EFFICIENCY OF SOLAR THERMAL ENERGY DEVICES WITH SELECTIVE RECEIVERS

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Annotatsiya: Ushbu tadqiqot spektral selektiv yutuvchi sirtlardan foydalangan holda quyosh issiqlik energiyasi tizimlarining samaradorligini o‘rganadi. Bunday yutuvchi sirtlar quyosh spektridagi nurlanishni maksimal darajada yutish, infraqizil diapazonda esa issiqlik nurlanishini kamaytirish uchun mo‘ljallangan bo‘lib, natijada nurlanish yo‘qotishlari qisqaradi va ayniqsa yuqori ish haroratlarida kollektor samaradorligi oshadi. Maqolada asosiy material va qoplama texnologiyalari ko‘p qatlamli yupqa plyonkalar, sermetlar, metall-dielektrik nanostrukturalar va metamateriallar tahlil qilinadi hamda spektral selektivlikning tekis va konsentratsiyalovchi kollektorlarning issiqlik samaradorligiga ta’siri miqdoriy baholanadi. Selektiv va no-selektiv yutuvchilarni taqqoslash uchun soddalashtirilgan modellashtirish usuli taklif etilgan bo‘lib, u adabiyotlarda keltirilgan tajriba va dala sinovlari natijalari bilan asoslanadi. Tadqiqot natijalari shuni ko‘rsatadiki, optimal ishlab chiqilgan selektiv yutuvchilar quyosh yutiluvchanligini (α_s) 0,92 dan yuqori va issiqlik nurlanishini (ε_T) 0,10-0,20 oralig‘ida ushlab tura oladi, bu esa kollektor turi va ish haroratiga qarab 5-25 foizgacha samaradorlik oshishiga olib keladi. Tahlilda asosiy samaradorlik omillari spektral selektivlik (α_s/ε_T nisbati), issiqlik barqarorligi, burchakka bog‘liq optik javob va ekologik chidamlilik aniqlangan. Yakunda maqola tannarx, ishlab chiqarish qulayligi va xizmat muddati o‘rtasidagi muvozanatni ko‘rib chiqadi hamda yuqori haroratli va keng ko‘lamli quyosh issiqlik tizimlari uchun istiqbolli tadqiqot yo‘nalishlarini belgilaydi.

Kalit so'zlar: selektiv yutgich, spektral selektiv qoplama, quyosh issiqlik kollektorining samaradorligi, emissiya, keramika, ko'p qatlamli qoplama.

Abstract: This paper examines the efficiency of solar thermal–energy devices employing spectrally selective (selective) absorber surfaces. Selective absorbers are engineered to maximize absorption in the solar spectrum while minimizing thermal emittance in the infrared, thereby reducing radiative losses and improving collector performance, especially at elevated operating temperatures. The work reviews material and coating technologies (multilayer thin films, cermets, metal-dielectric nanostructures, and metamaterials), quantifies how selective properties translate to thermal efficiency for flat-plate and concentrating collectors, presents a simple modeling framework to compare selective vs. non-selective absorbers, and analyses recent experimental and field results from the literature. Results show that well-engineered selective absorbers can raise solar absorptance (α_s) to >0.92

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while keeping normal-direction thermal emittance (ε_T) below 0.10–0.20, yielding efficiency gains of 5–25 percentage points depending on operating temperature and collector type. Key performance drivers include spectral selectivity (α_s/ε_T), thermal stability at operating temperature, optical angular response, and environmental durability. The discussion highlights trade-offs among cost, manufacturability, and longevity and outlines research priorities for high-temperature applications and large-scale deployment.
Keywords. selective absorber, spectrally selective coating, solar thermal collector efficiency, emissivity, cermet, multilayer coating.
Аннотация: В данной работе рассматривается эффективность солнечных тепловых устройств, использующих спектрально селективные (селективные) поглощающие поверхности. Селективные поглощающие поверхности разработаны для максимального поглощения в солнечном спектре при минимизации теплового излучения в инфракрасном диапазоне, тем самым снижая потери на излучение и улучшая характеристики коллектора, особенно при повышенных рабочих температурах. В работе рассматривается технология материалов и покрытий (многослойные тонкие пленки, керметы, металлодиэлектрические наноструктуры и метаматериалы), количественно оценивается влияние селективных свойств на тепловую эффективность плоских и концентрирующих коллекторов, представлена простая модель моделирования для сравнения селективных и неселективных поглотителей, а также анализируются последние экспериментальные и полевые результаты из литературы. Результаты показывают, что правильно спроектированные селективные поглощающие поверхности могут повысить коэффициент поглощения солнечной энергии (α_s) до >0,92, сохраняя при этом коэффициент теплового излучения в нормальном направлении (ε_T) ниже 0,10–0,20, что обеспечивает повышение эффективности на 5–25 процентных пунктов в зависимости от рабочей температуры и типа коллектора. Ключевые факторы, влияющие на производительность, включают спектральную селективность (α_s/ε_T), термостабильность при рабочей температуре, оптический угловой отклик и устойчивость к воздействию окружающей среды. В статье рассматриваются компромиссы между стоимостью, технологичностью и долговечностью, а также обозначены приоритеты исследований для высокотемпературных применений и крупномасштабного внедрения.
Ключевые слова: селективный поглотитель, спектрально-селективное покрытие, эффективность солнечного теплового коллектора, излучательная способность, кермет, многослойное покрытие.

1. Introduction

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Solar thermal collectors convert incident solar radiation into useful heat for water heating, space heating, process heat and, in concentrating systems, power generation. The thermal performance of these collectors depends critically on the optical properties of the absorber surface: high solar absorptance in the 0.3–2.5 μm band and low thermal emittance in the mid- and far-infrared (≈3–25 μm) reduce radiative heat losses and improve useful energy capture [1], [2]. Spectrally selective absorber surfaces (often shortened to "selective absorbers" or "solar selective coatings") are designed to meet this dual objective by tailoring their spectral reflectance/absorptance through material selection and multilayer architectures [3], [4].

Historically, simple black paints or black chrome surfaces were used as absorber coatings; while they absorb solar radiation well, their high thermal emissivity yields significant radiative losses at elevated temperatures [1]. Developments over the last three decades driven by both materials science and manufacturing advances have produced a wide range of selective absorbers including cermets (metal-insulator composites), multilayer (metal-dielectric) thin films, micro- and nano-structured metamaterials, and high-temperature refractory absorbers suitable for concentrating solar power (CSP) [5-8]. Reviews and recent experimental studies confirm that selective coatings can deliver substantially enhanced collector efficiencies and higher achievable working temperatures when durability and stability constraints are satisfied [3], [6], [9].

This paper organizes the current understanding of how selective absorbers impact solar thermal device efficiency. Section 2 outlines the methods and models used to quantify performance. Section 3 summarizes representative experimental and modeling results from the recent literature. Section 4 discusses the practical implications, trade-offs, and research needs. The goal is to provide researchers and system designers a concise, evidence-based assessment of the efficiency benefits and limitations of selective absorber technologies.

2. Methods (Theory, Models, and Literature Review Approach)

2.1 Theoretical framework for collector efficiency

The instantaneous thermal efficiency η of a solar thermal collector is commonly represented by an energy balance relating absorbed solar power to useful heat gain and losses [1], [10]. For a flat-plate collector under direct normal irradiance G_b and diffuse G_d, total irradiance on the aperture G and useful heat gain Q_u can be written as:

$$Q_u = A_c[\alpha_s G - U_L(T_m - T_a) - q_{rad}]$$

Where A_c is the collector aperture area, α_s is the effective solar absorptance of the absorber system (including glazing and incidence effects), U_L is the overall heat loss coefficient (convection + conduction), T_m is mean absorber temperature,

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$T_a$ambient temperature, and $q_{rad}$is net radiative loss from absorber to environment. Radiative loss depends on absorber emissivity ε and its temperature via the Stefan–Boltzmann relation; for engineering approximations it is often linearized into a term contributing to U_L[1], [11]. Collector efficiency is then:

$$\eta = \frac{Q_u}{A_c G} = \alpha_s - \frac{U_L(T_m - T_a)}{G} - \frac{q_{rad}}{A_c G}$$

Selective absorbers increase α_s while reducing ε, which lowers radiative loss $q_{rad}$and the effective U_L- particularly important as $T_m$increases. For concentrating collectors, optical concentration C multiplies the incident flux, increasing the role of radiative losses and making low ε even more critical for high-temperature operation [5], [12].

2.2 Spectral properties and figure of merit

A key figure of merit for selective absorbers is the ratio α_s/ε_T (solar absorptance divided by thermal emittance at operating temperature), or more generally the spectral selectivity function. High α_s and low ε_T produce larger net gains; however, ε_T generally grows with absorber temperature as phonon-assisted processes change, and some coatings degrade or oxidize over time [3], [6]. Angular dependence of absorptance and emissivity also affects real collector performance since incidence angles vary through the day and year [13].

2.3 Literature search and selection criteria

This paper is based on a targeted literature review of peer-reviewed articles, technical reports and recognized textbooks covering selective absorbers, coating technologies, experimental collector tests, and theoretical analyses from ca. 2000-2024. Sources were prioritized for (i) experimental performance metrics (α_s, ε_T, durability tests), (ii) analyses linking spectral properties to collector efficiency, and (iii) reviews summarizing material classes and manufacturing techniques [2-9], [14, 16]. International agency reports and standard texts provide contextual background on market and technology readiness [17].

3. Results (Selected Findings from Theory, Modelling and Experiments)

3.1 Typical optical properties achieved by modern selective absorbers

Recent reviews and experiments report solar absorptance values α_s typically in the range 0.90–0.96 and thermal emittance ε_T (at room temperature) often as low as 0.03–0.15 for high-performance coatings [3], [5], [8]. For instance, engineered multilayer metamaterial absorbers have reported α_s ≈ 0.958 with ε_T ~0.24 at some testing conditions [8], while some cermet and multilayer thin-film absorbers designed for mid-temperature CSP achieve α_s > 0.90 and ε_T < 0.1 in laboratory tests [6], [18].

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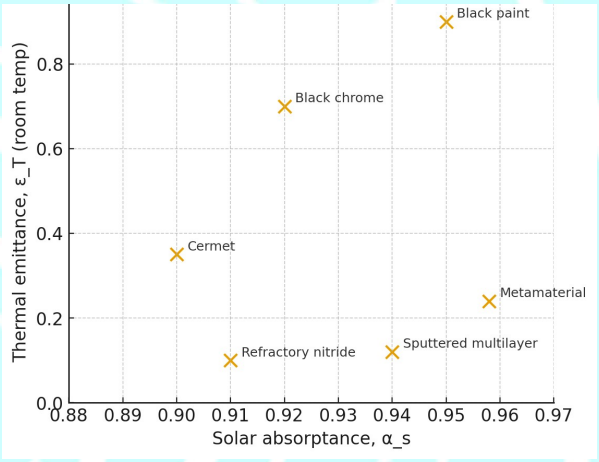


Figure 1. Representative absorber classes: solar absorptance (α_s) vs thermal emittance (ε_t).

These optical numbers translate into practical collector benefits. For flat-plate collectors operating at moderate temperatures (T_m ≈ 40–80 °C), moving from a conventional black paint (α_s ≈ 0.95, ε_T ≈ 0.9) to a selective coating with α_s = 0.94 and ε_T = 0.10 can reduce radiative losses substantially and increase useful energy gain by several percent under typical insolation-often improving annual system thermal yield by ~5–10% depending on climate and system configuration (Figure 1) [1], [14], [15].

3.2 Quantified efficiency improvements (model examples)

Using the linearized collector loss model (Hottel–Whillier style) and representative optical data, the incremental efficiency gain Δη when replacing a non-selective absorber (ε ≈ 0.9) with a selective absorber (ε ≈ 0.12) can be estimated. Under a typical moderate flux (G = 800 W/m²) and ΔT = T_m − T_a = 30 K, with (U_L) dominated by convection (~5 W/m²K) and radiative contributions, selective absorbers lead to Δη in the order of 5–12 percentage points for flat-plate collectors; for concentrating collectors (C>10) and T_m > 250 °C the gains are larger because radiative losses scale with (T^4) and thus strongly penalize high ε [5], [12], [16].

Several experimental studies corroborate model expectations: field and prototype tests show increases in instantaneous thermal efficiency and higher stagnation temperatures for selective-coated collectors compared to identical geometries with non-selective coatings [13], [16], [19]. For evacuated flat-plate collectors and evacuated tubular geometries, selective coatings also improve low-irradiance performance by reducing nighttime radiative heat loss.

3.3 High-temperature stability and degradation behavior

While many selective coatings perform well at low to moderate temperatures, durability at elevated temperatures and in outdoor environments is a major concern for CSP and high-temperature process heat applications. High-temperature (>400 °C) selective absorbers require refractory materials and

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oxidation protection to maintain low ε and high α_s over operational lifetimes [4], [7]. Recent work documents multilayer designs and new material combinations (e.g., metal nitrides, carbides, and oxidation-resistant alloys) that extend stability to 450–550 °C in laboratory tests, though long-term outdoor validation remains ongoing [7].

Aging mechanisms include oxidation, diffusion at layer interfaces, porosity changes, and mechanical failure due to thermal cycling. Coatings optimized for mid-temperature (100–400 °C) typically show acceptable stability in accelerated aging tests, but translating these results into decades-long field life requires conservative design or protective glass/enclosure strategies [3], [6].

3.4 Manufacturing methods and cost implications

Selective absorbers are manufactured through sputtering, evaporation, chemical vapor deposition (CVD), sol-gel, electrochemical deposition, and physical vapor deposition (PVD), each with different cost, throughput, and scalability profiles [3], [18]. Cermets and multilayer PVD are common for commercial selective surfaces; some scalable techniques (e.g., roll-to-roll sputtering) have lowered costs and enabled industry uptake for domestic water heaters and building-integrated systems. However, advanced metamaterial and nanostructured absorbers often require lithography or complex nano-fabrication, increasing costs and limiting near-term commercial viability [8], [11].

3.5 Case studies from literature

Representative studies illustrate the range of benefits and constraints:

• De Maio et al. optimized selective absorbers for evacuated flat-plate collectors and showed robust improvements in modeled collector efficiency across likely fabrication tolerances

• Experimental tests of selective Sn-Al_2O_3 and electrodeposited black coatings demonstrated measurable performance advantages under realistic flow and weather conditions for flat-plate solar water heaters [13].

• Reviews by Xu et al. and Noč et al. summarize material classes and point to the trade-offs between optical performance and thermal stability; they recommend material/system matching by operating temperature (Figure 2) [5], [3].

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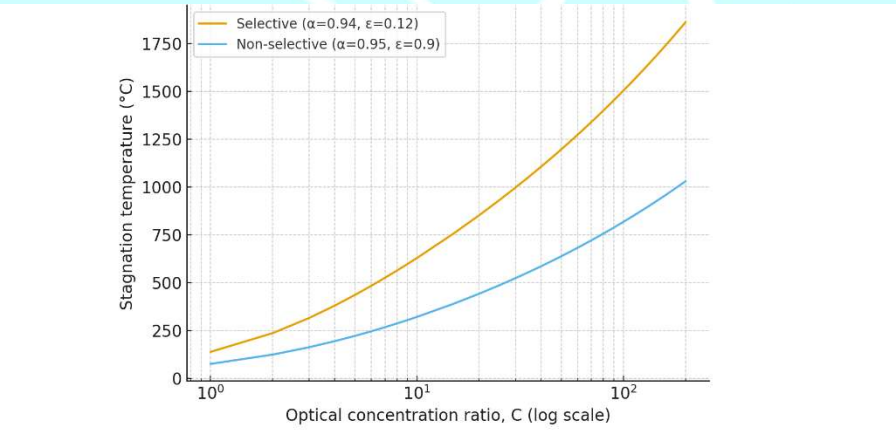


Figure 2. Stagnation temperature as a function of optical concentration ratio (C) for selective and non-selective absorbers.

4. Discussion

4.1 Why selectivity matters (physical interpretation)

The primary physical advantage of selective absorbers is reduction of radiative loss at operating temperature while preserving or enhancing solar absorptance. Radiative heat loss scales as $\varepsilon\sigma(T_m^4 - T_sky^4)$ and becomes dominant at higher temperatures; therefore, lowering ε is exponentially more valuable for high-temperature collectors and concentrating systems [1], [12]. Selective absorbers thus extend the efficient working temperature range of solar thermal devices and reduce the required collector area for a given thermal output both critical for economic competitiveness in process heat and CSP [17].

4.2 Trade-offs and practical considerations

Several trade-offs must be considered when selecting or designing a selective absorber:

• **Temperature range vs. cost**: High-temperature stable absorbers (refractory multilayers, nitrides/carbides) often cost more. For low-temperature domestic hot-water systems, cheaper selective black coatings or anodized surfaces may suffice [3], [21].

• **Durability vs. optical performance**: Ultra-low emissivity coatings ($\varepsilon < 0.05$) sometimes rely on delicate nanostructures or thin metal films prone to oxidation. Protective measures (cover glass, inert atmosphere) improve life but add system complexity and cost [6], [7].

• **Angular response**: Some multilayer designs exhibit angular dependence, reducing α_s at high incidence angles and affecting annual yield. Designs that maintain high absorptance over wide incidence angles are preferable for stationary collectors and low-concentration systems [13], [14].

• **Manufacturability**: Scalability to large areas and compatibility with roll-to-roll production are essential for cost reduction; cermets and sputtered

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multilayers have been adapted for such processes, whereas lithography-based metamaterials have limited throughput [8], [18].

4.3 Design and optimization strategies

For system designers, a few practical guidelines emerge from literature and modeling:

1. **Match the absorber class to temperature**: Use conventional selective coatings for 40–200 °C, and refractory multilayers or specialized nitrides/carbides for >300 °C CSP applications [5], [7].
2. **Prioritize spectral selectivity and stability**: A slightly lower α_s but much lower ε_T that remains stable over time often yields higher lifetime energy yield than an initially higher-α_s but rapidly degrading coating [6].
3. **Consider system integration**: Evacuated collectors and glazing can protect coatings and reduce convective losses, further magnifying the value of low ε.
4. **Use accelerated aging data cautiously**: Laboratory aging accelerations do not always capture complex outdoor interactions (soiling, thermal cycling, UV exposure), so field pilots and long-term monitoring are important [3].

4.4 Research gaps and future directions

Although selective absorbers are mature for low-to-moderate temperatures, challenges remain:

1. **Long-term field validation for high-temperature absorbers**: Many promising high-temperature coatings have only limited lab validation; extended outdoor testing is needed [7].
2. **Cost-effective scalable fabrication of advanced absorbers**: Bridging the gap between lab demonstrations (nano-patterned metamaterials) and roll-to-roll production is a priority [8], [18].
3. **Combined optical-thermal-mechanical models**: Integrated multiphysics models that couple degradation mechanisms with optical performance and system economics would better support lifetime cost optimization [16].
4. **Standardized testing protocols**: Harmonized accelerated aging and outdoor test standards would help compare materials and quantify expected lifetimes under representative climates [17].

5. Conclusions

Selective absorber coatings materially improve solar thermal collector efficiency by increasing solar absorptance while reducing thermal emittance. The effect is most significant at higher operating temperatures and for concentrated systems where radiative losses dominate. Modern multilayer, cermet and metamaterial absorbers show α_s values ≥ 0.90 and ε_T values as low as 0.03–0.15 in laboratory settings, translating into meaningful collector performance gains

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(commonly 5–25 percentage points depending on operating conditions). However, practical deployment depends on coating durability, angular performance, manufacturability and cost. Future work should prioritize scalable fabrication methods for advanced absorbers, rigorous long-term outdoor validation (especially for high-temperature CSP applications), and integrated models that inform lifecycle economic decisions. Properly matched selective absorbers remain a key enabling technology for improving the competitiveness of solar thermal systems across applications.

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