

Abstract

Solar energy, being clean and abundantly available, is well-suited to meet space cooling demands. Among the various solar thermal collector options, Compound Parabolic Collectors (CPC) have gained particular attention due to their ability to collect diffuse solar radiation, concentrate solar radiation, operate without tracking, and achieve higher temperatures than flat plate collectors. These features make CPC suitable for applications such as solar cooling using vapour absorption systems.

This research includes a detailed thermal and optical analysis of the CPC solar collector and a techno-economic analysis of the CPC integrated with a single-effect vapour absorption system. The heat losses are a critical aspect of the thermal performance of a solar collector and account for a considerable portion of the heat energy absorbed by the collector. Numerical models of CPC with a non-evacuated tubular receiver are developed in both 2D and 3D to examine the influence of various operating parameters (receiver temperature, inlet fluid velocity and inlet fluid temperature), environmental parameters (ambient temperature, wind heat transfer coefficient) and design parameters (truncation ratio, tilt angles, insulation and aperture cover thickness, surface emissivities) on the convective and radiative heat losses, fluid temperature rise, thermal efficiency and Nusselt number, further leading to development of Nusselt number correlations.

The operating and environmental parameters, as well as receiver emissivity, are found to significantly impact thermal performance, with the effect of inlet fluid velocity majorly on the rise in fluid temperature. The effect of tilt angles is found to be insignificant on heat losses. The truncation ratio affects the thermal performance by 9% when the height of the collector is reduced by 60%. The truncation also helps save reflector material by 43% in weight.

A comparative study analysing the effect of pure convection versus combined convection and surface radiation showed that total heat losses and Nusselt number increased by 7.7% and 41.2% for receiver emissivities of 0.05 and 0.9, respectively, compared to the pure convection case. This highlights the significant role of radiative effects in heat transfer, which have often been neglected in previous studies.

A notable difference is observed between the Nusselt number obtained from 2D and 3D numerical models, primarily due to enhanced fluid mixing and heat transfer in the 3D model resulting from vortex formation. The two Nusselt number correlations developed are compared with other correlations available from the literature, and the discrepancies are attributed to simplified modelling assumptions and the omission of radiative heat losses, all of which influence both the magnitude and trend of the Nusselt number.

A detailed ray-tracing optical model of the CPC is developed to investigate the effects of circumsolar ratio, sunshape, and surface errors on its optical performance. The results indicate that optical errors lead to a maximum variation of 1% in absorbed heat, suggesting that the CPC geometry is largely unaffected by minor optical imperfections. Further, the heat flux obtained from the optical model is integrated with the 3D numerical model of CPC for complete analysis.

A 3D model of an evacuated tubular receiver CPC is developed and compared with the non-evacuated receiver CPC. The analysis reveals a significant 56% reduction in total heat loss, primarily due to the elimination of convective losses. This results in an increase in thermal efficiency from 59% to 76% and a rise in fluid outlet temperature from 2.88 K to 3.76 K. Thermal efficiency equations are derived for both models and used in the solar absorption cooling model.

A CPC-based solar absorption cooling system model is developed in TRNSYS to study the thermal, economic, and environmental performance of the system. Analyses are performed to assess the effect of parameters like collector area, collector slope, storage tank specific volume ratio (STSVR) and CPC design (evacuated vs. non-evacuated) on solar fraction (SF), payback period (PBP), levelized cost of cooling (LCOC) and carbon dioxide emissions (CDE).

The collector area significantly affected the thermal, economic and environmental performance of solar absorption cooling systems, making it a key design parameter. In contrast, the collector slope primarily influenced thermal performance, with negligible effects on economic and environmental metrics. The STSVR directly impacted the economic and environmental outcomes by increasing the PBP, LCOC and CDE. However, thermal performance, measured in terms of the solar fraction, decreased with increasing STSVR for a fixed collector area. No substantial improvement is observed beyond an STSVR of $0.02 \text{ m}^3/\text{m}^2$, indicating limited thermal advantage at higher storage volumes.

The comparison of the performances of the non-evacuated and evacuated receiver CPC indicated an improvement in the solar fraction by 14%, a reduction in both the discounted payback period by 5.25 years, and CO_2 emissions by 4.3 tonnes annually for New Delhi.

A climatic comparison across global cities showed that locations with high solar potential (e.g., Cairo, Phoenix) achieved favorable economics, with LCOC less than 20 INR/kWh and discounted payback periods under 13 years. The medium solar potential cities (Rome, New Delhi) exhibiting different climatic conditions and cooling loads leading to comparable differences in their LCOC values of 25.73 INR/kWh and 33.95 INR/kWh respectively with a similar PBP of 17.3 years. In contrast, low solar potential cities (e.g., Kuala Lumpur, Taipei) resulted in LCOC above 37 INR/kWh and payback periods exceeding 24 years. This indicates that these locations are economically unviable and will require alternative strategies to improve economic viability.

The analysis also resulted in the proposal of two new metrics, the solar cooling cost metric (SCCM) and carbon dioxide emission factor for solar cooling (CDEFSC), aimed to assess the cost and environment-related aspects of solar cooling systems across different locations.

Overall, this work contributes to an enhanced understanding of the performance of CPC and its application in solar absorption cooling systems.