ADVANCED LOW-EMISSIVITY AND ROBUST MULTILAYER SELECTIVE COATINGS FOR HIGH-VACUUM FLAT PLATE SOLAR COLLECTORS

Summary

The decarbonisation of industrial heat processes requires efficient solar thermal technologies capable of operating at medium temperatures (100-300 °C). High-Vacuum Flat Plate Collectors (HVFPCs) represent a promising solution. This work proposes a combined strategy based on multilayer coating optimisation and low-emissivity thin films. Cr_2O_3/Cr multilayers are optimised via genetic algorithms, ensuring robustness against thickness variations, while Ag coatings with CrO_x barriers reduce radiative losses. The framework is further extended to account for the solar spectrum effectively transmitted through the glass envelope, enabling a more realistic optimisation of absorber selectivity. The results show absorptance of up to 0.97, emittance below 0.05, and efficiency improvements of up to 10%.

Keywords: selective solar absorber, low-emissivity coating, HVFPC, multilayer coatings, conversion efficiency.

Field of application for the findings: Solar thermal collectors, industrial heat, renewable energy systems.

Addressed audience: Researchers, engineers, and industry professionals in solar thermal energy.

1. Introduction

The transition to renewable energy sources is a key challenge in reducing greenhouse gas emissions, particularly in the industrial sector, which accounts for a significant fraction of global energy consumption. Half of the global industrial process heat demand is in the low and medium-temperature range (<400 °C), with about 35% below 150 °C and 15% between 150 and 400 °C (IEA, 2022). Currently, this demand is fulfilled by fossil fuels (IEA, 2018), but solar thermal technologies offer a viable alternative. However, conventional flat plate collectors are typically limited to temperatures below 100 °C.

In contrast, High Vacuum Flat Plate Collectors (HVFPCs) enable operation at higher temperatures by suppressing convective losses through vacuum insulation (Moss et al., 2018; Gao et al., 2020). In these systems, radiative losses become dominant, which makes the optimisation of selective solar absorbers (SSAs) crucial (De Maio et al., 2022). An ideal SSA should exhibit high solar absorptance in the solar spectrum ($0.3 - 2.5\mu m$) and low thermal emittance in the infrared region. However, in practical devices, there is a trade-off between these properties, especially at elevated temperatures, where thermal radiation losses increase with the fourth power of temperature (Caldarelli et al., 2023). Recent studies have focused on multilayer coatings based on metal–dielectric stacks, which allow precise tuning of optical properties through interference effects (Zhou et al., 2024). At the same time, reducing the absorber substrate's emissivity by means of a low-emissivity coating (LEC) offers an additional route to enhance overall efficiency.

In this context, the present work combines these two approaches to develop high-performance, robust, and scalable solutions for advanced solar thermal absorbers.

2. Methodology

2.1 Multilayer coating optimisation

Selective solar absorbers based on Cr_2O_3/Cr multilayer structures were designed and optimised for operating temperatures of 100 °C, 200 °C, and 300 °C (Fig.1a). The optimisation was performed using a genetic algorithm coupled with a transfer-matrix optical model, enabling the calculation of spectral reflectivity and derived quantities such as solar absorptance and thermal emittance. Unlike conventional approaches, the optimisation directly maximises thermal efficiency without predefined weighting between absorptance and emittance. Additionally, robustness against manufacturing errors was incorporated by constraining the efficiency loss to less than 2% under layer thickness variations of ±20%. To better reproduce actual HVFPC operating conditions, the framework is conceptually extended by replacing the standard AM1.5 irradiance with an effective incident spectrum defined as the product of the AM1.5 spectrum and the wavelength-dependent transmittance of the glass-envelope/AR-coating system. In this way, residual reflection losses and glass absorption are accounted for, especially at short wavelengths and in the near-infrared region.

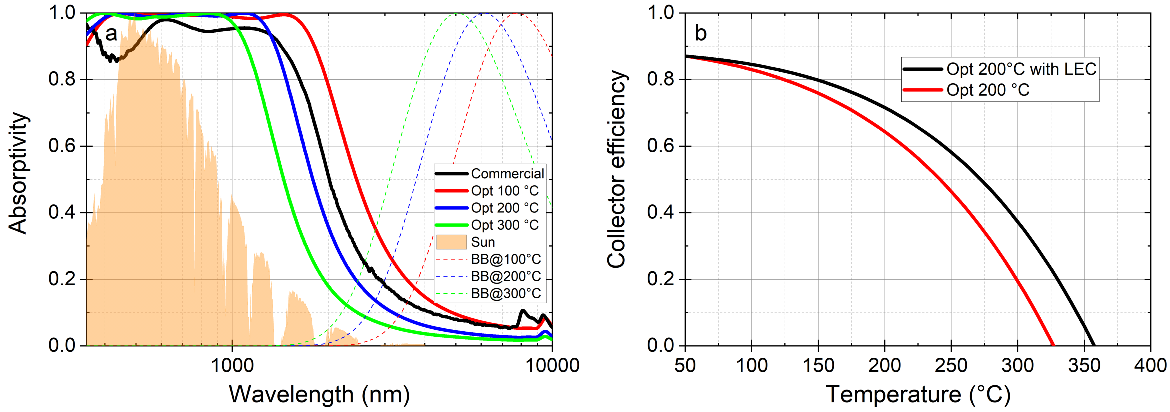

Fig. 1: (a) Absorptivity of a commercial and optimised coatings at 100, 200, and 300 °C in black, red, blue, and green solid lines, respectively. The solar spectrum and the blackbody (BB) emission curves are also shown in arbitrary units. (b) Collector efficiency curves of the optimised coating at 200 °C, shown with and without LEC as black and red lines, respectively.

2.2 Low-emissivity coating (LEC) integration

To further reduce radiative losses, thin silver (Ag) films were deposited on the backside of aluminium-based absorbers. A chromium oxide (CrO_x) diffusion barrier layer was introduced to prevent degradation at high temperatures. The coatings were fabricated using electron-beam deposition techniques, ensuring uniform thickness and compatibility with industrial processes. Thermal emittance was evaluated using a calorimetric approach under high-vacuum conditions, simulating real collector operation.

2.3 Combined strategy and system implications

The combination of multilayer optical optimisation and substrate emissivity reduction provides a synergistic effect. While the multilayer structure optimises the spectral selectivity, the low-emissivity coating reduces radiative losses that are otherwise not addressed by front-side optimisation alone. A further improvement is obtained by considering the cover-transmitted solar spectrum rather than the bare AM1.5 reference during absorber design. This integrated approach is particularly relevant for HVFPC technologies, where radiative losses dominate, and system efficiency is highly sensitive to absorber properties.

3. Results and Discussion

The optimised multilayer coatings achieved solar absorptance values up to 0.97 and thermal emittance values below 0.05 at temperatures up to 300 °C, in agreement with state-of-the-art selective coatings (Cao et al., 2014). The results confirm that, as operating temperature increases, thermal emittance becomes the dominant factor affecting efficiency, requiring a shift in optimisation strategy from absorptance-driven to emittance-driven design (De Maio et al., 2022). The robustness analysis demonstrated that efficiency losses remain below 2% even under significant layer thickness variations (±20%), highlighting the suitability of the approach for industrial-scale manufacturing (De Maio et al., 2022).

The introduction of a low-emissivity Ag layer reduced the thermal emittance by approximately 11% at 200 °C, leading to an increase in collector efficiency of about 8% (Caldarelli et al., 2023) (Fig.1b). The presence of a CrO_x diffusion barrier was found to be essential to maintain thermal stability up to 360 °C. Further improvements can be achieved by extending the low-emissivity coating to both sides of the absorber substrate, with predicted efficiency gains up to 10% at 200 °C (Caldarelli et al., 2023).

Overall, the combination of multilayer optimisation, emissivity reduction, and spectrum-aware design provides a synergistic effect, addressing both spectral selectivity and radiative losses in advanced solar collectors. The inclusion of the effective transmitted spectrum is expected to improve the matching between absorber optical properties and real operating conditions, especially in high-performance HVFPCs.

4. Conclusion

This work presents a comprehensive strategy for improving the performance of selective solar absorbers for medium-temperature solar thermal applications. The optimisation of Cr_2O_3/Cr multilayer coatings enables high absorptance and low emittance, while ensuring robustness against manufacturing variations. In parallel, the integration of Ag-based low-emissivity coatings with diffusion barriers significantly reduces radiative losses from the substrate. The combined approach leads to efficiency improvements up to 10% at 200 °C, demonstrating strong potential for industrial-scale implementation. Extending the optimisation to the solar spectrum effectively transmitted by the glass envelope provides a more realistic design criterion and should further enhance the correspondence between absorber selectivity and actual operating conditions. These results contribute to the advancement of high-performance solar thermal collectors and support the transition towards sustainable industrial heat production.

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