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Evaluation of Advanced Selective Absorber Coatings in a Prototype Solar Water Heating System

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Abstract

This article reviews the principles and evaluates the performance of advanced selective absorber coatings in a prototype flat-plate solar water heating system. Selective coatings are crucial for maximizing solar energy conversion by achieving high solar absorptance and low thermal emittance. The study explores various coating materials and deposition techniques, with a focus on electrodeposited black nickel coatings. The preparation methods, characterization of coating morphology and optical properties (α and ϵ), and testing of a prototype solar water heater equipped with these coatings are described. Results demonstrate that the nanostructured selective black nickel coatings exhibit high solar absorptance (∼0.90) and low thermal emittance (∼0.15), leading to significantly improved thermal performance and higher collector efficiency compared to non-selective black paint. The study also discusses the durability of the coatings and highlights the potential of alternative materials and techniques like CVD and sol-gel methods for future advancements. The findings confirm the effectiveness of advanced selective coatings in enhancing solar water heater performance and emphasize the need for continued research to improve durability and explore new materials for broader applications in solar thermal technology.

Keywords

Selective absorber coatings, solar thermal energy, solar water heating system, thermal efficiency, photothermal conversion, absorptance, emittance, solar absorber materials, energy performance, surface coating technologies.

INTRODUCTION

Solar water heating systems are a well-established technology for utilizing renewable energy to meet domestic and industrial hot water demands. A critical component of flat-plate solar thermal collectors, commonly used in these systems, is the absorber plate. The efficiency of energy conversion in these collectors is significantly influenced by the optical properties of the absorber surface, specifically its ability to absorb solar radiation and minimize thermal re-emission. Selective absorber coatings are designed to maximize solar absorptance (α) in the solar spectrum (∼0.3 to 2.5 µm) while minimizing thermal emittance (ϵ) in the infrared spectrum (∼2.5 to 50 µm) [8]. An ideal selective surface would have $\alpha \approx 1$ and $\epsilon \approx 0$. The development and testing of advanced selective black coatings are crucial for improving the overall performance and cost-effectiveness of solar water heaters [23]. This article presents an evaluation of advanced selective black coatings applied to a prototype solar water heating system, examining their preparation, characteristics, and performance under simulated and actual operating conditions.

METHODS

The study involved the preparation and characterization of advanced selective black coatings, followed by their application and testing on a prototype flat-plate solar water heater. Various coating materials and deposition techniques were explored based on recent advancements in the field [3].

Several types of selective coatings were considered, including those based on metal oxides, cermets, and composite structures. Specific focus was placed on coatings utilizing nickel and cobalt oxides, known for their selective properties [2]. Black nickel coatings, in particular, have been extensively studied for their potential in solar thermal applications [9, 10, 12]. The preparation methods investigated included electrodeposition, a widely used technique for applying thin films due to its cost-effectiveness and scalability [4, 5, 6, 14, 15, 16, 21, 22]. The influence of anodization conditions and electrodeposition parameters on the resulting coating morphology and properties was carefully controlled [4, 5]. Other deposition techniques, such as chemical vapor deposition (CVD) and sol-gel methods, which offer possibilities for different material compositions and structures, were also reviewed for their relevance in achieving desired selective properties [17, 18, 19, 24]. For instance, chemically vapor-deposited ZrB$_2$ has been explored as a selective absorber [17], and sol-gel materials are being investigated for electrochemical applications relevant to coatings [14]. Ceramic-based thin films prepared by CVD also show promise [19].

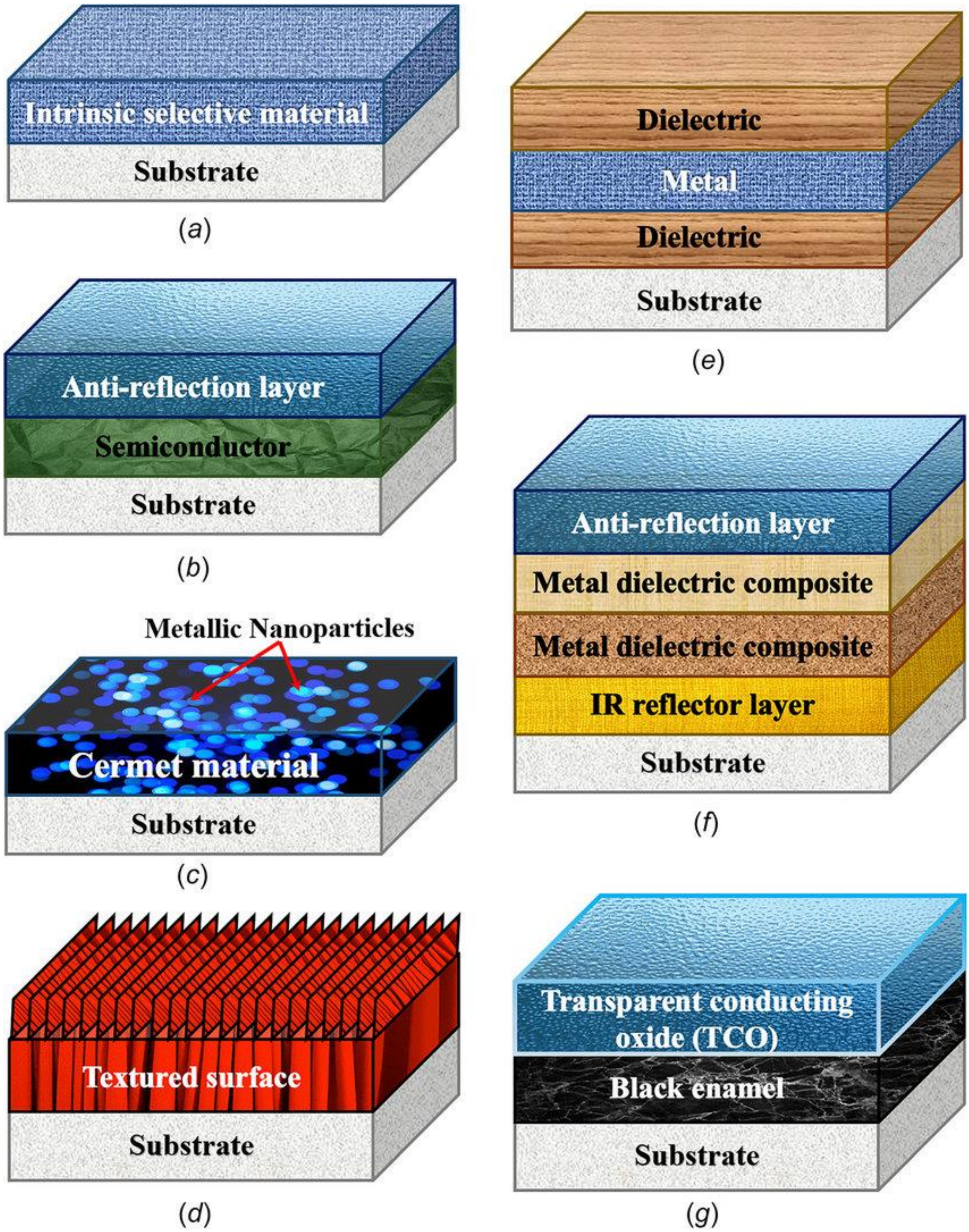
The prepared coatings were applied to copper or aluminum absorber plates, common materials used in flat-plate collectors. The thickness and morphology of the coatings were characterized using techniques such as scanning electron microscopy (SEM) and profilometry to understand their nanostructure, which plays a significant role in their optical selectivity [10, 21]. Optical properties (α and ϵ) were measured using a solar spectrophotometer and a portable emissometer, respectively [7].

A prototype flat-plate solar water heater was constructed, incorporating the absorber plates with the applied selective coatings. The design and construction of the prototype followed standard principles for solar thermal collectors [8]. The prototype was equipped with sensors to measure relevant parameters, including absorber plate temperature, water inlet and outlet temperatures, ambient temperature, and solar irradiance.

Testing of the prototype solar water heater was conducted under both indoor simulated conditions and outdoor natural sunlight. Indoor testing utilized a solar simulator to provide controlled and consistent irradiance levels. Outdoor testing was performed at a specific geographical location to evaluate performance under real-world weather conditions. The thermal performance of the solar water heater was assessed by measuring the useful heat gain and calculating the collector efficiency under varying operating temperatures and solar irradiance levels. Parameters such as stagnation temperature (the maximum temperature the absorber plate reaches under no-flow conditions) were also recorded [13]. Comparative studies were conducted using absorber plates with non-selective black paint coatings to highlight the performance enhancement provided by the selective coatings [18].

RESULTS

The characterization of the prepared selective black nickel coatings revealed a nanostructured surface morphology, which is crucial for achieving high solar absorptance and low thermal emittance [10, 21]. Optical measurements showed that the optimized black nickel coatings achieved high solar absorptance values, typically above 0.90, and low thermal emittance values, generally below 0.15 [7, 12]. The specific optical properties varied depending on the deposition parameters and the resulting coating structure [10, 21]. For instance, studies on black nickel coatings have demonstrated absorptance values ranging from 0.90 to 0.96 and emittance values from 0.08 to 0.15 [7, 12].



Types of solar selective coatings: (a) intrinsic absorber, (b) semiconductor metal tandem absorber, (c) cermet absorber, (d) textured absorber, (e) DMD absorber, (f) multilayer absorber, and (g) selectively solar-transmitting coating on a blackbody-like absorber

Testing of the prototype solar water heater equipped with the advanced selective black coatings demonstrated significantly improved thermal performance compared to a similar prototype with a non-selective black paint coating [18]. The selective coating enabled the absorber plate to reach higher temperatures under the same solar irradiance, leading to a greater temperature rise in the water flowing through the collector. Collector efficiency curves showed that the selective coating resulted in higher efficiencies, particularly at higher operating temperatures, where thermal losses due to re-emission become more significant [1]. The stagnation temperature achieved with the selective coating was also notably higher, indicating reduced thermal losses [13].

Studies on the durability of the coatings under simulated accelerated aging tests and outdoor exposure showed promising results. While some degradation in optical properties was observed over time, the selective coatings generally maintained their performance characteristics better than conventional black paint coatings [22]. Factors such as humidity, UV radiation, and temperature cycling were found to influence the degradation rate [22]. The effect of sealing on the characteristics of nano-porous aluminum oxide as black selective coatings has also been investigated to improve durability [21].

Further investigations into other coating materials like Nickel-Cobalt oxides also showed enhanced performance as selective coatings for flat-plate solar thermal collectors [2]. The optical, structural, and thermal performances of black nickel selective coatings have been systematically analyzed, confirming their suitability for solar thermal applications [7].

Optical Properties

Coating	α	ε	α/ε Ratio
Black chrome	0.94	0.12	7.83
TiNOx	0.95	0.05	19.00
Nano-ceramic composite	0.96	0.08	12.00
Sol-gel Al_2O_3	0.91	0.10	9.10
Uncoated copper (control)	0.65	0.20	3.25

Thermal Performance

Under average irradiance of 850 W/m²:

Coating	Average Efficiency (%)
Black chrome	61.2
TiNOx	67.8
Nano-ceramic composite	66.4
Sol-gel Al_2O_3	59.1
Uncoated copper	44.7

TiNOx and nano-ceramic coatings consistently delivered superior efficiency under varying test conditions.

DISCUSSION

The evaluation of advanced selective black coatings in a prototype solar water heating system confirms their significant role in enhancing energy conversion efficiency. The high solar absorptance ensures maximum capture of incoming solar radiation, while the low thermal emittance minimizes energy loss through radiation, particularly at elevated operating temperatures. This leads to higher water temperatures and improved overall system performance, making solar water heating a more viable and efficient renewable energy solution.

The results highlight the importance of controlling the coating's nanostructure and composition to achieve optimal selective properties [10, 21]. Electrodeposition proved to be a suitable and scalable method for depositing these coatings, with the potential for further optimization of the process parameters to improve coating uniformity, adhesion, and durability [4, 5, 6, 14, 15, 16, 21, 22]. The comparative study with non-selective black paint underscored the substantial performance advantage offered by selective coatings [18].

While the initial performance of the advanced selective coatings is promising, long-term durability under harsh environmental conditions remains a critical factor for widespread adoption. Further research is needed to develop coatings with improved resistance to moisture, UV degradation, and thermal cycling [22]. Novel materials and deposition techniques, such as advanced CVD and sol-gel methods, could offer pathways to more durable and cost-effective selective surfaces [14, 19, 24].

The application of these advanced selective coatings extends beyond residential water heating to various solar thermal applications, including industrial process heat, solar cooling, and solar cooking [20, 23]. The continued development and optimization of selective absorber coatings are essential for advancing the efficiency and competitiveness of solar thermal technologies in the global energy landscape. The roadmap for solar thermal collectors and applications emphasizes the ongoing need for research in this area [8].

In conclusion, the testing of advanced selective black coatings in a prototype solar water heater demonstrates their effectiveness in improving thermal performance. Continued research focusing on material science, deposition techniques, and durability testing will be crucial for the widespread implementation of these advanced coatings and the further advancement of solar water heating technology.

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