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Enhancing Energy Efficiency through the Application of Thermal Insulation Coatings

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Abstract— An object's surface temperature increases due to the absorption of solar energy, resulting in heat accumulation. The increase in temperature caused by solar radiation can lead to numerous harassment and pose challenges in different spheres of life. Thus, much energy is needed to maintain the appropriate body temperature. The issue of energy consumption has grown tremendously with the fast development of modern industry, and the issue of energy shortages has gained more attention. Everyone's attention has gradually turned to energy conservation and reducing consumption. Thus, materials with low energy consumption and high performance have become a research hotspot. Given the diversity of options available for thermal insulation materials, thermal insulation coatings have become increasingly popular because of their capacity to lessen the buildup of heat inside coated objects, thus enhancing the working environment and supplying energy. By integrating effective fillings of thermal insulation, known as filling, into the coating system, the resulting films can show a significant thermal insulation effect through temperature, radiation, or insulation mechanisms. Therefore, applying the insulating heat coatings leads to a significant reduction in body surface temperature. In this scenario, significant energy savings can be achieved by applying a temperature insulation layer to sun-prone objects. This approach reduces energy efficiency by reducing the need for refrigeration. In light of the current issues with thermal insulation coating, this paper reviews the most common types of coatings currently in use and their development, provides a brief overview of thermal insulation, and projects how new coatings will evolve.

Keywords— Thermal Insulation Coatings, Composite, Mechanism, Energy Saving, Functional Fillers.

1. Introduction

Paints and coatings are commonly employed to enhance aesthetic appeal and provide protection. However, numerous instances exist where specialist coatings are utilized to fulfill other tasks. The user has provided a numerical sequence [1, 2]. The emergence of "functional" coatings has been a prevailing phenomenon within the industry for a prolonged duration. This trend is exemplified by various instances, including the utilization of soft-feel coatings in consumer electronics [3], the implementation of sound-damping coatings to reduce noise in automobiles [4, 5], and the development of antimicrobial coatings intended to eradicate microorganisms upon contact with the coated surface [6]. The paint and coatings business has witnessed a notable trend in advancing coatings designed to regulate energy consumption.

Energy availability is crucial for economic development and the long-term well-being of our environment and society. Coatings technology enhances energy efficiency, specifically those that can withstand reduced temperatures. Cool-roof coatings reduce building heat gain, reducing reliance on air conditioning—high solar reflectivity and thermal emissivity aid in deflecting solar radiation, reducing heat transfer. Innovative coatings on building outer walls also serve this purpose.

Cool coatings also effectively mitigate the urban heat island phenomenon, which refers to the elevated temperatures observed in urban areas characterized by extensive dark roofs and paved surfaces compared to the surrounding rural regions. Thermal insulation coatings are employed for the goal of effectively managing thermal energy, serving both to ensure human safety and to promote energy conservation. The user's text does not contain any information to rewrite. Nevertheless, thermal insulation coatings operate by another mechanism, impeding heat transmission between materials under their diminished thermal conductivity. In light of the current issues with thermal insulation coating, this paper reviews the most common types of coatings currently in use and their development, provides a brief overview of thermal insulation, and projects how new coatings will evolve.

2. THE MECHANISM UNDERLYING THERMAL INSULATING COATINGS

The predominant conversion of solar radiation occurs as it is transferred to an object, resulting in thermal energy generation, following the principles of heat transfer. Consequently, when the surface of the object mentioned above is exposed to solar radiation, thermal energy can propagate from the surface towards the inside of the object. Consequently, there is a proportional increase in the temperature of the object. However, the application of thermal insulation coatings to the surface of the object can effectively insulate a significant amount of excess heat created by sunlight before it is transported to the object's surface **Fig 1**

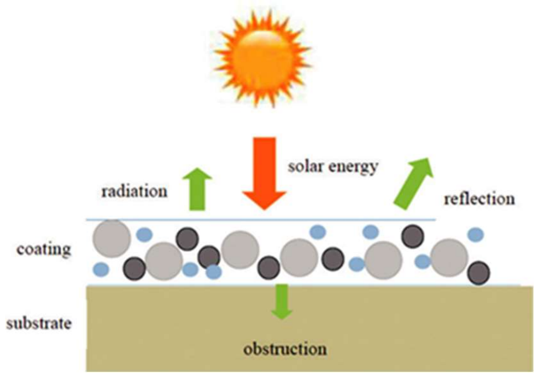

Figure 1: Mechanism diagram of coating thermal insulation[7]

2.1 *Obstructive Coating Thermal Insulation*

Obstructive thermal insulation coatings are passive forms of thermal insulation that use specific fillers to hinder heat flow. These coatings comprise the resin, fillers, pigments, additives, and solvents. Due to their low heat conductivity, functional fillers are essential for obtaining high-quality thermal insulation. These fillers include diatomaceous Earth, asbestos fibers, expanded perlite, sepiolite, closed-cell perlite, compounds based on inorganic silicates, and other materials, which contain densely arranged hollow particles that create a gas layer, acting as a thermal barrier and obstructing the occurrence of a "thermal bridge." The thickness of the coating has typically been regulated within the range of 5-20 mm since the 1980s. **[9, 10]**.

While it is accurate that thicker films are required to improve thermal insulation properties, it is unfortunate that they also present several related concerns, including diminished impact resistance, visible dry shrinkage, and an increased moisture absorption rate.

The situation will demonstrate significant deviations if the empty structure of the fillers is enclosed, For example, using hollow glass beads, hollow ceramic beads, hollow porous silica ceramics, and similar materials. Numerous studies [11, 12] have revealed that films with a closed hollow structure exhibit exceptional thermal insulation qualities, mainly when the functional fillers for thermal insulation are shrunk to nanoscale sizes. Moreover, these films can be efficiently utilized as thin films **Fig 2.**

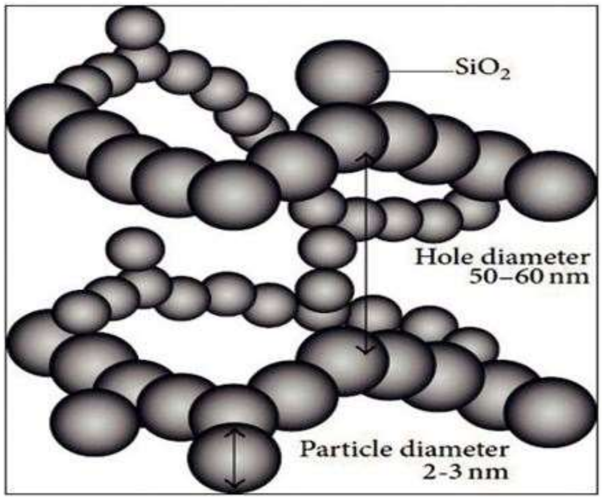

Figure 2: Network architecture of an aerogel[13]

The study demonstrates that using Architectural structures can greatly benefit from closed hollow structure fillers, such as ceramic microbubbles in thin films, to increase their thermal insulation. The film was created by filling it with hollow silica spheres. showed a thermal conductivity value of 0.05 W·m−1·K−1, demonstrating its efficient thermal insulation capacity. **[14]**. The research employed hollow polymer microspheres subjected to modification with nano-TiO2 as a functional filler within a thermal insulation layer. According to the experimental findings, the thermal conductivity of the coated film was determined to be 0.1687 W·m−1·K−1, while the film achieved a temperature differential of 5.8°C **[15]**.

Despite significant advancements in enhancing thermal insulation efficiency in thin obstructive coatings, classic thick-coated obstructive coatings continue to dominate the trading industry. As previously mentioned, using thick-coated obstructive coatings in buildings is not ideal due to the inherent conflict between thermal insulation and overall performance. Further research is required to investigate the efficacy of thin obstructive coating products in building energy conservation.

2.2 *Reflective Coatings for Thermal Insulation*

Solar energy can be reflected by reflective thermal insulation coatings on films, as opposed to being absorbed or resisted. Total solar reflectance (TSR), with a 75% value indicating a 75% redirection and a 25% absorption, is used to assess a material's reflectivity. Solar radiation encompasses wavelengths from 200 to 2500 nm, with approximately 43% falling within the near-infrared spectrum and over 50% within the visible spectrum. The choice of material is based on the material's capacity to exhibit high reflectivity in both the visible and near-infrared spectra. High reflectivity improves thermal insulation. **[16, 17]** Adding film additives enhances their thermal insulation capabilities compared to conventional materials. The fillers' visible color, which reflects and absorbs noticeable spectrum wavelengths, determines the apparent color of a film. The best color for an infrared reflective filler is white because it successfully reflects a large percentage of the visible spectrum. Black fillers are rarely used for thermal insulation because they absorb much solar radiation. Various colours' effects on the interior **[18-20]**. Experimental experiments show white fillers have better thermal insulation qualities than black fillers. As a result of prolonged solar light exposure, black fillers raise the room temperature by 7°C. Coatings employ pigments to add specific colors, which alter the film's optical characteristics in the visible range. Adding reflective fillers like metal, metal oxide, and ceramic beads may improve thermal insulation properties. The characteristics of fillers, especially those with nanocrystal structures, also affect the effectiveness of thermal insulation **[21, 22]**.

Reflective thermal insulation coatings typically combine various fillers to enhance the film's thermal insulation properties. However, the mixture of fillers' reflectivity cannot be calculated simply by adding the values of each separate filler's reflectivity. For instance, the total solar reflectance (TSR) of CoAl blue and MnSbTi brown, when blended, drops to 26.9%, which is lower than the mean (TSR) of 34.15% and the minimum TSR of 32.6% for MnSbTi brown. Since the primary reflection process takes place at the film's surface, the efficiency of thermal insulation is not simply dependent on film thickness. The amount of solar energy that may flow through and be absorbed depends on the film's thickness, with a thinner film being less effective **[23, 24] Fig 3**.

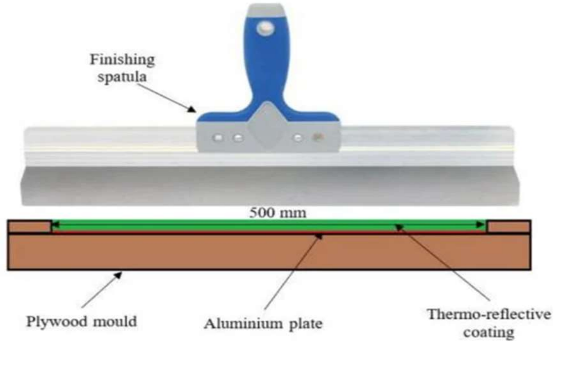

Figure 3: Application of thermo-reflective coating **[46]**

The utilization of reflective thermal insulation functional fillers facilitates the capacity of films to directly reflect solar radiation into the atmosphere rather than absorbing it and emitting it as thermal energy through a thermal conductive coating. Hence, it may be postulated that reflective thermal insulation coatings possess a higher thermal insulation efficacy than obstructive thermal insulation coatings, as indicated by previous research **[17]**. It is imperative to acknowledge that the observed increase in thermal reflectivity in the film can be attributable to the concurrent decrease in surface roughness. In the study by **[25],** nickel-coated hollow glass microspheres were employed as fillers. The findings of the study demonstrated the film's exceptional thermal insulation performance. Ceramic balls composed of ZrO_2, when coated with potassium silicate, exhibit significantly elevated levels of light scattering and reflectance, surpassing those observed in conventional ZrO_2 ceramic balls by a factor of approximately 10 to 20. The efficacy of modified ZrO_2 ceramic balls is enhanced by one-third when compared to rutile TiO_2 fillers of equivalent size **[26]**.

Fillers with a high level of reflectivity and emissivity were utilized to increase the films' reflectivity in the visible (400–720 nm) and near-infrared (720–2500 nm) ranges. Researchers in this sector have made notable advancements, resulting in comprehensive investigation and application of reflecting thermal insulation coatings **[17, 27].** In the Hangzhou region of China, which experiences scorching summers and chilly winters, applying heat-reflective insulating film on the outer walls of buildings has demonstrated a significant reduction in wall surface temperature, reaching a maximum decrease of 10°C. By employing computational analysis, it has been ascertained that applying heat-reflecting insulation coating on the outer surfaces of walls results in an annual decrease in power consumption for air-conditioning purposes, amounting to roughly 5.8 kilowatt-hours per square meter per month. This discovery provides empirical support for utilizing heat-insulating layers to preserve energy [28] substantially.

Because so many reflecting thermal insulation coating products on the market offer superior thermal insulation performance, they are the most popular option in the thermal insulation coating sector.

2.3 *Radiative Thermal Insulation Coatings*

Solar energy absorption and radiation occur when objects absorb more energy than they emit, causing a rise in their temperature. Conversely, their temperature decreases if they release more energy than they absorb. This process results in thermal radiation, which is undetectable infrared light and electromagnetic waves. Thermal radiation occurs when an object releases its energy into the surrounding space, and the space reciprocally emits energy back to the object. That occurs due to energy conservation, with outer space being an ideal energy reservoir. However, Earth's outer air layer hinders the transfer of energy radiation from terrestrial objects to outer space. Thermal radiation can pass through the atmosphere, a barrier between an object and space made up of carbon dioxide and water vapor. This "infrared window" enables direct radiation emission from Earth's surface radiators into the surrounding space. Radiant thermal insulation coatings enable objects coated with these coatings to emit more energy from solar radiation than they absorb because they contain fillers that transform absorbed energy into the rotation and vibration of molecules' energy. In contrast to reflective and obstructive coatings, which only passively block solar radiation, radiant thermal insulation films enable active cooling **Fig 4.**

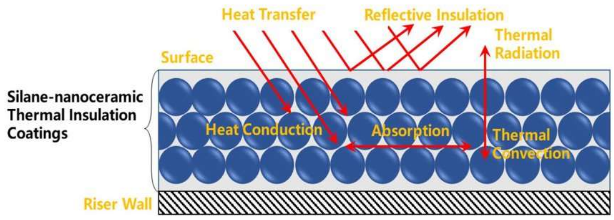

Figure 4: Application of thermo-radiative coating **[47]**

As previously mentioned, radiative fillers have demonstrated exceptional thermal radiation capabilities when utilized as a medium through which the outer atmospheric layer of the Earth functions as a "window." To increase the film's ability to emit thermal radiation., it is essential to include fillers that strongly absorb light within the 8 to 13 µm wavelength range in the coatings. Prior studies **[29]** To make materials with an ant spinel structure suitable for thermal radiation functional fillers, such as Fe_2O_3, MnO_2, Cr_2O_2, TiO_2, SiO_2, Al_2O_3, La_2O_3, and CeO, ITO, a metal oxide, increases their energy emissivity **[30, 31]**.

For coatings to achieve the desired heat radiation, reflective fillers are essential. The properties of thermal insulation have improved recently. Elements like filler concentration, diameter size, surface characteristics, and doping influence effectiveness. However, finding affordable fillers remains challenging due to their high cost.

2.4 *Composite Coatings of Thermal Insulation*

As relying solely on one mechanism is insufficient for thorough thermal insulation, Researchers are developing composite thermal insulation coatings that combine radiative, reflecting, and obstructive properties to produce a combined thermal insulation effect **[32, 33].**

Due to its significant reflectivity, Nano titanium oxide used as a filler in hollow beads produces a film with exceptional thermal insulation qualities. [34]. To achieve R-21.1 thermal insulation, 0.79 total solar reflectance, and 0.83 energy emissivity, a thermal insulation coating was created using obstructive, reflecting, and radiative fillers. The film cools the substrate, reflects solar energy, and prevents heat transfer. Thermal insulation performance can be enhanced by utilizing obstructive, reflective, and radiative fillers with acrylic or fluorocarbon substrates instead of a single filler system [35, 36]. Composite thermal insulation coatings have emerged as a prominent area of focus in the field of thermal insulation coating research Fig 5.

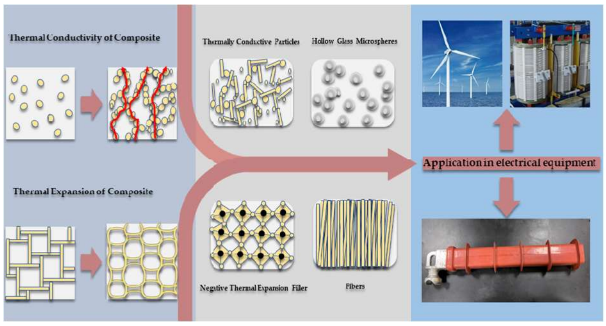

Figure 5: Application of Composite Coatings for Thermal Insulation **[48]**

3. THERMAL INSULATION COATINGS APPLICATION AND DEVELOPMENT

Thermal insulation coatings can save energy, but how well they work depends on the characteristics of the substrate. Multipurpose coatings with features like thermal insulation and other specialized functions can better satisfy consumer demand. Thermal insulation solutions for structural components like colored steel plates, aluminum profiles, glass doors, and windows are urgently needed in modern construction. Researchers are developing multifunctional coatings to meet the needs of thermal insulation and other functional areas. Windows, thermal insulation, and corrosion protection can all benefit from transparent thermal insulation coatings.

3.1 *Transparent Coatings for Thermal Insulation*

The transparent thermal insulation coating is characterized by its transparency in the visible light spectrum, achieved by incorporating semiconductor powder as fillers. Functional fillers with high transmittance in the visible spectrum and infrared light can be utilized in various materials. Examples of such fillers include Nano tin oxide antimony (ATO) and Nano indium-tin oxide (ITO) **[37]**. Nano-sized antimony-doped tin oxide (ATO) has been used to develop a thermal insulation coating as a filler. Due to the addition of Nano-ATO particles, the coatings exhibit favorable transparency and thermal insulation performance. The scientists discovered that the weight of ATO increases the thermal insulating capabilities of the film. Glass doors, windows, and automobile windows can all use this coating. **[38].** The test findings further demonstrated that the transparent thermal insulation coatings containing antimony-doped tin oxide (ATO) exhibit favorable resistance to artificial accelerated weathering **Fig 6.**

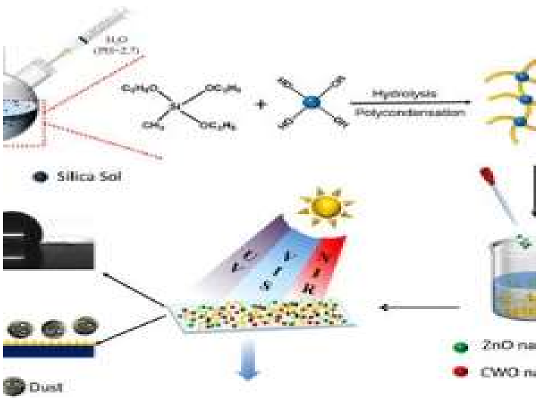

Figure 6: Transparent Coatings for Thermal Insulation **[49]**

3.2 *Vacuum Coatings of Thermal Insulation*

A film's capacity to create a vacuum structure accounts for its thermal insulation in a vacuum environment. Researchers used aerogel as a filler in the 1970s to create a superior thermal insulating layer. This layer effectively blocks and reflects solar light, raising room temperature in the winter and lowering it in the summer. [39] Furthermore, empirical evidence indicates that the film exhibits a thermal insulation capacity of up to 95%. Consequently, its application in buildings leads to a notable reduction in energy consumption from 30% to 60%. The vacuum thermal insulation coatings exhibit exceptional thermal insulation and comprehensive performance owing to their unique structure [40]. It is widely acknowledged as among the most effective materials for conserving energy and holds great potential for future applications Fig 7**.**

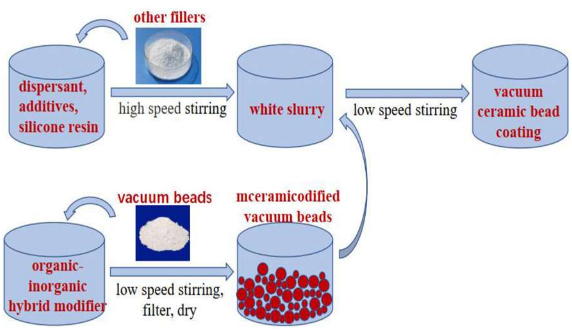

Figure 7: Application of Vacuum Coatings for Thermal Insulation **[50]**

3.3 *Nano Porous Thermal Insulation Coatings*

When the pore size is less than 50 nm, the nonporous filler material aerogel provides excellent thermal insulation performance. Despite the difficulties in creating a wholly vacuumed environment, researchers have found that using aerogel with a hoover can produce a coating with a lower thermal conductivity value than static air. **[41] .**This characteristic significantly impacts the thermal insulation capabilities of the film. Utilizing fillers possessing a nonporous structure has presented novel and unparalleled prospects for advancing thermal insulation coatings **Fig 8.**

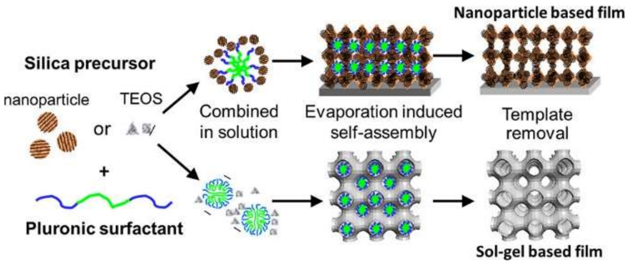

Figure 8: Nano Porous Thermal Insulation Coatings [51]

3.4 *Intelligent Coatings for Thermal Insulation*

There has been a growing interest in smart thermal insulation coatings in recent years. These coatings can effectively insulate heat in situations where the external temperature is excessively high, while also facilitating heat escape when the external temperature is excessively low. This dual functionality of energy storage and thermal insulation has garnered significant attention. Various types of thermal insulation coatings, such as thermochroic, photochromic, electrochromic, and gastro-mic films, have been showcased in research studies as practical means of conserving energy **[42, 43].** Thermo-chromic films exemplify the ability of thermo-chromic materials to experience changes in their optical characteristics in response to heat energy. The occurrence of phase transition can elicit substantial modifications in the degrees of transmittance and reflectance. Metal oxides, such as vanadium, titanium, iron, and niobium lower oxides, can function as fillers within coating systems. Integrating these chemicals into the coating process enables alterations in the hue of the film following temperature variations. In recent years, there has been a discernible increase in academic focus on intelligent coatings utilizing vanadium dioxide (VO_2). The increased level of attention can be ascribed to the coatings' reduced transition temperature and distinctive transition characteristics. At temperatures below 68°C (Tc), The compound VO_2 displays a monoclinic phase that is semiconducting and insulating.

Nevertheless, the structure changes into a metallic tetragonal rutile phase when the temperature rises above Tc [44]. Different VO_2 structures transition to produce different levels of light selectivity. In particular, visible and infrared light can pass through the VO2 film when the temperature drops below the critical temperature (Tc). Conversely, when the temperature exceeds Tc, the VO2 film permits the passage of visible light while effectively blocking infrared light. Consequently, films containing VO2 exhibit color shifts in response to temperature fluctuations. Researchers have made significant advancements in enhancing the luminescence transmittance and modulation capabilities of solar energy sources **[45]**.

The adaptability of the coating system has garnered significant attention from researchers, leading to an increasing interest in the study of intelligent thermal insulation coatings. Consequently, there is anticipation for the eventual widespread deployment of these coatings.

4. CONCLUSIONS:

- Thermal insulation coatings are a category of functional coatings that hinder heat flow due to their reduced thermal conductivity. Coatings have been discovered to possess practical applications in improving personnel protection, energy management, and condensation control for both high-temperature and low-temperature surfaces.
- Insulation coatings are a viable alternative for substituting conventional insulation in industrial settings characterized by corrosion under insulation (CUI).
- A comprehensive understanding of the mechanics and principles underlying heat transmission is crucial for comprehending the design and performance of thermal insulation coatings.
- Regarding domestic use, thermal insulation coatings continue to be the most technically advanced and popular. The development of reflective, radiant, and composite insulation coatings is still pending.

5. RECOMMENDATIONS:

- A comprehensive understanding of the mechanics and principles underlying heat transmission enables us to conduct a comparative analysis between them and conventional insulation and other forms of coatings that play a role in energy management, such as cool roof coatings, to discern the disparities in their functionality.
- To increase their service life and lower their use cost, thermal insulation coatings should be developed with weather-resistant and anticorrosion qualities in mind.
- When concentrating on thermal insulation performance, environmental friendliness should also be taken into account. The general direction in coatings development should be waterborne, solvent-free, and highly solid content.

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تعزيز كفاءة الطاقة من خلال تطبيق طلاءات العزل الحراري

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الخلاصة – تحدث الزيادة في درجة حرارة سطح الجسم نتيجة امتصاص الطاقة الشمسية ، مما يؤدي إلى تراكم الحرارة. يمكن أن تؤدي الزيادة في درجة الحرارة الناتجة عن الإشعاع الشمسي إلى العديد من المضايقات وتشكل تحديات في مجالات الحياة المختلفة. وبالتالي ، يلزم قدر كبير من الطاقة للحفاظ على درجة حرارة الجسم المناسبة. مع التطور السريع للصناعة الحديثة أصبحت مسألة استهلاك الطاقة أمراً مذهلاً ، وأصبحت مشكلة نقص الطاقة بارزة بشكل متزايد .إجتذب الحفاظ على الطاقة وخفض الاستهلاك انتباه الجميع تدريجياً . لذا أصبحت المواد الموفرة للطاقة وتقليل الاستهلاك ذات الاداء الممتاز نقطة ساخنة للبحث .نظرًا لتعدد الخيارات المتاحة لمواد العزل الحراري ، اكتسبت الطلاءات العازلة للحرارة شعبية متزايدة بسبب قدرتها على تحسين بيئة العمل وتوفير الطاقة عن طريق تقليل تراكم الحرارة داخل الاجسام المطلية. وكذلك الفعالية من حيث التكلفة ، وسهولة الاستخدام ،عبر مجموعة متنوعة من المواد المتفاعلة. من خلال دمج الحشوات الفعالة للعزل الحراري ، المعروفة باسم الحشو ، في نظام الطلاء ، تكون الأفلام الناتجة قادرة على إظهار تأثير عزل حراري ملحوظ من خلال آليات مثل انعكاس الحرارة أو الإشعاع أو العزل. وبالتالي ، يؤدي تطبيق الطلاءات العازلة للحرارة إلى انخفاض كبير في درجة حرارة سطح الجسم. في هذا السيناريو ، يمكن تحقيق وفورات كبيرة في الطاقة من خلال تطبيق طبقة عازلة للحرارة على الأجسام المعرضة لأشعة الشمس. يقلل هذا النهج من استهلاك الطاقة بكفاءة عن طريق تقليل الحاجة إلى التبريد.تستعرض هذه الورقة الأنواع الرئيسية لطلاءات العزل الحراري في هذه المرحلة وتطورها ،وتقدم بإيجاز الية العزل الحراري ، وتتنبأ باتجاه التطور لطلاءات العزل الحراري الجديدة في ضوء المشكلات الحالية لطلاء العزل الحراري..

الكلمات الرئيسية – الطلاءات العازلة للحرارة ، المركب ، الية ، توفير الطاقة ، حشوات وظيفية