International Journal of Advanced and Applied Sciences, 12(5) 2025, Pages: 168-176

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Experimental investigation into multi-stage parabolic dish concentrators for smart village energy applications

Pravin Katare [1, 2, *], Santosh Bopche [3], Suraj Vairagade [3], Meenakshi Tumane [4], Ling Shing Wong [5], Choon Kit Chan [1]

[1]*Faculty of Engineering and Quantity Surveying, INTI International University, Nilai, Malaysia*
[2]*Faculty of Mechanical Engineering, Marathwada Mitra Mandal's College of Engineering, Pune, India*
[3]*Faculty of Mechanical Engineering, Bajaj Institute of Technology, Wardha, India*
[4]*Gyanakshi Analytics LLP, Pune, India*
[5]*Faculty of Health and Life Sciences, INTI International University, Nilai, Malaysia*

A R T I C L E I N F O

Article history:
Received 16 January 2025
Received in revised form
1 May 2025
Accepted 7 May 2025

Keywords:
Solar concentration
Parabolic dish
Copper receivers
Steam generation
Energy efficiency

A B S T R A C T

Due to the increased level of solar concentration, high-temperature zones ranging from 700 to 800 °C can be generated at the focal point of a solar dish collector, enabling steam production. This study presents experimental investigations of newly developed, efficient, and compact solar equipment that requires less land area. The experimental setup includes two parabolic dish collectors with diameters of 1.83 m and 3.05 m, and three copper receivers—two hemispherical (cavity-type, internally heated) and one conical (externally heated). The performance of this system is compared with that of a simple single-stage system under similar concentration ratios. At lower Reynolds numbers, the solar collection efficiency improves by 12%. The steam generated in the receiver can be further pressurized and stored for later use in various rural applications.

1. Introduction

Improving the performance of solar collectors enhances the system's ability to generate steam. In rural areas, steam is needed for various purposes such as parboiling paddy (rice husk) (Kwofie and Ngadi, 2017), cooling spaces for community use, oil extraction from lemongrass, jaggery production (Sai and Reddy, 2020), sanitizing contaminated clothing and hospital items, bleaching in the textile industry, washing utensils (dishwashers), synthesizing alumina from boehmite (Padilla et al., 2014), and in dairy processing (Solanki and Pal, 2021), among others. Paraboloid collector systems have gained interest in the global research community due to their high solar concentration capability, up to a concentration ratio of 1000, which enables them to maintain temperatures of 800–900 °C at the focal point (Trieb and Müller-Steinhagen, 2008). These high temperatures can be used to generate power up to 0.5 MW (Solankı and Pal, 2021). As a result, these systems are suitable for a wide range of applications, including agricultural drying, solar cooking (both direct and indirect heating), air and water heating, energy storage, refrigeration, and air conditioning.

The working fluid in these systems is heated in a receiver positioned at the focal point of the concentrator. Such concentrating systems are known for their compact and cost-effective designs (Bushra and Hartman, 2019). Bushra and Hartman (2019) proposed four twin-stage collector designs, including Cassegrain systems, twin-stage collectors, paraboloid dishes, and concentrating troughs. The Cassegrain design uses a paraboloid collector as the primary stage and a hyperbolic or parabolic shape as the secondary stage. In these twin-stage systems, the concentration ratio (C) is defined as the ratio of the aperture area of the primary concentrator to the area of the receiver. Collectors with C values from 1 to 10 are considered low-concentration, 11 to 100 are medium, 101 to 1000 are high, and values above 1000 are classified as extra-high concentration collectors. A combination of a secondary compound parabolic concentrator (CPC) with a primary parabolic dish can achieve concentration ratios up to 3000 (Bushra and Hartman, 2029). Even higher ratios—up to 25,000—are possible using a primary heliostat system with a secondary spherical concentrator. For daylighting applications, solar-cell-based absorbers with optical fibers are often used. When there are deviations in focusing the solar beam, larger receivers are needed to capture the

* Corresponding Author.
Email Address: pravinkatare10@gmail.com (P. Katare)
https://doi.org/10.21833/ijaas.2025.05.016
Corresponding author's ORCID profile:
https://orcid.org/0000-0003-4898-550X

energy (Reddy and Sendhil Kumar, 2009). However, using larger receivers increases heat losses. Bader et al. (2009) addressed these optical issues by introducing a secondary reflector system. They found that traditional single-stage reflectors result in more energy loss compared to multi-stage systems, due to better redistribution of reflected rays at each stage. The gradual and uniform heating of the working fluid in multi-stage receivers also contributes to improved performance.

The overall working temperature could be controlled by the slow and steady heating of coolants in the multiple receiver type system that ultimately reduces losses (Kribus et al., 1999). Omer and Infield (2000) exhibited improved performance of the multi-stage system design with a primary parabolic reflector and a secondary CPC reflector that is by minimizing natural convection energy losses. Concentration ratio enhancement up to fourfold can be attained using multi-stage concentrators with CPC as a secondary reflector (O'Gallagher et al., 1987). The conversion energy efficiency of the modified system could also be improved substantially. After examining multi-stage reflector systems, Friedman et al. (1996) found that a truncated conical type of reflector performs better than the CPC type. At a high level of energy concentration, a PDC as a primary stage with a concave hyperbolic reflector as a secondary gives improved efficiency (Feuermann and Gordon, 1999).

A hyperbolic-trumpet type secondary reflector enhances the solar concentration as compared to the CPC type secondary reflector, as seen by Suresh et al. (1987). It might be attributed to the skew ray as well as reflection energy losses, which were minimum in the hyperbolic trumpet-type concentrator. Reddy and Sendhil Kumar (2009) have observed reduced convective losses in the case of a hemispherical-shaped receiver with CPC, conical, and trumpet shapes as secondary concentrators. Among these three secondary stages, trumpet shaped receiver exhibited improved performance. Similarly, Zhang et al. (2014) have studied the performance of five shaped secondary stages: flat, parabolic, hyperbolic on both sides, and elliptical with PDC as a primary concentrator. They preferred convex secondary reflectors in case the rim angle is more than 90 degrees. Efficient multi-stage PDC systems can be employed for industrial applications like preheating air in thermal power plants for complete combustion of coal. It can also be used in applications where non-humid air is to be used for drying as well as for carrying pulverized coal.

In such cases, the air needs to be filtered. It may choke the filter material used for the prescribed purposes. This air is preheated in the advanced PDC systems before being supplied to the filters discussed in Katare et al (2021). Wang et al. (2017) have worked on PDC with double stages power generation. It improved the intercept and concentration factor of the system, wherein hyperbolic mirrors were used as secondary concentrators. Using this technology, the focus-size was reduced by 11 %, *C* improved with 31.4% whereas intercept parameter improves by 17% (Wang et al., 2017). But such systems portray two drawbacks: 1) Complicated designed structures, and 2) Alignment out-of-axis due to asymmetric construction. To overcome these limitations, Schmitz et al. (2015) have recommended twin-winged configurations and nested reflector designs. Parida et al. (2011) proposed a new photovoltaic reflector having asymmetric geometry and non-imaging type, wherein they have connected reflectors in series, which results in 62 % power improvement as compared to conventional non-reflecting type PV geometry.

In addition to this, Khamooshi et al. (2014) have stated the advantages of various geometries of concentrating collectors, e.g., Dot (quantum) collectors, trough parabola, CPC, concave type reflector, Dielectric and hyperboloid type, Fresnel type lenses, which help improve the overall system efficiency. Cooper et al. (2013) have introduced twin twin-staged line-focus to point-focus solar concentrating type reflector system. This system was found suitable for a wider range of power applications, generating solar concentration up to 2000. Winston and Zhang (2010) have examined hollow-type CPC and dielectric-type CPC without tracking requirements and having a wider range of solar acceptance angle. The use of solar energy for refrigeration or cooling (chilling or for cold storage) of milk products, as well as heating processes (milk processing) in dairy applications, has been suggested by Solankı and Pal (2021). The lesser temperature applications (<100 °C) comprise; initial heating (preheating), washing of milk bottles/utensils (crate or can), separation of cream, pasteurization, cleaning, preparation of Curd, Paneer, Chakka, multi-stage evaporation. The higher temperature applications (>100 °C) comprise sterilization, drying, product manufacturing like Khoa, Pedha, Burfi, etc., and the making of Ghee.

Kasaeian (2019a) has recommended higher fractions of Propylene Glycol in water as a working fluid for the power generating/Brayton cycle. They have examined volume fractions of 55%, 50%, 25%, and 0%. Additionally, Kasaeian (2019b) has compared the use of thermal oil and air in the case of a cavity-type solar absorber, and it is observed that the peak temperature of the cavity wall is observed with air and is minimum with thermal oil as a coolant. Tekkalmaz et al. (2020) have examined energy loss (combined convective as well as radiative) from the glass and plastic cover employed at a flat plate collector for some tilt angles (0 to 45°) and cover materials (acrylic, lexan, and glass). It's found that the energy loss coefficient from the plastic cover top is smaller than that of glass glazing. The values of 'loss coefficients' as well as 'cover surface temperatures' increase linearly with the rise of radiation input. In addition to parabolic dish concentrators, Kumar (2021) has examined the performance of Scheffler reflectors for middle temperature uses, and he strongly recommended them for middle-temperature usage. He observed 59.3% efficiency, which is reported to be higher than that of a parabolic dish concentrator. Regue et al. (2021) have observed a uniform distribution of energy over the receiver tube due to the secondary concentrator. The performance of setups inbuilt with secondary staged concentrators was improved by a factor of 1.65 in comparison with no secondary type of reflector. Xuyı et al. (2021) provided converging and diverging sections to the receiver tube, which increased the average Nusselt number value by about 66%. Aboelmaarefa et al. (2020) reviewed a hybrid solar desalination system using CSP technologies with multi-stages, focusing on parabolic trough systems. The study identified multi-effect distillation with thermal vapor compression (MED-TVC) integrated with parabolic troughs as the most efficient approach.

Li et al. (2023) proposed a non-focal two-stage parabolic dish system with spectral beam splitting to enhance solar energy utilization. The optimized design improved optical efficiency (80.7%) and boosted photovoltaic and thermal efficiency by 17.6% and 10.2%, respectively. The system demonstrated stable performance under varying irradiation, highlighting its potential for efficient solar spectrum utilization.

Abdessemed et al. (2019) developed a four-stage solar still with a CPC, finding V-shaped trays more efficient and cost-effective than L-shaped ones. The first stage reached 53.7 °C, with heat losses of 6–10 K. The test results indicate that the system generates approximately 9 kg of fresh water daily, achieving a solar collector efficiency of around 68%.

Zhang et al. (2023) developed a honeycomb-type multi-stage solar-thermal-electricity co-generation device (MSTE) for simultaneous freshwater and power generation. The system achieved a solar-to-vapor conversion efficiency of 187% and a water production rate of 2.79 $kg \cdot m^{-2} \cdot h^{-1}$. The design optimizes heat transfer, reduces energy loss, and enhances scalability, making it a promising solution for sustainable water and energy production.

Peng and Sharshir (2023) reviewed multi-stage solar stills, emphasizing their higher efficiency over single-stage systems. Vertical diffusion still showed the best performance due to effective stage utilization. Various modifications, such as optimizing the design and implementing vacuum conditions, were explored. The study highlighted the need for improved materials and cost-effective solutions for broader adoption, especially in rural areas.

Babaeebazaz et al. (2021) studied a solar PDC using a multi-stage flash desalination system. The finding reported that solar radiation and feed water flow rate strongly impact productivity. The optimal distillate output was achieved at 94.25 °C under vacuum pressure, improving efficiency by up to 82.98%. Thermal energy storage was suggested for stability, and scaling up reduced costs, making the system more viable for large-scale use.

These types of solar concentration systems can be an integral part of a smart home. Mere installation of sustainable energy components may not fulfill the requirements of a smart home. It must be controlled and operated via recent technological amendments. A home that is connected to the Internet allows all its appliances and systems to communicate with one another via the Internet of Things (IoT), making it a component of a sustainable smart home (Purwanto et al., 2023).

Researchers used various shapes of reflectors as secondary concentrators, e.g., conical, flat, CPC, elliptical, and hyperbolic shapes. The receiver was located at one of the focal locations to harness concentrated energy. The studies report that overlapping kinds of concentrators with staging of receivers positioned at respective focus locations are very few in the open literature. The presented design occupies less space for almost similar solar concentration levels. The novelty of this work involved the staging of a system with proper distribution of solar concentration. Experimentation has been executed on a twin-staged concentrator/reflector with three receivers. The objective was to develop an efficient solar concentrator system that helps efficient generation of steam for various village applications.

2. Methodology

The main objective behind developing a multi-stage PDC system is to develop such a system that is energy efficient and compact in nature. The geometry as well as the dimensions of these systems have been designed in such a way that they will maximize the radiative energy gain. The modified system helps water to absorb radiative energy gradually, thereby attaining a temperature up to the boiling point of water, to produce the steam for various household and commercial applications. The efficiency values of this modified system and the simple system were compared for equal concentration ratios. Line diagrams are as shown in Figs. 1 and 2.

The concentration ratio in the case of a single-stage PDC system is calculated using Eq. 1.

$$C_{geo} = \frac{A_C}{A_r} \tag{1}$$

Whereas the concentration ratio for the modified multi-stage reflector is evaluated using Eqs. 2 and 3 for stages I and II, respectively.

$$C_{geo-I} = \frac{A_{C-1} - A_{C-2}}{A_{r-III}} \tag{2}$$

$$C_{geo-II} = \frac{A_{C-2}}{A_{r-II}} \tag{3}$$

The system performance is analyzed for thermal collection efficiency, estimated using Eq. 4 (Reddy and Sendhil Kumar, 2009).

$$n_{th} = \frac{Energyabsorbedbythecoolant}{ApertureArea \times Incidentbeamradiation} = \frac{Q_u}{A_c \times Q_{Rad-b}} = \frac{\dot{m}C_p(T_{out} - T_{in})}{A_c \times Q_{Rad-b}} \tag{4}$$

2.1. Experimental program

Figs. 1 and 2 show the schematic diagrams of concentrating collector systems with single-stage and multi-stage configurations, respectively. The larger dish has a diameter of 3.0 m, while the smaller dish has a diameter of 0.45 m. A hemispherical cavity receiver with a diameter of 45 cm is positioned at the focal point of the larger dish, and a 30 cm diameter receiver is placed at the focal point of the smaller dish.

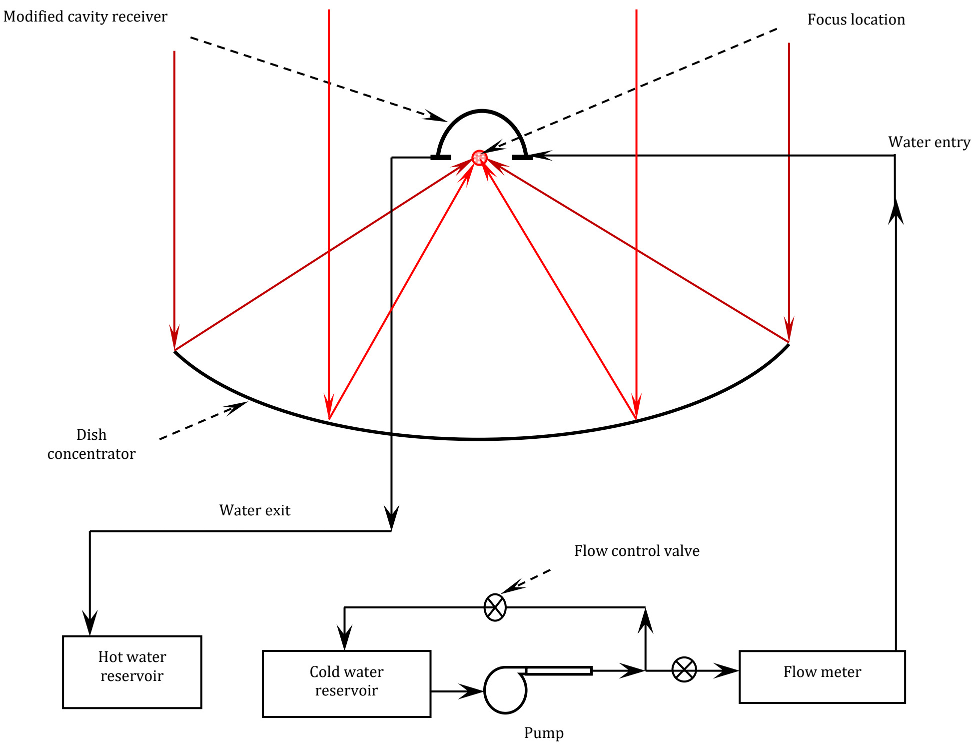

Fig. 1: Single-staged PDC system

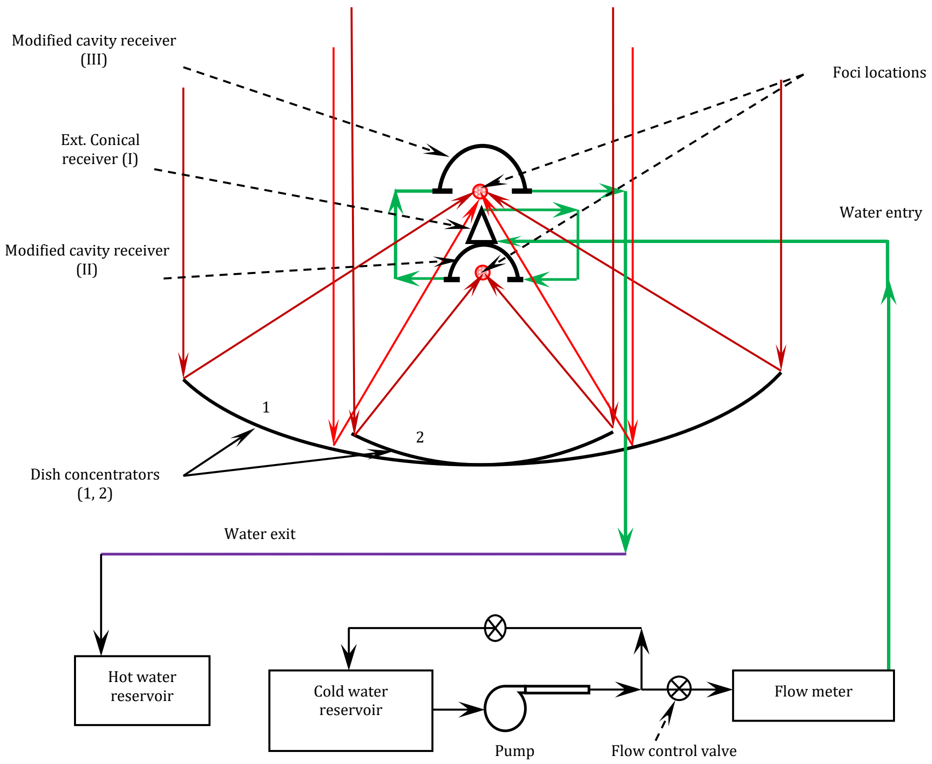

Fig. 2: Multi-stage PDC system

Water flows through a copper tube that is brazed in a spiral pattern on the outer surface of the hemispherical receiver. A conical receiver is also constructed from copper tubing, with adjacent coils brazed together to form the shape. This conical receiver, with a diameter and height of 15 cm each, is placed between the two main receivers. It is externally heated by reflected solar radiation and is designed to capture any deviated rays.

The receivers were fabricated in the laboratory, as shown in Fig. 3. A centrifugal pump is used to maintain continuous water circulation through the tubing, and the water flow rate is measured using a digital flow meter. The gradual and steady increase in water temperature helps lower the system's peak temperature, which in turn reduces heat loss and improves the overall efficiency of the system.

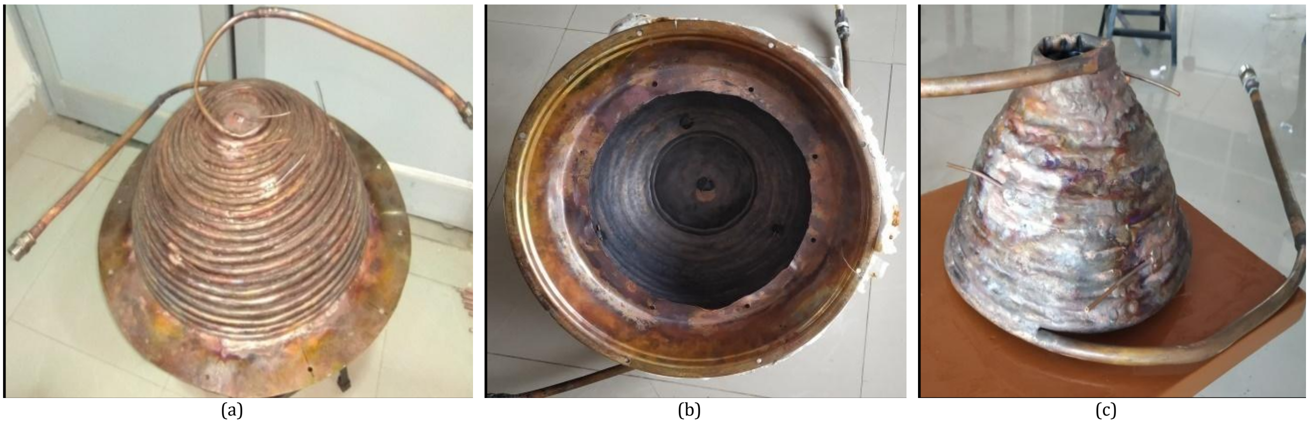

Fig. 3: Snapshots of (a) hemispherical receiver, (b) hemispherical receiver from inside, and (c) cone-shaped receiver

Fig. 4 shows a photograph of the single-stage concentrator, while Fig. 5 displays the modified multi-stage Parabolic Dish Concentrator (PDC) system. The larger and smaller dishes have aperture diameters of 10 feet and 6 feet, respectively. To reduce heat loss through conduction, the receivers are externally insulated using ceramic wool.

Water temperatures at the inlet and outlet are measured using Resistance Temperature Detectors (RTDs) connected to a digital temperature indicator. Solar radiation is monitored using solar flux meters, which are calibrated with a pyranometer (Brand: KIPP and ZONEN). Wind speed is recorded using a vane anemometer.

All experiments were carried out during peak sunshine hours, between 11:30 a.m. and 1:30 p.m. The estimated measurement uncertainties are ±1.4% for radiation flux, ±9.5% (average) for flow rate, ±3.5% for temperature, and ±13% for system efficiency.

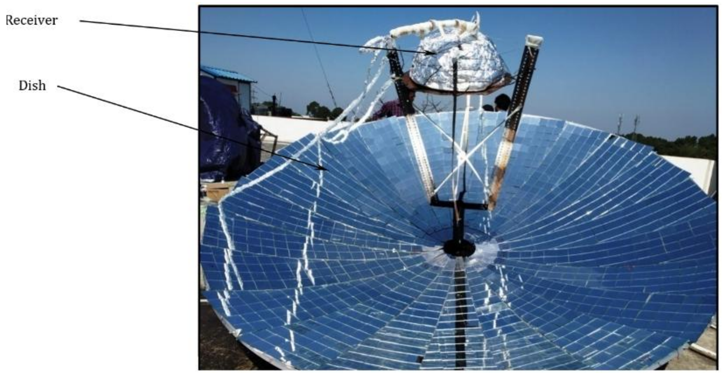

Fig. 4: Single-stage PDC system

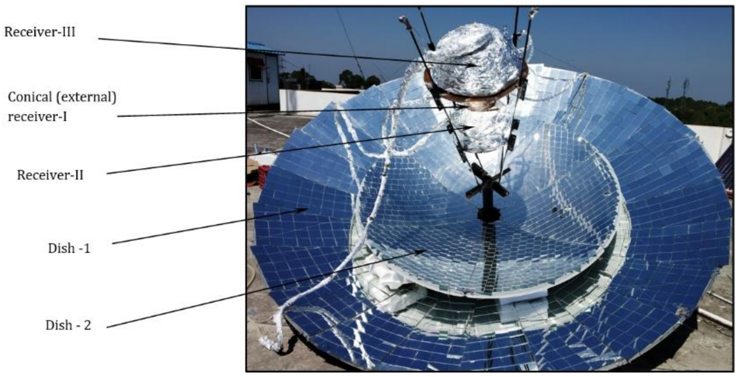

Fig. 5: Multi-stage PDC system

As far as the experimental procedure is concerned, water is first allowed to flow through the system. The facility is then rotated manually to track the Sun so that all radiation is focused on the apertures of the receivers. The flow rate is reduced, and it's restricted to the boiling of water. The readings for solar radiation, water flow rate, and water temperatures were recorded after attaining the steady state.

2.2. Test situations and challenges faced

Experimental tests were conducted to record the water mass flow rate, solar irradiation, and water temperatures at both the inlet and outlet. These measurements were carried out for two configurations:

1. A single-stage Parabolic Dish Concentrator (PDC) system, and
2. A multi-stage PDC system with coolant flowing through three-stage cavity receivers.

To accurately measure solar irradiation, the PDC system had to be precisely aligned with the Sun to ensure that the full solar flux was concentrated into the cavity receivers. This alignment was particularly challenging for the multi-stage system due to its structural complexity and rigidity. Achieving accurate positioning and assembly of the multi-stage components during experimentation proved to be difficult. Furthermore, the installation and material costs for the multi-stage system were higher compared to the conventional single-stage system. The experimental results and observations are presented in the following section.

3. Results and discussion

To check the system performance, the experimental tests were conducted using a single dish-receiver system as depicted in Fig. 4. Later, tests were executed using multi-stage dish receiver system, for similar flow Reynolds number (Re), geometric concentration value, C_{geo} = 123 and during sunny weather conditions 11.30 AM to 02.30 PM. The solar radiation flux remains almost equal on all the sunny days in this duration. The outlet temperatures of water were measured at each steady state condition attained for the chosen Reynolds number.

The outlet temperatures of water have been plotted for the selected *Re*, as depicted in Fig. 6. It was found that the circulated water could be heated up to 96 °C at a flow rate close to 0.3 LPM (Liter per minute). During experimentation, steam was produced in the tubing associated with the receiver system at flow rates of water less than 0.3 LPM. This efficiently generated steam could be used for various household applications, as mentioned earlier.

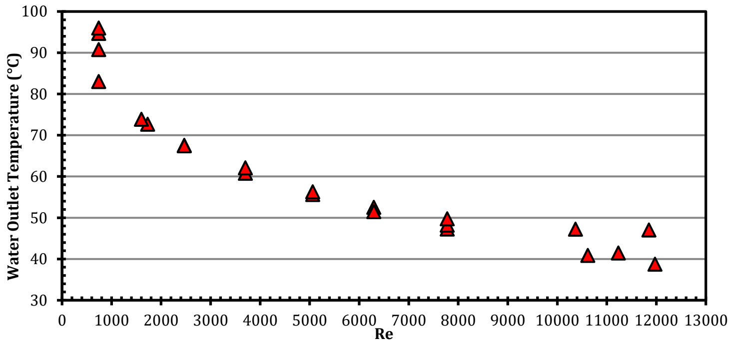

Fig. 6: Outlet water temperature vs. *Re*

3.1. Single-stage PDC system

The system performance is estimated as solar to thermal collection efficiency given by Eq. 4. The efficiency values have been compared at equal concentration ratio value, C_{geo} =123, of both systems. Thermal efficiency values of the single-stage system are plotted in Fig. 7 for the studied *Re* values.

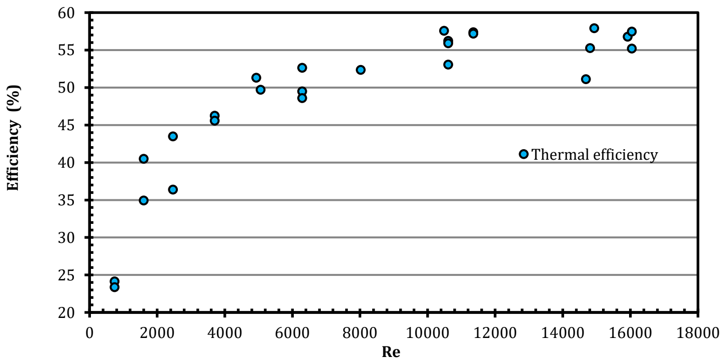

Fig. 7: System efficiency vs. flow *Re*

It is seen that the efficiency values vary non-linearly with the flow *Re*. The system's performance increases with the flow rate of water. The efficiency rises to *Re* equal to 11000, and later the effect of flow on efficiency seems to be negligible. A little dip at 8000 was noticed. It may be due to the transition of flow.

3.2. Single-stage vs. multi-stage PDC system

The efficiency of the developed systems, calculated using Eq. 4 for single and multi-stage receiver systems, is shown in Fig. 8, for the selected values of *Re* for investigation. The thermal efficiency in the case of multi-stage PDC shows an improvement up to *Re* = 4000. Later, it seems unaltered with the flow rate. This value was 11000 in the case of a single-stage PDC system. The enhancement of efficiency was quite fast at a lower range of *Re*, i.e., up to *Re* = 4000. Conducting repeated test runs, the outcome was widely spread and unpredictable closer to *Re*, 8000. It is attributed to the occurrence of flow transition close to *Re* = 8000. The multi-stage PDC system demonstrated improved performance at Reynolds numbers (Re) below 6000. At lower flow rates, the thermal efficiency of the multi-stage system was approximately 12% higher than that of the single-stage system. Additionally, the multi-stage PDC showed only a slight improvement in the transition flow regime. On average, the increase in thermal efficiency across the tested flow range was estimated to be 8.6%.

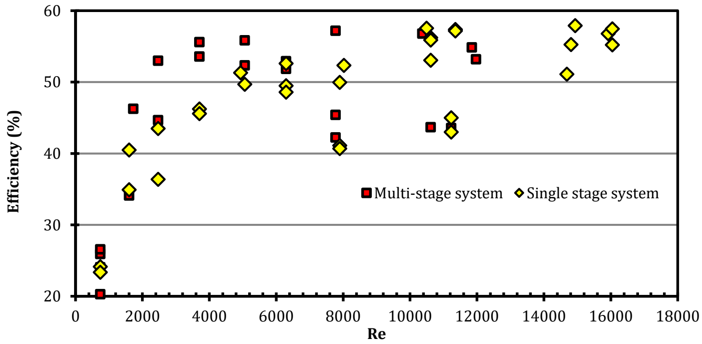

Fig. 8: Single-stage vs. multi-stage system thermal efficiency

3.3. Comparison of studies

The multi-staging can be adopted for both the reflector as well as receiver systems, for various applications, as presented in the cited references. The comparison among the presented studies in the revised manuscript is as presented in Table 1.

4. Conclusions

This study presents a novel design of a multi-stage PDC system, developed to enhance steam generation. The performance of the proposed multi-stage system was evaluated and compared with that of a conventional single-stage system under similar outdoor thermal conditions. The results indicate that the multi-stage design achieved an efficiency improvement of approximately 12% compared to the conventional system, particularly at lower flow rates, conditions favorable for steam production. In contrast, the single-stage system demonstrated higher efficiency at higher flow rates. This paper focuses on the performance testing of PDC systems under relatively low solar concentration levels. However, it is expected that the efficiency of the multi-stage system could be further enhanced under higher solar concentration conditions. This design concept also has potential applications in solar tower systems, where solar concentration varies with the elevation of reflectors. Such configurations may help minimize the required ground area.

Enhancing the efficiency of solar concentrators directly increases the system's steam generation capacity. The produced steam can be utilized for various rural applications, including community cooking, rice husk (paddy) parboiling, lemongrass processing, jaggery production, sanitizing clothing, textile thread bleaching, dishwashing, alumina synthesis from boehmite, and other similar uses.

Table 1: Comparison of performance

No.	Reference	Type of geometry	Efficiency values/performance improvement over conventional designs
1	Parida et al. (2011)	Reflectors connected in series	62% improvement compared to Single stage
2	Li et al. (2023)	Two-stage parabolic dish system	17.6 % and 10.2 % Improvements
3	Abdessemed et al. (2019)	Four-stage solar still with CPC	68% efficiency (maximum efficiency value)
4	Zhang et al. (2023)	Multi-stage solar-thermal-electricity generation device	87% Improvement
5	Babaeebazaz et al. (2021)	Multi-stage flash desalination system	82.98% Improvement
6	Present study	Multi-stage PDC system	57% (maximum efficiency value) 12% improvement compared to single-stage system

List of abbreviations

Ac	Reflector opening area
A	Opening/surface area
C	Concentration / Aperture opening related
Cp	Specific heat
d	Receiver aperture diameter
D	Receiver diameter
ṁ	HTF flow rate
Q	Energy gain rate
T	Temperature
ΔT	Temperature difference
Re	Reynolds number
ɳ	Efficiency
amb	Atmospheric
b	Beam irradiation
f	Fluid
geo	Geometric
in	Inlet or interior situation
out	Outlet or exterior situation
r	Receiver
r-out	Outside condition of receiver
rad-b	Solar beam radiation
s	Surface related
th	Thermal
u	Useful heat increase
CPC	Compound parabolic concentrator
CSP	Concentrated solar power
Cgeo	Geometric concentration ratio
HTF	Heat transfer fluid
IoT	Internet of Things
LPM	Liters per minute
MED	Multi-effect distillation
MSTE	Multi-stage solar-thermal-electricity device
MW	Megawatt
PDC	Parabolic dish concentrator
PV	Photovoltaic
RTDs	Resistance temperature detectors
TVC	Thermal vapor compression
V	Voltage

Acknowledgment

The authors appreciate the support from INTI International University, Nilai, Malaysia, and Marathwada Mitra Mandal's College of Engineering, Pune, India.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Abdessemed A, Bougriou C, Guerraiche D, and Abachi R (2019). Effects of tray shape of a multi-stage solar still coupled to a parabolic concentrating solar collector in Algeria. Renewable Energy, 132: 1134-1140. https://doi.org/10.1016/j.renene.2018.08.074

Aboelmaaref MM, Zayed ME, Zhao J, Li W, Askalany AA, Ahmed MS, and Ali ES (2020). Hybrid solar desalination systems driven by parabolic trough and parabolic dish CSP technologies: Technology categorization, thermodynamic performance and economical assessment. Energy Conversion and Management, 220: 113103. https://doi.org/10.1016/j.enconman.2020.113103

Babaeebazaz A, Gorjian S, and Amidpour M (2021). Integration of a solar parabolic dish collector with a small-scale multi-stage flash desalination unit: Experimental evaluation, exergy and economic analyses. Sustainability, 13(20): 11295. https://doi.org/10.3390/su132011295

Bader R, Haueter P, Pedretti A, and Steinfeld A (2009). Optical design of a novel two-stage solar trough concentrator based on pneumatic polymeric structures. Journal of Solar Energy Engineering, 131(3): 031007. https://doi.org/10.1115/1.3142824

Bushra N and Hartmann T (2019). A review of state-of-the-art reflective two-stage solar concentrators: Technology categorization and research trends. Renewable and Sustainable Energy Reviews, 114: 109307. https://doi.org/10.1016/j.rser.2019.109307

Cooper T, Ambrosetti G, Pedretti A, and Steinfeld A (2013). Theory and design of line-to-point focus solar concentrators with tracking secondary optics. Applied Optics, 52(35): 8586-8616. https://doi.org/10.1364/AO.52.008586 **PMid:24513906**

Feuermann D and Gordon JM (1999). Solar fiber-optic mini-dishes: A new approach to the efficient collection of sunlight. Solar Energy, 65(3): 159-170. https://doi.org/10.1016/S0038-092X(98)00129-7

Friedman RP, Gordon JM, and Ries H (1996). Compact high-flux two-stage solar collectors based on tailored edge-ray concentrators. Solar Energy, 56(6): 607-615. https://doi.org/10.1016/0038-092X(96)00015-1

Kasaeian A (2019a). Thermal evaluation of cavity receiver using water/Pg as the solar working fluid. Journal of Thermal Engineering, 5(5): 446-455. https://doi.org/10.18186/thermal.624341

Kasaeian A (2019b). Comparison study of air and thermal oil application in a solar cavity receiver. Journal of Thermal Engineering, 5(6): 221-229. https://doi.org/10.18186/thermal.654628

Katare P, Krupan A, Dewasthale A, Datar A, and Dalkilic AS (2021). CFD analysis of cyclone separator used for fine filtration in separation industry. Case Studies in Thermal Engineering, 28: 101384. https://doi.org/10.1016/j.csite.2021.101384

Khamooshi M, Salati H, Egelioglu F, Hooshyar Faghiri A, Tarabishi J, and Babadi S (2014). A review of solar photovoltaic concentrators. International Journal of Photoenergy, 2014(1): 958521. https://doi.org/10.1155/2014/958521

Kribus A, Doron P, Rubin R, Karni J, Reuven R, Duchan S, and Taragan E (1999). A multistage solar receiver: The route to high temperature. Solar Energy, 67(1-3): 3-11. https://doi.org/10.1016/S0038-092X(00)00056-6

Kumar A (2021). Experimental investigation of a Scheffler reflector for the medium temperature applications. Journal of Thermal Engineering, 7(5): 1302-1314. https://doi.org/10.18186/thermal.978197

Kwofie EM and Ngadi M (2017). A review of rice parboiling systems, energy supply, and consumption. Renewable and Sustainable Energy Reviews, 72: 465-472. https://doi.org/10.1016/j.rser.2017.01.014

Li J, Yang Z, Wang Y, Dong Q, Qi S, Huang C, Wang X, and Lin R (2023). A novel non-confocal two-stage dish concentrating photovoltaic/thermal hybrid system utilizing spectral beam splitting technology: Optical and thermal performance investigations. Renewable Energy, 206: 609-622. https://doi.org/10.1016/j.renene.2023.02.078

O'Gallagher J, Winston R, Suresh D, and Brown CT (1987). Design and test of an optimized secondary concentrator with potential cost benefits for solar energy conversion. Energy, 12(3-4): 217-226. https://doi.org/10.1016/0360-5442(87)90080-6

Omer SA and Infield DG (2000). Design and thermal analysis of a two stage solar concentrator for combined heat and thermoelectric power generation. Energy Conversion and Management, 41(7): 737-756. https://doi.org/10.1016/S0196-8904(99)00134-X

Padilla I, López-Delgado A, López-Andrés S, Álvarez M, Galindo R, and Vazquez-Vaamonde AJ (2014). The application of thermal solar energy to high temperature processes: Case study of the synthesis of alumina from boehmite. The Scientific World Journal, 2014(1): 825745. https://doi.org/10.1155/2014/825745 **PMid:24523648 PMCid:PMC3913068**

Parida B, Iniyan S, and Goic R (2011). A review of solar photovoltaic technologies. Renewable and Sustainable Energy Reviews, 15(3): 1625-1636. https://doi.org/10.1016/j.rser.2010.11.032

Peng G and Sharshir SW (2023). Progress and performance of multi-stage solar still–A review. Desalination, 565: 116829. https://doi.org/10.1016/j.desal.2023.116829

Purwanto H, Nugraha RW, Ferdiansyah FR, Dewi DA, Sofian R, and Rizaldy MF (2023). Sustainable smart home IoT to open and close the house fence using a scanning method. International Journal of Advanced Computer Science and Applications, 14(10): 679-685. https://doi.org/10.14569/IJACSA.2023.0141072

Reddy KS and Sendhil Kumar N (2009). Convection and surface radiation heat losses from modified cavity receiver of solar parabolic dish collector with two-stage concentration. Heat and Mass Transfer, 45: 363-373. https://doi.org/10.1007/s00231-008-0440-2

Regue HM, Bouali B, Benchatti T, and Benchatti A (2021). Analysis and simulation of thermal performance of a PTC with secondary reflector. Journal of Thermal Engineering, 7(6): 1531-1540. https://doi.org/10.18186/thermal.991097

Sai PV and Reddy KS (2020). 4-E (energy-exergy-environment-economic) analyses of integrated solar powered jaggery production plant with different pan configurations. Solar Energy, 197: 126-143. https://doi.org/10.1016/j.solener.2019.12.026

Schmitz M, Cooper T, Ambrosetti G, and Steinfeld A (2015). Two-stage solar concentrators based on parabolic troughs: Asymmetric versus symmetric designs. Applied Optics, 54(33): 9709-9721. https://doi.org/10.1364/AO.54.009709 **PMid:26836527**

Solanki A and Pal Y (2021). A comprehensive review to study and implement solar energy in dairy industries. Journal of Thermal Engineering, 7(5): 1216-1238. https://doi.org/10.18186/thermal.978029

Suresh D, O'Gallagher J, and Winston R (1987). A heat transfer analysis for passively cooled "trumpet" secondary concentrators. Journal of Solar Energy Engineering, 109: 289-297. https://doi.org/10.1115/1.3268220

Tekkalmaz M, Timuralp Ç, and Sert Z (2020). The effect of the use of different cover materials on heat transfer in flat solar collectors. Journal of Thermal Engineering, 6(5): 829-842. https://doi.org/10.18186/thermal.800158

Trieb F and Müller-Steinhagen H (2008). Concentrating solar power for seawater desalination in the Middle East and North Africa. Desalination, 220(1-3): 165-183. https://doi.org/10.1016/j.desal.2007.01.030

Wang J, Yang S, Jiang C, Yan Q, and Lund PD (2017). A novel 2-stage dish concentrator with improved optical performance for concentrating solar power plants. Renewable Energy, 108: 92-97. https://doi.org/10.1016/j.renene.2017.02.059

Winston R and Zhang W (2010). Pushing concentration of stationary solar concentrators to the limit. Optics Express, 18(S1): A64-A72. https://doi.org/10.1364/OE.18.000A64 **PMid:20588575**

Xuyi Z, Fuqiang W, Xuhang S, Ziming C, and Xiangtao G (2021). Analysis of heat transfer performance of the absorber tube with convergent-divergent structure for parabolic trough collector. Journal of Thermal Engineering, 7(Supp 14): 1843-1856. https://doi.org/10.18186/thermal.1051232

Zhang D, Wan Y, Zhuang W, Geng X, and Yang P (2023). Monolithic multistage solar-to-steam device for tandemly generating freshwater and electricity with superb efficiency. Chemical Engineering Journal, 466: 143047. https://doi.org/10.1016/j.cej.2023.143047

Zhang Y, Xiao G, Luo Z, Ni M, Yang T, and Xu W (2014). Comparison of different types of secondary mirrors for solar application. Optik, 125(3): 1106-1112. https://doi.org/10.1016/j.ijleo.2013.07.113