)	To analyse the effect of plane and curved reflector on the performance of solar cooker.	The solar cooker performed 7% better when it is subjected with curved reflector than flat plate reflector.
(Guidara et al., 2017)	To investigate numerically and experimentally the performance of solar furnace with flat reflector.	The performance of solar system is increased by 24% with used of four sided flat reflector over the system.

The experimental study of solar water heater having FPTRs was conducted, made-up of aluminium foils are employed to enhance the overall performance was conducted (Kostić & Pavlović, 2012). The results obtained indicate that the η_{thr} of the FPTR augmented solar collector increased by approximately 12 % compared to the conventional system commercially available in the market. A numerical investigation was performed to understand the impact of FPTRs on a similar kind of solar system as discussed previously (Baccoli et al., 2015). The findings indicated that the modified system with the FTPR outperformed the traditional system. Moreover, the additional cost of the reflector can be recovered by achieving higher efficiency. In another study, FPTRs were utilized in a compound parabolic collector to maximize intercepting area of the STS (Saberi et al., 2023). The final results indicated that incorporating a compound parabolic collector with FPTR led to an almost 40% increase in the overall power generation. A study on a solar photovoltaic mirroring system aimed at enhancing the energy extraction of an existing solar photovoltaic system by employing reflectors was conducted (Mansoor O et al., 2020). Their findings concluded that the proposed system achieved an energy extraction approximately of the order of 30% higher than conventional photovoltaic systems.

A comparative analysis between CTR and FPTR is presented. According to a comprehensive evaluation of the literature, choosing CTR usually results in a much higher initial cost roughly 30% more than FPTR (Pereira et al., 2020). The primary cause of this financial barrier is the complex design and sophisticated materials required for the production process coupled with specialised technology for making CTR reflectors. The statistical data reveals that the manufacturing capability and process of CTR is notably lower than that of FPTR and it is demonstrating a discrepancy in production efficiency of almost 25% (Duan et al., 2020). Because of the complex shape specifications and required precision, manufacturing takes longer than expected, which affects overall output and may result in higher prices per unit. A statistical study demonstrates that the long-term maintenance expenses for CTR are 20% more than those for FPTR. Because of its intricate designs, CTR requires specialist technicians and equipment, which raises the expense of continuous operations. In a broader context, material cost analysis indicates that the advanced materials required for CTR significantly contribute to their higher production costs, reflecting a material cost disparity of approximately 15% (Nydal, 2014). It is important to note that such disparity in the cost can be even more severe in developing country, e.g. India.

The principle cause of this is production of CTR in that case will have additional component of technology transfer cost to produce curved reflector surfaces. This aspect further underscores the economic implications of opting for CTR in solar thermal devices. The comparative studies underscore a complex trade-off between the cost and the efficiency, with FPTR emerging as a more economically viable solution in certain scenarios, especially, in developing economy. Despite the higher costs associated with CTR, its unique optical properties may justify investment in specific applications, demonstrating its superiority and resulting an efficiency gain of approximately 10% under optimal conditions (Jebasingh & Herbert, 2016). In summary, the decision-making process between CTR and FPTR involves a comprehensive analysis of cost components that involves; manufacturing efficiency, maintenance expenditures, material considerations, technology available (if not cost of importing) and the specific requirements of solar ray tracing simulations. This analysis suggests that, in the long run, FPTR has enough potential to emerge as a cost effective choice compared to CTR.

The effect of CTR and FPTR on solar photovoltaic system performance was examined in one of the literature (Choi et al., 2017). The study included three scenarios: one with CTR, one with FPTR, and one without using any reflectors. Fig. 2.6 shows the reflected solar radiation affects to the performance of solar photovoltaic system. However, Fig. 2.7 illustrates the normalized illuminance on the solar photovoltaic, revealing that FPTR performed best compared to CTR, and overall, FPTR outperformed CTR in terms of normalized illuminance. Furthermore, employing a dedicated numerical tool or software, along with a meticulous test methodology, proves instrumental in comprehending the optical and thermal behaviours of STS under single-beam conditions (Okonkwo et al., 2020). This approach helps in forecasting potential outcomes for FPTR based STS using the tool and testing methodology, as discussed in previous sections. The comparative analysis of numerical prediction validated by corresponding experimental results becomes more straightforward with the utilization of referred tool. In the subsequent discussion, review of literature is focused on the use of numerical tool for examining the behaviour of a single ray and its predicted path and how this method can be employed for testing of entire reflector system are systematically discussed.

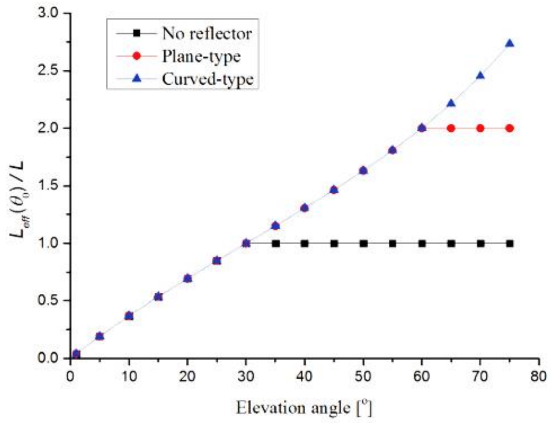


Fig. 2.6 Effect of actual reflection on solar photovoltaic with different elevation angles (Choi et al., 2017).

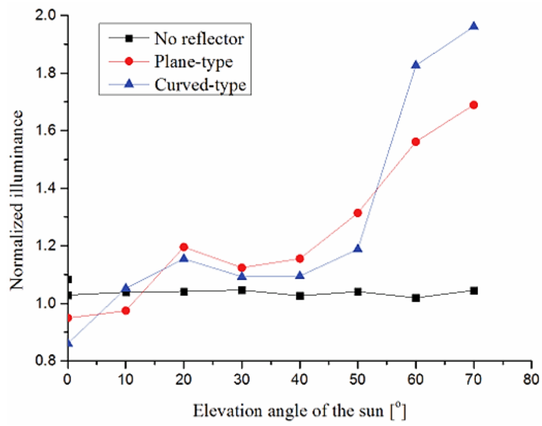


Fig. 2.7 Experimental results of solar photovoltaic augmented with different types of reflectors (Choi et al., 2017).

2.5 Testing procedures for predicting optical performance of STS with FPTR.

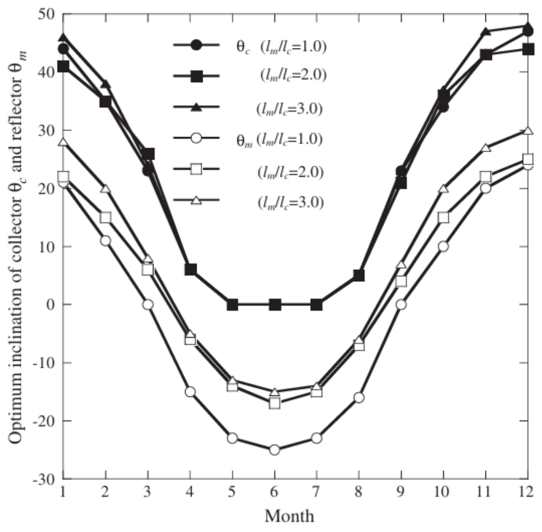
This section comprehensively discusses the diverse testing methodologies utilized for predicting and assessing the optical characteristics of STS with FPTR. The discussion that follows explores several techniques for optical characterization, including the Radiation area reflection method (RARM), Shadow light reflection (SLR) techniques, Collective ray method (CRM) and Multiple ray reflection procedure (MRRP).

Reviewing the open literature it was revealed that FPTR is not a new invention. It has been invented and utilized for many years and has a proven track record and well-demonstrated history. However, two fact are visible from the literature; a) there is very less proven commercial applications of it and b) there is currently very few relevant studies under taken for experimentally or numerically conducting investigations on it. In one of the study the experimental investigation of the impact of the FPTR on the performance of STS was studied to understand the optical performance of the proposed system (Alhaj & Al-Ghamdi, 2018). The experiment was done with the use of CRM. In the CRM, behaviour of several rays were studied and overall performance of the system was defined instead of considering only a single ray behaviour. The obtained results demonstrated that the improved system performed 21% better than the original or base system. In another literature, the application of FPTR used for harnessing solar energy with the use of evacuated tube water collectors was statistically studied and the numerical model of heat transfer into the evacuated tube was examined by considering CRM approach (Olczak & Olek, 2016). The results showed that the proposed system performed better in the months of winter. The other two methods discussed herein; RARM and MRRP also works on the similar principle of the CRM. The difference is that in CRM the path of rays cannot be exclusively observed or tracked while in later method the path can be easily tracked and analysed and can be studied under different possible scenarios.

An experimental investigation quantitatively analysed the effectiveness of a solar cooker equipped with FPTR for the North Asian region. The optical performance of the solar cooker was studied with the use of RARM. The result shows that that the optimized mirror placements suggested by the model helps in increasing the effectiveness as well as efficiencies of the solar cooker by 32.07% and 35.5%, respectively (Zamani et al., 2015). Besides, the complex nature of handling multiple solar rays and reflecting it to a specific area was made possible with the use of MRRP method for the setup having the Azimuth tracking of fixed mirror solar concentrators (ATFMSC). The overall performance of the ATFMSC was tested particularly in the low altitude solar radiation region. The results demonstrated that the ATFMSC achieved an annual net value of (i.e. η_{thr}) 61% and the temperature is reached up to 230°C on most of the sunny days. This efficiency actually surpasses that of parabolic trough collectors and even that achieved by fixed mirror solar collectors (L. Li et al., 2015).

Certain studies have shown that the use of FPTRs in solar thermal applications has significant potential to improve the overall efficiency and can reduce operational expenses and maintenance cost of the system in the long run, this may be due to simplified operations (Sareriya et al., 2022; Taki et al., 2018). These reflectors' simplifies design and makes it possible to extend the utility of STSs for both domestic as well as industrial applications. The application of solar flat plate type collector is also studied and used with booster FPTR for improving the thermal performance of the system for the region of Gazipur, Bangladesh (Bhowmik & Amin, 2017). The results demonstrated a significant increase in the collector efficiency with improved collector. The resulting increase in the overall efficiency reaches up to 12% high. The experimental investigation was performed using the SFPC with three-sided FPTR to analyse the impact of substituting water with surfactant-free rutile TiO_2-water nanofluids as the Heat transfer fluid (HTF) in the collector (Moravej et al., 2020). The outcomes emphasize the substantial advantages of employing nanofluids and booster reflectors in augmenting collector performance, especially in conditions of elevated solar irradiance and higher HTF flow rates. An experimental and numerical investigation were conducted in the desert region of Iran to optimize multilayer absorbing systems in solar flat plate type collector using cluster analysis (Khatibi et al., 2019). The results demonstrated a remarkable 23% improvement in overall thermal performance (i.e. η_{thr}) when compared to conventional model. Overall, from the above literatures, one can clearly conclude that the FPTR is therefore; a useful, cost effective and an efficient alternative to increase the effectiveness of solar thermal applications and can effectively contribute to a sustainable and affordable energy future. Looking to the relevance of the methods under consideration the mathematical description of the few of the above methods is briefly discussed in the subsequent section.

The numerical investigation with use of SLR method to observe the effect of booster FPTR on the performance of the solar thermal collector was studied (Tanaka, 2011). The results of optimum the angle made by the FPTR to the horizontal surface (θ_m) and the angle made by the collector to the horizontal surface (θ_c) for different months of the year is presented in Fig. 2.8 and the corresponding maximum solar radiation that can be received at the receiver plate is shown in Fig. 2.9. From the results it is observed that the optimum values of θ_m and θ_c are attained in the month of June while these values were maximum for the month of January and December. However there is no variation in the daily solar radiation absorbed at the absorber plate for the period spanning from spring to autumn, i.e. during months of March to September. Solar radiation received at the receiver surface attained maximum value in summer and the same is minimum during winter session.



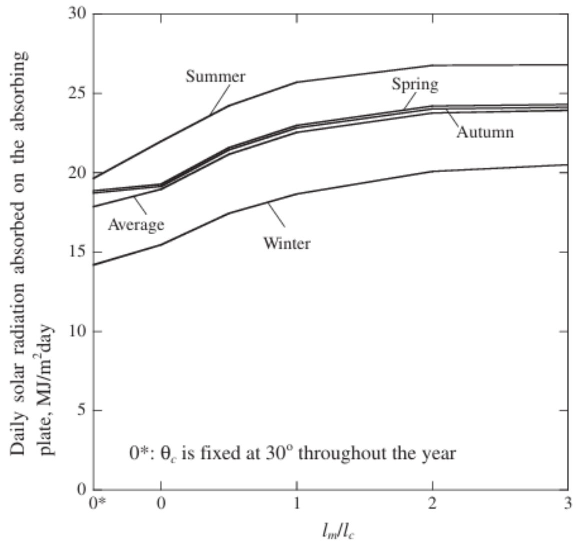


Fig. 2.8 Optimum angle of reflector and receiver to the horizontal plate for a year (Tanaka, 2011).

Fig. 2.9 Total yearly solar radiation received at the receiver plate (Tanaka, 2011).

The effect of FPTR on the performance of flat plate solar collector was numerically investigated and the optical performance was studied (Tanaka, 2015a). The schematic representation of numerical model of FPTR with flat plate type collector is as shown in Fig. 2.10. The Fig. 2.11 shows the mathematical description of FPTR augmented solar collector with utilisation of SLR method and it is observed that the data handling reaches very complex and it is difficult to keep track the record of the rays, especially when numbers of reflector and its size increases or number of rays considered are high.

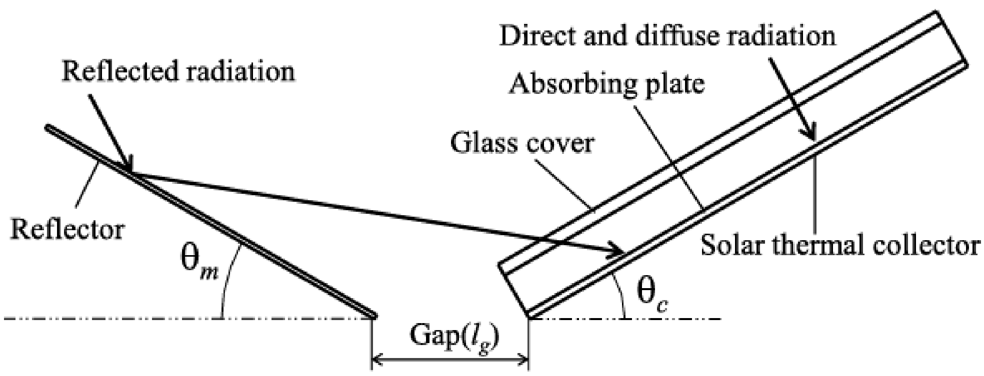


Fig. 2.10 Schematic representation of utilisation of FPTR in solar flat plate collector (Tanaka, 2015a)

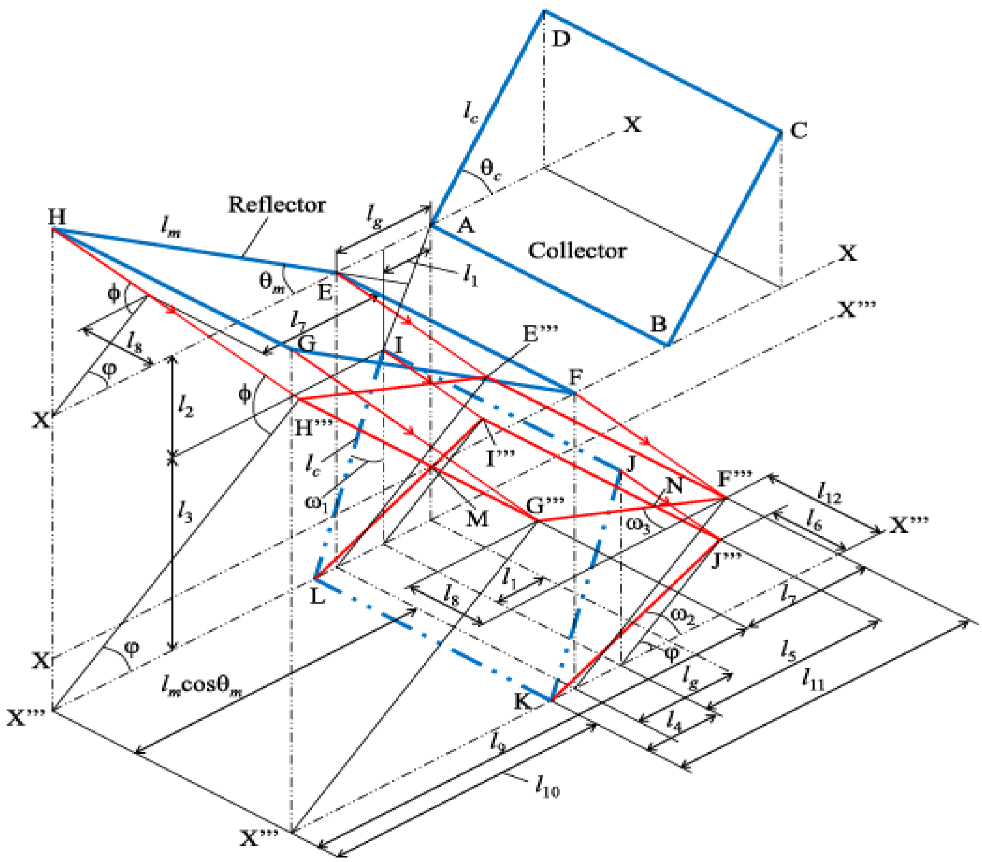


Fig. 2.11 Mathematical description of FPTR with flat plate collector with use of SLR method (Tanaka, 2015a).

All previous literature reviewed demonstrated a very strong capability to capture the behaviour of a ray in terms of mathematical formulations, thought its journey from entry to the exit of a given reflector system. However, it is essential to have a similar but effective method to experimentally capture the journey of a ray traversing under a given configuration. Prediction obtained by both methods can approve; a) reliability of an individual method followed, b) appropriateness of reflector design, c) design modification or optimisation of overall system. For this reason few of the relevant experimental studies are discussed herein.

The experimental study conducted to demonstrate the use of laser light to track the path of a single rays after reflection from the CTR (More et al., 2018). The schematic diagram and pictorial view of such experimental study when used to test CTR based solar system is as shown in Fig. 2.12 and 2.13. The result obtained by this study when compared with the numerical analysis conducted using Soltrace® software, it was observed that the testing methods employed are very effective in predicting the ray's path. Surprisingly, no dedicated study has been conducted till date to test configuration or for an application of FPTR-based solar systems. This is may be due to perception of lower feasibility of FPTR for thermal applications. Based on the above discussion, present study observed a clear research gap for testing of FPTR in line with CTR. One issue observed in this task is that the best way to test the FPTR is to understand the behaviour of single ray and its interaction as unlike in CTR, FPTR has multiple reflections before it reaches the targeted receiver surface. This calls for a fundamental requirement of a dedicated testing method to understand the complex behaviour of rays and the path it follows after it undergoes multiple reflections once reflected from the first reflectors and so on.

In pursuing dedicated path of each ray (as discussed above), the next relevant question is how many rays are sufficient for an accurate determination of the optical performance. There are conflicting answers found in the literature; some advocate an arbitrary approach, others following number of rays beyond which the performance variation ceases to exist. Without clearly specifying for which particular configuration of parameters one should carry out this exercise is a loosely defined criteria. There is also a limiting condition beyond which one cannot increase number of rays. Under this choosing a correct number of rays for the study is certainly a fundamental issue. In literature the problem of choosing particular number of rays is similar to choose an appropriate grid size for the discretisation. This makes it clear that the literature lacks a clear and a complete definition of grid refinement criteria. A detailed discussion on this aspect is covered in the subsequent section.

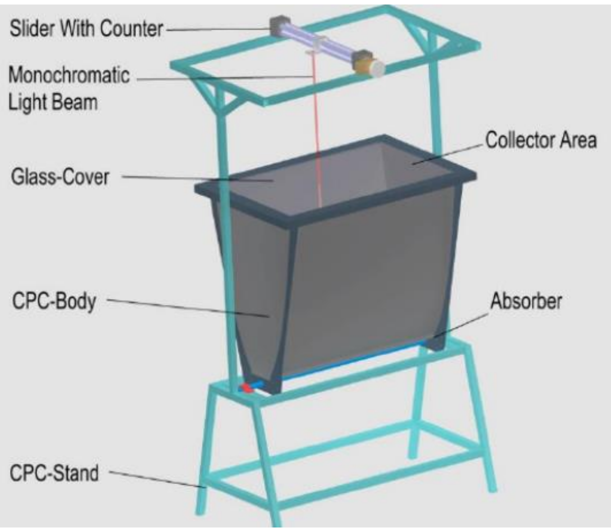


Fig. 2.12 Schematic representation of compound parabolic collector with laser light testing method (More et al., 2018).

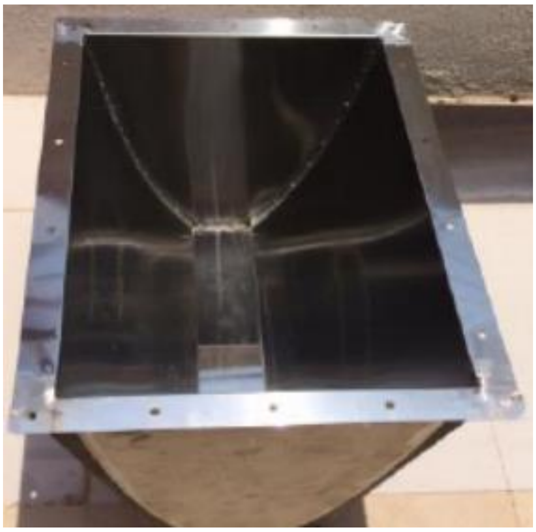


Fig. 2.13 Actual model of compound parabolic collector with CTR (More et al., 2018).

2.6 Grid refinement process for STS.

Numerical methods in general play a crucial role in engineering by bridging the theoretical concepts with practical applications. It serves as an initial step in verifying ideas or products, offering precise analyses and solutions for complex mathematical models to comprehend real-world phenomena. In order to make precise predictions and find effective solutions, engineers rely heavily on numerical software and tools. These tools help automate complicated calculations, handle large amounts of data, and simulate intricate systems (Burrage et al., 2022). Moreover, solutions obtained by these software serve as the solid foundation of contemporary engineering and aid in the challenging engineering issues (Giraldo, 2020). The grid or mesh is the data points considered for the complex analysis. The grid generation is the backbone of any numerical computational problems. Grid helps in providing a structured framework that transforms complex equations into manageable segments. It assures a realistic representation of the systems and permits simulations of real-world occurrences separating physical structures into a network of interconnected nodes (Cascón et al., 2006). Efficient computation in engineering and scientific endeavours relies heavily on the meticulous selection of grid structures tailored to specific problems. These grids serve as foundational frameworks, enabling the analysis of intricate interactions and the optimization of designs. By employing sophisticated grid selection techniques the engineers and scientists can navigate complex datasets and phenomena which helps in making well-informed decisions for advancements in their respective fields (Porta et al., 2012).

Transforming physical problem into network of grid points is a crucial step towards an accurate result. A sizable fraction of mistakes may result from choosing the grid number incorrectly (Cant et al., 2022). If the correct care isn't taken to minimise these numerical errors brought on by erroneous grid size selection, it will result in significant fluctuation in the validity of the results. Moreover, under these circumstances, incorrect meshing or grid number selection is the main contributor to error generation (Garanzha et al., 2019). Referring the literature, it is evident that determining the grid size is largely a subjective issue and there isn't a well-accepted set procedure for determining the adequate grid size for any numerical computing problems. The issue of inadequate mesh is many times perceived to be resolved by following contours of the governing parameters, as a basis for the mesh distribution (Langer & Schafelner, 2022). However, this approach certainly will find limitations involving situation where several parameters. Also there are situations where sometimes, there are no clarity on which governing parameters are dominating and thus which one to follow. In those cases, approach of refining the mesh or intensifying mesh density step-by-step and the increment is based on the previous results until the variation in the chosen parameter stabilises. According to a few studies, process of mesh refinement under a Conventional method (CM) may involve an approach of grid number improvement arbitrary in critical zones. Surprisingly, such an approach is authenticated even by many authors and several commercial software also. The improved results are then compared with the previously computed results (Weihing et al., 2020). The process of grid refinement is carried out iteratively until the outcomes are almost identical or stable. However, this method lacks a scientific approach primarily as the method is being iterative and also because the iterative process is performed in the region, which is not verified to be a critical one.

A Simple random sampling (SRS) approach is widely followed to identify the N to address the issue of mesh distribution. Although the SRS method does not follow any scientific basis however it is the most often chosen method to determine the N for any particular problem i.e. the selection of the grid number is entirely random (Shi et al., 2021). One of the drawbacks of the SRS approach is this may not be effective while dealing with problems that exhibit multiple characteristics and involve more than one or several key parameters. In one of the study, researchers studied into the matter of mesh refinement while simulating fluid flow around a cylinder. They utilized SRS methods to refine the mesh and examined its effect on various factors like flow rate, temperature, and time. The author asserted that employing SRS for meshing is a highly time-consuming process (Lee et al., 2020b). In another study, the SRS approach was applied to determine N for a '*base transceiver station*' employing phase change materials (Quecedo et al., 2004). The results revealed a numerical variation of over 6% compared to the experimental findings. It was argued that the variation was mainly due to inadequate meshing. In a similar another study, the k-ε turbulence model was employed to analyse the performance of a blade in the wake region, downstream of the blade, for a non-uniform flow. The results were investigated using two alternative profiles following same size of coarse mesh scheme. It was noted in that study that the SRS method for the grid refinement process is not an accurate and reliable method. The method may led to a significant change in the power coefficient once the choice of the mesh is altered (Masters et al., 2013). In an another study, the N was determined using the SRS approach while considering space- and time-dependent parameters for the computational model of a small-scale horizontal-axis wind turbine (Rocha et al., 2014). The results revealed a 6.2% deviation between the overall efficiency values obtained from computational analysis and experimental data. The report stated that the discrepancy highlights the necessity to consider a denser value for N to minimize the substantial variance observed in the results. These studies highlight the limitations of the SRS approach in assessing various simulation models involving multi attributes and complex interaction of parameters for such cases.

However, choosing the right value for N in computational problems that involves transient behaviour requires following a certain procedure in order to obtain the adequate value for N. This problem involves not only space parameters as governing parameter but the problem involves the combined influence of both, space and time parameters. The problem can be visualised with the help of a simple example of motion of a fluid particle around a fixed point with a constant radius. The problem when visualised; first in space coordinate only (i.e. behaving as independent of time) and in second attempt variation in space plus time coordinate. The movement can be shown as represented in Fig. 2.14. The particle's description is circular fashion when considering only spatial variables, while its motion will follow a sine wave when space and time variables both considered simultaneously, as shows in Fig. 2.14 (a) and Fig. 2.14 (b) respectively (Erickson et al., 2005). This example is sufficient to emphasise the need of a separate approach for the grid allocation or grid refinement while dealing with only space and both space plus time variation combined in a given computational domain.

Following similar understanding, employing SRS approach for a space alone, and space plus time-dependent scenarios combined may lead to inaccuracies or inconsistency.

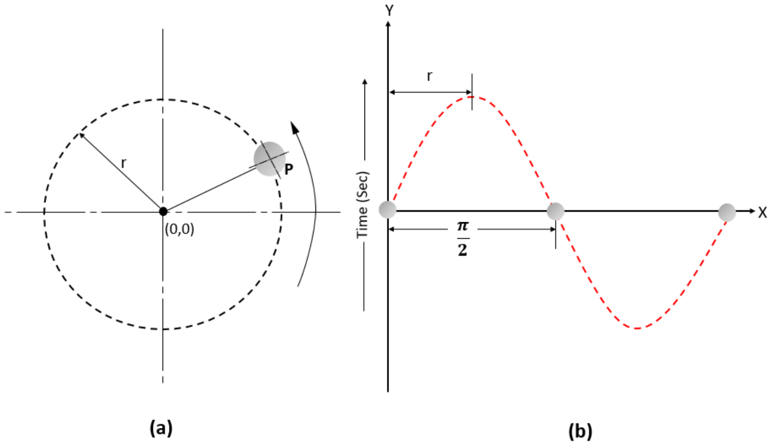


Fig.2.14 Circular particle travelled in (a) space and (b) space plus time (Erickson et al., 2005).

Literatures emphasize the significance of Local grid independence (LGI) and Global grid independence (GGI) for a space dependent problem (Y. Wang et al., 2014). It is observed that under certain cases, the value of N works well for a specific zone (or combination of parameters) and at the same time it may fails when applied for the entire domain. Such discrepancies may take place due to the severity of the parameters may vary from domain-to-domain. Such wrongly chosen or generalised grid approach can be a source of significant errors in the final results. A simplified way of explanation towards this can be explained by considering a case of simple fluid flow taking place under a variation of cross section, as represented in Fig. 2.15. For a very basic and a simplified grid distribution purpose, the entire domain is considered as a 2D grid problem. It is observed that the value of N applicable for region ABCD and EFGH can be considered as a same. However, for rest of the zones imposing similar grid distribution is not an adequate one. In other words declaring LGI and superimposing the same as GGI for entire geometry is not correct. However LGI prevail in certain zones may qualify for GGI. This means that LGI being valid only for a localized region and fail to cover the critical part of the domain where the variation of the most significant parameters takes place. On other hand GGI considered at IJ zone qualifies as GGI for the entire domain or for the entire problem. The statistic shows wide variation in the adequate mesh size at LGI and GGI, i.e. N values of 236,000 for LGI at zone ABCD and 485,000 for zone IJ which qualifies as GGI (Coelho & Argain, 1997). This basic discussion highlights necessity for a universal N value to render the domain globally go grid-free, and which is valid across all sections of the domain. The literature further states that employing grid size following GGI for entire domain actually reduces the computational time, this can be served as an additional benefit in following this approach (ElCheikh & ElKhoury, 2019).

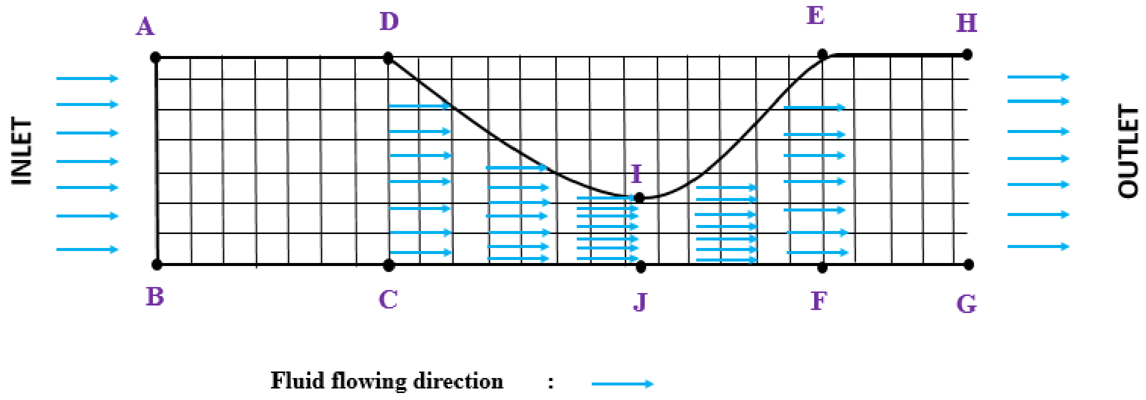


Fig. 2.15 Schematic representation of the flowing fluid in to the specific cylindrical domain (Coelho & Argain, 1997).

The application of LGI and GGI concepts in transient problems are a real challenge. Since, it is very difficult to visualize LGI and GGI and so to estimate the value of N. In conventional practices, forming a grid for a transient problem general y involves a two-step process in which space and time dependent parameters are handled separately. First, the focus is on managing space coordinates and the grid is finalized satisfying this criteria. In second step, time dependent parameters are considered and the grid size are updated. Unfortunately, this approach often prioritizes grid size based on convergence criteria rather than seeking the best solution or grid independence. The selection of grid numbers and the time step combinations relies on stability criteria since both significantly impact the outcomes of a numerical simulation. Therefore, at times such approach fail to ensure the most optimal or independent grid solution (Kourakos & Harter, 2021). The issue of convergence is critical for computational problems, and therefore the issue is dealt with higher priorities. Especially, for the problem involving space and time combination, wherein criticality of having combination of large number of non-linear equations reaches high, e.g. one or more combination of; turbulence model, radiation model and two phase model, etc. may lead to a real complex conditions and highly disrupting the guarantee of convergence. Courant–Friedrichs–Lewy (CFL) stability condition when followed in numerical schemes to ensure stability during computation fluid dynamic (CFD) analysis of a transient problem is a good example to cite (Kapusta et al., 2023). In other word the number shows the size of the time step for a transient problem in a case where a space wise grid is already pre-existed. The discussion distinguishes between grid intensity for grid independence solution and converge solution, both are different numbers.

However, grid independence in transient scenarios, involving time variables, remains unverified scientifically. Without this verification, the model's reliability in transient situations is uncertain. Few literature argue that adhering to the CFL criteria for selecting transient steps be sufficient to ensure grid independence in specific cases (Kowalczuk & Tatara, 2021). It's crucial to note that while the CFL criteria ensure convergence of the problem, they may or may not guarantee the accuracy or quality of grid and therefore the results obtained can be under question. In line with this certain literature raise a strong concern on following a conventional belief of relying solely on stringent convergence criteria and argue that this doesn't necessarily fulfil the requirement of a grid-independent solution (Gnedin et al., 2018). However, there is currently no scientific method to verify this claim, and very few studies addressed this aspect. This highlights the pressing need for a '*scientific and quantifiable*' method to determine the N that doesn't rely on subjective assessments or past experiences of researchers. Besides, reviewing of the open literature suggests that the use of certain statistical methods followed by investigators help in determining the value of N and the same is discussed briefly in the following discussion.

The first one in this methods is SRS method. The SRS method, commonly used in literature, is based on random sampling. In SRS method, each element in a population has an equal chance of being selected for the sample. There are other methods in this categories, these methods point out the zone of refinement, instead of specifying an exact number of grid points. Two relevant methods for limiting grid refinement are the Effective grid reduction (EGR) and Length of characteristic (LC) methods. The LC method helps define the scale of a physical system. The exact number of grid points is determined using the Coefficient of variation of root-mean-square error (CVRMSE) and Coefficient of determination (R^2) methods. The CVRMSE method is derived from the Root-mean-square error (RMSE) method, which helps in identifying the N that provides an accurate suitable model and demonstrates the closeness of predicted values to actual data points. On the other hand, the R^2 method serves as a statistical measurement technique assessing the variance in outcomes of a specific event due to differences in each variable. Its primary utility lies in revealing trends within obtained results. The R^2 ranges from 0 to 1 where, 1.0 indicating a perfect fit and implying a highly reliable model for future projections, while a value of 0 suggests a failure to adequately describe the data.

Table 2.8 gives summary of literature review of different methods used to obtain the value of N for different computational problems. It can be noted that the widespread use of SRS method persists due to its intuitive approach and low mathematical complexity. However, literature asserts that employing SRS methods often results in substantial variations between numerical estimation and experimental observations, primarily due to inadequate adoption of N (Lee et al., 2020a; Zhang et al., 2019). Despite its simplicity, SRS method is not recommended for numerical computation particularly in determining N. to highlight this fact, several investigators compared SRS method with various other methods, summary of their finding after systematic comparison, and highlighting their limitations can be found in the Table 2.8. In one of the study it was researched and mentioned the limitation of using the SRS and CVRMSE methods in determining the N with noting a significant drawback by claiming the extensive computational time required (Liu et al., 2021). Similarly, P. Console et al. (Console & Hairer, 2014) employed the RMSE method and observed the similar problem in the computational process. Additionally, Table 2.8 reviews the detailed application of different methods in various computational studies, along with their respective limitations and it is observed that none of these studies have proposed a single and a unified concluding method or a viable alternative that neither address the issues of defining N nor explicitly specify the rationale behind choosing these methods.

Table 2.8 Summary of literature review on different methods used to predict the value of N

Literature	**Method used**	**Observation**
(Lee et al., 2020b)	SRS, CVRMSE	Two methods, SRS and CVRMSE are considered for the grid refinement process. It's noted that the CVRMSE method provides results that are 12% more accurate than the SRS method, even though with significantly higher computational time.
(Masters et al., 2013)	SRS	Value of N obtained using SRS method is 2,300,000 when measuring the parameter as velocity of stream, while it was 2,600,000 while changing the measuring parameters for the same computational domain in case of the tidal stream turbine analysis. However, an average value of N was taken arbitrarily as 2,450,000 without giving any justification or valid reason being provided for this selection, leading to erroneous results.
(Zhang et al., 2019)	SRS, RMSE	During a numerical analysis of the building's ventilation system, conducted using the RMSE technique, yielded superior results and exhibited faster computational efficiency when compared to the SRS methods.
(Naik et al., 2019)	SRS	Thermal analysis of an evacuated U-tube solar collector was performed using SRS method for a grid refinement test. Around 6 % error in the result was reported between the output temperature of the result obtained by simulation and that by experiments.
(Roache, 1997)	SRS, LC	A numerical model of a solar water collector was developed using ANSYS software, employing a coarse grid for meshing the model. The value of N is adopted with use of SRS and it falls within the range of 100,000 to 150,000. The conclusion drawn reveals an 8.2% variation between the experimental and numerical results.
(Siddharth et al., 2016)	EGR	The 3D mesh of a turbine blade was simulated using the standard k-ε and SRS models in ANSYS CFX. There's a substantial difference of 23,000 between the fine and coarse grid numbers. In spite of this large variation the precise rationale behind selecting these grid

		numbers remains unspecified. Furthermore, the reported results exhibit an observed error of 4.6%.
(Samat et al., 2017)	R^2	The performance of tetrahedral and hexahedral type elements in finite element analysis of an IC package was investigated. The variation in N was ranged from 600,000 to 750,000 and an inaccuracy in outlet temperature of 5.8 % was reported.
(Fernandes et al., 2007)	SRS	A difference of 6.2% was observed between the experimental and numerical results for the output temperatures of the plate heat exchanger. The CFD analysis employed the SRS method for meshing, yet there was no clarification regarding the specific choice of N during the process.
(Almohammadi et al., 2013)	SRS	A numerical analysis of the hydraulic performance of chevron-type plate heat exchangers was performed. The inaccuracy between the five different models examined ranges from 3.8 to 4.7 %. The study fails to specify whether the variation is attributed to incorrect input parameters or grid refinement ratios.
(H. Wang & Zhai, 2012)	RMSE	Study uses the normalised RMSE technique to determine *N*. It was noted that around 10% improvement in the outcome was observed when choosing a finer grid over a course.

From the above discussion, it is evident that selecting the value of N for any computational problem requires consideration of both time and space-dependent parameters. However, there is currently no dedicated method for this, and previously used methods have been applied in a completely random manner without any guidelines. Since grid refinement is an essential and always necessary method in numerical problems, a step-by-step guideline for utilizing available methods with prescribed limits can solve this problem across all levels of the numerical computational domain.

2.7 Topological optimisation of STS and its importance

Topology optimization in STS is an indeed approach aimed at improving the efficiency and effectiveness of these systems through the optimal design of their components, especially when incorporating FPTRs. This process involves a complex interplay of defining objectives, identifying design spaces, parameterization, and employing sophisticated simulation models to predict the changes in design that affect system's performance. The basic understanding of the optimization is the maximisation of thermal output or minimizing material usage, while specifically focusing on the unique characteristics of FPTR in STS. However, certain literature has suggested that practical constraints related to materials, manufacturing processes, and operational limits should also be taken into account while optimisation of topology. This ensures that the final design is not only theoretically optimal but also viable in practical application. The optimization process is inherently iterative, with each cycle refining the design based on feedback until an optimal configuration is achieved. In the following discussion few literature on the optimisation is discussed.

The experimental investigation of five differently configured solar funnel cookers, made from FPTR and tested at high sun elevation with glycerine as the working fluid or load, is demonstrated for the Portugal region (Ruivo et al., 2022). The reflective surface area of the solar cookers ranges from 0.63 m^2 to 1.063 m^2, corresponding to configurations range from model SC 60 to SC 100. The temperatures achieved in the glycerine load throughout the day for all five types of solar funnel cookers are presented in Fig. 2.16.

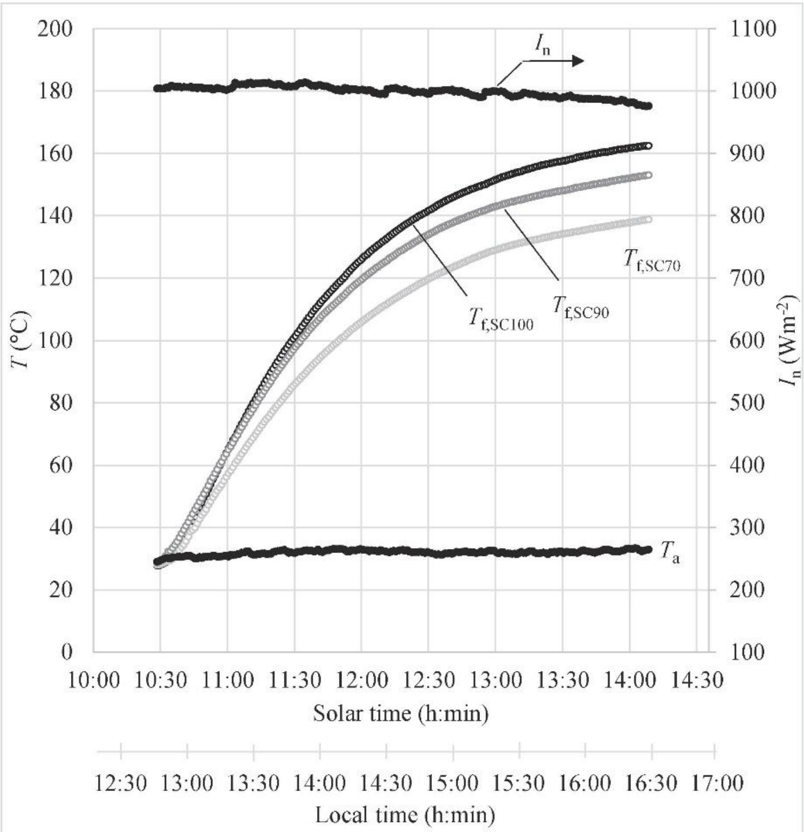


Fig. 2.16 Plots of global solar irradiance (I_n), ambient (T_a) and glycerine temperature (T_f) measured for the experiment conducted on 29th June 2021 (Ruivo et al., 2022).

The results show that model SC 100 performed better compared to the remaining alternatives, attributed to its larger aperture area. In a similar study, two types of solar funnel cooker constructed from FPTR, named solar funnel cooker-1 and solar funnel cooker-2 and they were experimentally investigated (Ruivo et al., 2021). Where, the design solar funnel cooker -1 had an aperture area of 0.23 m² and design solar funnel cooker -2 had a larger aperture area of 0.36 m². The study was conducted in the region of Malaga, Spain, under conditions of very low solar elevation. The experimental setup involved placing two different types of pots in the cookers, one with a metal lid and the other with a glass lid. The results showed that both cookers performed identically over the same period of time. However, a variation in performance was observed when pots with different lids were used. Specifically, solar funnel cooker -2 demonstrated better performance when the pot with the glass lid was used.

The mathematical modelling and experimental validation of the thermal performance of a novel solar cooker design having three different configurations, are studied (Khallaf et al., 2020). Among these, the first employs a FPTR with a simple box-type solar cooker oriented towards the south. Similarly, for the other two configurations, additional reflectors are used on the north and west sides. The results indicate that the solar cooker performs optimally with two FPTRs placed on the south and west sides, demonstrating that this configuration yields the best outcome for the optimized design. The impact of minor changes in the reflector angle on the thermal performance of the solar funnel cooker was experimentally investigated (Apaolaza-Pagoaga et al., 2021). The experiments were conducted with variations in the height of the trivet ranging from 0 mm to 100 mm. The estimated changes in thermal performance due to these design alterations were found to be low but not negligible. The results indicate that this novel approach is promising, as it enables the determination of the impact of minor design changes on the power output of the cooker. An experimental study was conducted on four different configurations of Copenhagen solar cookers, tested simultaneously under identical weather conditions (Apaolaza-Pagoaga et al., 2022). The experiment was carried out with three different loading conditions across the proposed configurations. The results obtained indicate that the thermal performance of the system can improve by 10% to 25% with careful consideration of the system's topology. In essence, topology optimization for STS with FPTR is a comprehensive and iterative process that blends simulation and practical considerations to yield highly efficient designs. This approach not only enhances the performance of individual components like solar reflectors but also ensures their optimal integration into the broader system, paving the way for more sustainable and effective solar thermal solutions.

2.8 Problem formulation and objectives

Based on observations from the literature, it's evident that by converting solar energy to thermal energy offers a 23% higher thermal performance compared to the conversion of the same into electrical energy through solar photovoltaic system. The STSs are increasingly recognized for their vital role in reducing reliance on NRESs and this is because of their application in cooking, baking, and various essential household tasks. The adoption of STS in Indian households has seen a notable rise, highlighting a shift towards sustainable energy practices. However, the technology fail to make a mark as far as largescale application is concern.

Moreover the STS are further classified based on their core components like (a) collectors and (b) reflectors. Collector-based systems present operational challenges due to their inherent weight, making solar tracking a cumbersome process. Conversely, reflector-based systems offer a more user-friendly operation since the tracking mechanism primarily involves the reflector, simplifying the alignment process with the sun. Diving deeper into the reflector based technology, STS is differentiated into CTR and FPTR systems, each catering to specific thermal applications. The CTR systems demand constant solar alignment to achieve operational efficiency, a requirement that complicates their deployment and escalates costs, rendering them less accessible to the average consumer. On the other hand, FPTR systems emerge as a practical solution for widespread adoption. Their design leverages locally available materials, significantly reducing manufacturing costs. These systems also benefit from a less stringent need for precise solar tracking and making them an appealing choice for everyday applications by the general populace.

A critical gap identified in the literature is the absence of a specific testing methodology to analyse the overall performance of large scale system and behaviour of individual solar beam rays within these systems. Understanding the trajectory of a single ray from entry to its destination or exit point is crucial for optimizing system design and efficiency. This gap underscores the need for research focused on elucidating the journey of solar beam rays in STSs, paving the way for advancements in solar thermal technology. Furthermore, integrating STS with FPTR enhances overall system accessibility and affordability with ensuring ease of use for a wider demographic. This would contribute to environmental conservation and enhance energy security for further facilitating the transition towards cleaner energy sources.

Based upon the literature survey, the following research gaps are identified:

- There is a need to develop a STS using indigenous materials to reduce costs and it has also ensuring low operation and maintenance expenses.
- The need to develop a general-purpose RTA to optimize the different configuration of FPTR based SRS.
- The need to design and analyse the behaviour of an STS augmented with FPTR for a large scale thermal applications, and to develop a numerical tool for analysis.
- Recommending guidelines for the grid refinement process which will work as an aid during numerical analysis or modelling of complex problems.

In formulating the problem, it is evident that utilizing CTR in STS necessitates constant tracking, thereby increasing overall operational and maintenance costs. Conversely, employing FPTR in STS can mitigate the need for dual-axis tracking, consequently reducing system costs. Moreover, adopting a testing methodology to analyse single beam performance that can provide critical insights into the optical performance of the system. The utilization of a generalized RTA offers significant potential in optimizing real systems for varying geographical locations. The successful integration of STS with

FPTR coupled with RTA holds significant potential for application in both small-scale and large-scale commercial and industrial applications.

Based on the observed research gaps and problem formulation, the following research objectives have been selected for the present study:

1. To develop a physical scaled-down model of a flat plate solar reflector system consisting of multiple reflectors to test and record traversing of a single solar beam ray using a laser light.
2. To validate the proposed testing methodology using a generalized ray tracing algorithm for tracking a single ray which undergoes multiple reflections.
3. To optimize a given topology by conducting simulation runs and maximizing the output parameter.