

MULTI-LAYER THERMAL-REGULATING SURFACE COATING AND RELATED METHODS

PRIORITY CLAIM

[0001] This application claims priority from Singapore Patent Application No. 10202011772T filed on 26 November 2020.

TECHNICAL FIELD

[0002] The present invention relates broadly, but not exclusively, to thermal-regulating surface coatings and, more particularly, to a multi-layer thermal-regulating surface coating and methods for fabrication thereof.

BACKGROUND OF THE DISCLOSURE

[0003] Surface coatings commonly applied on surfaces of buildings and/or structures may achieve thermal regulating effects by regulating thermal convection and/or solar reflectance to reduce heat exchange between an environment and the surfaces. Some surface coatings can also achieve thermal regulating effects by regulating emission of infrared from the surface coatings. Although heat transfer from the environment to the surfaces can be reduced in this manner, a cooling effect cannot be achieved. In other words, a temperature of the surfaces cannot be made lower than an environment temperature.

[0004] Further, the surface coatings applied on surfaces of buildings and/or structures may be exposed to different weather conditions such as sunshine and rain. A thermal regulating effectiveness of the surface coatings under the different weather conditions may differ. For example, when exposed to rain or moisture in humid areas, a surface coating with a wet surface may have reduced solar

reflectivity and/or infrared emissivity, negatively affecting the thermal regulating effects of the surface coating.

[0005] A need therefore exists to provide a thermal-regulating surface coating that seeks to address at least some of the above problems. Furthermore, other desirable features and characteristics will become apparent from the subsequent detailed description and the appended claims, taken in conjunction with the accompanying drawings and this background of the disclosure.

SUMMARY

[0006] According to a first aspect, there is provided a multi-layer thermal-regulating surface coating, comprising: an outer layer comprising a material having a porous structure, wherein: in a dry state, a first refractive index of the material mismatches a second refractive index of air in pores of the porous structure to exhibit a first solar transmittance; and in a wet state, the first refractive index of the material matches a third refractive index of water in the pores of the porous structure to exhibit a second solar transmittance.

[0007] According to a second aspect, there is provided a method for fabricating a multi-layer thermal-regulating surface coating, comprising: fabricating an outer layer comprising a material having a porous structure, wherein: in a dry state, a first refractive index of the material mismatches a second refractive index of air in pores of the porous structure to exhibit a first solar transmittance; and in a wet state, the first refractive index of the material matches a third refractive index of water in the pores of the porous structure to exhibit a second solar transmittance.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Embodiments and implementations are provided by way of example only, and will be better understood and readily apparent to one of ordinary skill in the art from the following written description, read in conjunction with the drawings, in which:

[0009] Figure 1 is a schematic representation of a multi-layer thermal-regulating surface coating, according to an example embodiment.

[0010] Figure 2A is a schematic representation of an outer layer of the multi-layer thermal-regulating surface coating of Figure 1 in a dry state.

[0011] Figure 2B is a schematic representation of the outer layer of the multi-layer thermal-regulating surface coating of Figure 1 in a wet state.

[0012] Figure 3 is a schematic representation of the multi-layer thermal-regulating surface coating of Figure 1 in a cooling mode.

[0013] Figure 4 is a schematic representation of the multi-layer thermal-regulating surface coating of Figure 1 in a balance mode.

[0014] Figure 5A is a schematic representation of the multi-layer thermal-regulating surface coating of Figure 1 at a beginning of a transition mode.

[0015] Figure 5B is a schematic representation of the multi-layer thermal-regulating surface coating of Figure 1 at an end of the transition mode.

[0016] Figure 6(a) shows an opaque outer layer of the multi-layer thermal-regulating surface coating of Figure 2A in the dry state.

[0017] Figure 6(b) shows a transparent outer layer of the multi-layer thermal-regulating surface coating of Figure 2B in the wet state.

[0018] Figure 6(c) is a graph showing solar transmittance of the outer layer of the multi-layer thermal-regulating surface coating of Figure 1 in the dry state and the wet state.

[0019] Figure 6(d) is a graph showing long wavelength infrared (LWIR) emittance of the outer layer of the multi-layer thermal-regulating surface coating of Figure 1 in the dry state.

[0020] Figure 7(a) shows an image of a middle layer of the multi-layer thermal-regulating surface coating of Figure 1 when the outer layer is in the wet state.

[0021] Figure 7(b) shows an infrared image of the middle layer of the multi-layer thermal-regulating surface coating of Figure 1 after being exposed to direct sunlight.

[0022] Figure 8 shows a prototype of a two-layer surface coating comprising the outer layer and the middle layer of the multi-layer thermal-regulating surface coating of Figure 1.

[0023] Figure 9(a) shows an image of concrete blocks with no surface coating and applied with different surface coatings.

[0024] Figure 9(b) shows an infrared image of the concrete blocks of Figure 9(a) after being exposed to direct sunlight.

[0025] Figure 9(c) shows graphs illustrating temperature profile of the concrete blocks of Figure 9(a) under solar irradiance over a period of time.

[0026] Figure 10 is a flowchart illustrating a method for fabricating a multi-layer thermal-regulating surface coating, according to an example embodiment.

[0027] Skilled artisans will appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been depicted to scale.

DETAILED DESCRIPTION

[0028] Embodiments will be described, by way of example only, with reference to the drawings. Like reference numerals and characters in the drawings refer to like elements or equivalents.

[0029] As mentioned above, surface coatings commonly applied on surfaces of buildings and/or structures are unable to achieve a cooling effect. In other words, a temperature of the surfaces cannot be made lower than an environment temperature. However, the cooling effect may be achieved by radiating heat to atmosphere. For example, the cooling effect may be achieved via thermal infrared radiation within an atmospheric window. The atmospheric window refers to thermal infrared with a wavelength within the range of 8-13 μm that can be transmitted through an atmosphere. This may resemble a natural process - radiative passive cooling. Passive cooling is an essential process for heat balancing of atmosphere. It can be achieved by an organic film with properties such as the ability to reflect solar radiation and high emissivity of thermal infrared within the atmospheric window. In other words, the organic film may decrease heat received by the surfaces of buildings and/or structures from solar radiation and enhance heat dissipation into the atmosphere within the atmospheric window. Examples of structures that can be used for continuous passive thermal regulation purposes are porous poly(vinylidene fluoride-hexafluoropropylene) (PVDF-hfp), porous polyethylene (PE) and porous polydimethylsiloxane (PDMS).

[0030] Further, as mentioned above, the surface coatings applied on surfaces of buildings and/or structures can be exposed to different weather conditions such as sunshine and rain. A thermal regulating effectiveness of the surface coatings under the different weather conditions may differ. For example, when exposed to rain or

moisture in humid areas, a surface coating with a wet surface may have reduced solar reflectivity and/or infrared emissivity.

[0031] Embodiments of the invention advantageously provide a thermal-regulating surface coating with self-adaptive properties so that the surface coating may achieve continuous thermal regulation under different weather conditions. Specifically, a multi-layer thermal-regulating surface coating that may enhance thermal regulating effectiveness of the surface coating under the different weather conditions, without consuming additional energy, is provided. In other words, external energy supply is not required. The multi-layer thermal-regulating surface coating may have switchable optical and/or thermal properties. When exposed to different weather conditions such as rain and shine, the multi-layer thermal-regulating surface coating beneficially accelerates transition from a wet state to a dry state. This property may be especially useful in regions, such as tropical regions, where weather conditions change relatively quickly.

[0032] As will be explained in more details later, the multi-layer thermal-regulating surface coating may comprise a polymeric structure of an organic material. The organic material may have low thermal conductivity. As such, heat isolation is enhanced. Other than heat isolation, the multi-layer thermal-regulating surface coating also exhibits solar reflection and continuous passive cooling properties.

[0033] Further, modification of the polymeric structure of the organic material at an outer surface of the multi-layer thermal-regulating surface coating may advantageously achieve self-cleaning effects under solar stimulation. Dust contamination issues may thus be improved in this manner.

[0034] In addition, the layered coating structure can be fabricated via self-assembly methods without a need for treatment methods such as hot pressing. For example, the

layers of the multi-layer thermal-regulating surface coating can be fabricated using a sol-gel method with a one-step mixing for facile preparation. Facile coating methods can be applied layer-by-layer to form the multi-layer structure. A free-standing film may also be fabricated. The material(s), including the organic material, used in the multi-layer thermal-regulating surface coating can comprise cost-effective and environmentally friendly material(s) that may be biocompatible and recyclable. The material(s) can also be reused to fabricate new multi-layer thermal-regulating surface coatings, thereby providing further environmental benefits.

[0035] Figure 1 is a schematic representation of a multi-layer thermal-regulating surface coating 100, according to an example embodiment. As shown in Figure 1, the multi-layer thermal-regulating surface coating 100 may comprise a three-layer structure, namely an outer layer 102, a middle layer 104 and an inner layer 106. The outer layer 102 can be an optical switchable layer, the middle layer 104 can be a photo-thermal layer, and the inner layer 106 can be a supporting and/or heat isolation layer.

[0036] The three layers may comprise polymeric structures. Further, the three layers may comprise a same polymeric structure of a same organic material. According to one embodiment, the organic material may comprise cellulose acetate (CA) and/or polyvinylidene fluoride (PVDF). CA and PVDF are inflammable and biocompatible. The inflammable property beneficially enables the multi-layer thermal-regulating surface coating 100 to meet basic safety requirements for construction materials. Biocompatibility of the material advantageously reduces or prevents hazards to human and/or animal health. Further, CA and PVDF are stable in practical conditions such as at a temperature of approximately 100°C, and under long periods of UV exposure. Materials such as polyethylene (PE), ethyl acetate, poly(vinylidene fluoride-

hexafluoropropylene) (PVDF-hfp) and polydimethylsiloxane (PDMS) may also be used for the multi-layer thermal-regulating surface coating 100.

[0037] With the same organic material, the three layers beneficially strongly adhere to one another. Further, with the three layers comprising polymeric structures, structural integrity is achieved or enhanced. Hence, the multi-layer thermal-regulating surface coating 100 may be used as an integrated free-standing film. The free-standing film has mechanical strength to facilitate transportation and installation. The multi-layer thermal-regulating surface coating 100 may also be used as three separate coating gels. Both usage methods of the multi-layer thermal-regulating surface coating 100 can be applied on surfaces of buildings and/or structures to achieve continuous thermal regulation under different weather conditions.

[0038] The outer layer 102 of the multi-layer thermal-regulating surface coating 100 may be a thin, porous membrane. Diameter of pores of the outer layer 102 may be smaller than 500 μm . As mentioned above, the outer layer 102 may comprise the polymeric structure of the organic material. The outer layer 102 may further comprise a nanomaterial(s) or composited nanomaterial(s). According to one embodiment, the outer layer 102 may further comprise a viral-phobic and/or bacterial-phobic nanomaterial disposed (e.g. deposited or incorporated) on an outer surface 108 of the outer layer 102 for reducing cultivation of virus and/or bacteria on the multi-layer thermal-regulating surface coating 100. The viral-phobic and/or bacterial-phobic nanomaterial may comprise a photocatalyst material. In some implementations, the viral-phobic and/or bacterial-phobic nanomaterial may comprise nanoparticles of TiO_2 and/or nanoparticles of Ag. In this manner, the multi-layer thermal-regulating surface coating 100 advantageously has self-cleaning capability and also capability to purify

surrounding air by killing virus and bacteria and/or degrading organic contaminants.

An improved surrounding air condition is thus achieved.

[0039] In a dry state, the outer layer 102 may be opaque. In this state, the outer layer 102 may exhibit a high solar reflectance property. As a non-limiting example, the outer layer 102 in the dry state may be white in colour. Upon exposure to water and/or moisture, the outer layer 102 may transit into a wet state and may portray a transparent appearance.

[0040] According to one embodiment, the material of the outer layer 102 may further comprise a hydrophilic structure. This advantageously allows the outer layer 102 to absorb water (e.g. rainwater) to switch solar transmittance levels. In some implementations, a hydrophilic modifier may be further disposed (e.g. deposited or incorporated) on the outer surface 108 of the outer layer 102. This beneficially enables the outer surface 108 of the outer layer 102 to be ultra-hydrophilic to absorb more water and at a faster rate. Polyethylene glycol (PEG), for example PEG with a molecular weight of approximately 400 g/mol, may be used as the hydrophilic modifier.

[0041] A change in solar transmittance levels may occur due to matching or mismatching a refractive index (n) of a material having a porous structure and a component in pores of the porous structure. For example, the component in the pores of the outer layer 102 in the dry state may be air, and in the wet state may be water. As a non-limiting example, the outer layer 102 may have a refractive index of approximately 1.43 (refractive index of PVDF) in the visible light range.

[0042] According to one embodiment, a multi-layer thermal-regulating surface coating 100 comprises an outer layer 102. The outer layer 102 comprises a material having a porous structure. In a dry state, a first refractive index of the material mismatches a second refractive index of air in pores of the porous structure to exhibit a

first solar transmittance. In a wet state, the first refractive index of the material matches a third refractive index of water in the pores of the porous structure to exhibit a second solar transmittance. The first solar transmittance of the outer layer 102 in the dry state may be lower than the second solar transmittance of the outer layer 102 in the wet state. The outer layer 102 may be individually used for energy-saving smart windows.

[0043] Figure 2A is a schematic representation 200 of an outer layer 102 of the multi-layer thermal-regulating surface coating of Figure 1 in a dry state. It will be appreciated that the outer layer 102 is exposed to surrounding air. In a scenario that the outer layer 102 in the dry state is exposed to sunlight, strong scattering of light may occur at the plurality of material-air interfaces in the outer layer 102 due to mismatch of refractive indexes of the material of the outer layer 102 and air in the pores of the material. For example, the difference in the refractive indexes (Δn) may be approximately 0.43.

[0044] Diameter of pores of the outer layer 102 may be similar to the wavelength of solar radiation. As such, Mie scattering may be the predominant type of light scattering in the outer layer 102. Strong Mie scattering in the outer layer 102 may cause the outer layer 102 to portray a white colour appearance and reduce solar transmission to surfaces of buildings and/or structures to which the multi-layer thermal-regulating surface coating 100 is applied on.

[0045] Further, the organic material of the outer layer 102 may have intrinsic light absorbance property mainly in the infrared range, thus achieving high emission in a same wavelength range. Accordingly, the outer layer 102 in the dry state advantageously achieves high reflectance and reduced solar heating of the surfaces of buildings and/or structures. In addition, the outer layer 102 may also have high emissivity within the atmospheric window in the dry state. In this manner, radiative passive cooling is achieved by emitting thermal infrared through the atmosphere.

[0046] Figure 2B is a schematic representation 200 of the outer layer 102 of the multi-layer thermal-regulating surface coating of Figure 1 in a wet state. It will be appreciated that the outer layer 102 is exposed to surrounding air. When the outer layer 102 is wetted with water (water typically has a refractive index between 1.33 to 1.35), the difference in the refractive indexes (Δn) of the material of the outer layer 102 and water in the pores of the material may be approximately 0.1. Scattering of light at the plurality of material-water interfaces in the outer layer 102 may be reduced due to matching of the refractive indexes, thereby enabling relatively high solar transmittance and causing the outer layer 102 to portray a transparent appearance.

[0047] Referring back to FIG. 1, according to one embodiment, the multi-layer thermal-regulating surface coating 100 may further comprise a middle layer 104 disposed adjacent an inner surface 110 of the outer layer 102. The middle layer 104 may be a thin layer. The middle layer 104 may comprise a photo-thermal material and may function as a heating layer after absorption of solar radiation. In some implementations, the middle layer 104 may portray a grey colour appearance. The middle layer 104 can convert solar energy into heat and can be individually applied as a heating layer for buildings and/or structures in areas with low temperature.

[0048] As mentioned above, the outer layer 102 and the middle layer 104 may comprise the same organic material. However, different additive materials may be added to the outer layer 102 and the middle layer 104. In some implementations, the photo-thermal material in the middle layer 104 may comprise a MXene compound and/or carbon. The photo-thermal material may be dispersed in the structure of the middle layer 104 for converting solar energy into heat. The photo-thermal material may be well encapsulated in the layered structure of the multi-layer thermal-regulating surface coating 100, hence safety is not compromised.

[0049] When the outer layer 102 is wetted and portrays a transparent appearance, light can pass through the outer layer 102 and thereby activate the middle layer 104. The light that passes through the outer layer 102 in the wet state can be absorbed by the middle layer 104 for heat generation. Advantageously, the generated heat accelerates drying of the outer layer 102, hence reduces solar transmittance through the outer layer 102. The reduction in solar transmittance may lead to a decrease in heat generation by the middle layer 104. Heat generation by the middle layer 104 may stop when the outer layer 102 is fully dried. According to one embodiment, the middle layer 104 may comprise less than 10 mg/cm^3 of the photo-thermal material disposed in the polymeric structure of the organic material to reduce a possibility of overheating.

[0050] In a preferred implementation, the multi-layer thermal-regulating surface coating 100 may further comprise an inner layer 106 disposed adjacent an inner surface 112 of the middle layer 104. As mentioned above, the material of the outer layer 102 may comprise the polymeric structure of the organic material. Each of the middle layer 104 and the inner layer 106 may also comprise the polymeric structure of the organic material. A thickness of the outer layer 102 and a thickness of the middle layer 104 may each be smaller than a thickness of the inner layer 106. The thickness of the inner layer 106 may be greater than 1 mm. The inner layer 106 may function as a supporting layer. With heat isolation properties, the inner layer 106 may also be individually used as a protection layer on self-heating devices to prevent fire hazards.

[0051] With the same organic material, the inner layer 106 may also comprise a porous structure and exhibit passive cooling properties. Due to the relatively greater thickness of the inner layer 106, it beneficially reduces thermal convection between the surfaces of buildings and/or structures and air in the surrounding environment, thereby achieves heat isolation.

[0052] In use, an outer surface 114 of the inner layer 106 may directly contact the surfaces of buildings and/or structures. In this manner, the inner layer 106 may absorb heat or thermal infrared from the surfaces of buildings and/or structures and emit it through the atmosphere.

[0053] To enhance fire resistance, fire-retardant material(s) may be added to the multi-layer thermal-regulating surface coating 100. In some embodiments, the outer layer 102, the middle layer 104 and the inner layer 106 may comprise a fire-retardant material disposed in the polymeric structure of the organic material. As a non-limiting example, the fire-retardant material may comprise bromide.

[0054] In the following paragraphs, working principle of the multi-layer thermal-regulating surface coating 100 according to an example embodiment will be described.

[0055] In the dry state, the outer layer 102 may portray a white colour appearance and have high solar reflectance. Solar transmittance to the middle layer 104 is reduced, hence reducing solar heating of the middle layer 104 and/or the surfaces of buildings and/or structures. Further, the multi-layer thermal-regulating surface coating 100 achieves heat isolation by reducing thermal convection between air in the surrounding environment and the surfaces of buildings and/or structures.

[0056] Generally, when buildings and/or structures get heated due to ground heating and/or inner heating, surfaces of the buildings and/or structures emit thermal infrared to the surrounding environment, hence decreasing temperature on the surfaces. Typically, a material of the surfaces (e.g. concrete or metal) has relatively low infrared emissivity, hence thermal radiation is impeded. For example, infrared emissivity of concrete is approximately 0.54 and metal is approximately 0.25. Relatively higher thermal infrared emissivity of the multi-layer thermal-regulating surface coating 100 advantageously enhances thermal radiation to the surrounding environment. With

relatively higher emissivity in the range of 8-13 μm , thermal radiation is also emitted through the atmosphere. Accordingly, passive cooling is achieved. When coated with the multi-layer thermal-regulating surface coating 100, the surfaces of buildings and/or structures may be cooler than the surrounding environment.

[0057] In a scenario when water (e.g. rainwater) comes into contact with the outer layer 102, the outer layer 102 can absorb the water and change to a transparent appearance. This may allow light to directly shine on the middle layer 104. It will be appreciated that solar power density can be relatively low during rainy weather. Under such a condition, a main function of the multi-layer thermal-regulating surface coating 100 can be to isolate heat. Isolating heat during rainy weather advantageously reduces temperature drop at the surfaces of buildings and/or structures, hence a more comfortable indoor temperature for human living is achieved.

[0058] When the rain stops, solar power density and environment temperature can increase quickly. Sunlight transmitted through the outer layer 102 can cause the middle layer 104 to generate heat. Water can be evaporated from the outer layer 102, as such it can be dried. This process can be completed within a short period of time as a water evaporation rate is enhanced due to the heat generated by the middle layer 104. As the outer layer 102 dries, light transmitted to the middle layer 104 is reduced, hence heat generation by the middle layer 104 is impeded.

[0059] The ability to intrinsically switch states, such as between the wet state and the dry state, beneficially allows the multi-layer thermal-regulating surface coating 100 to continuously achieve cooling effect under changing weathers and maintain indoor temperature within a comfortable temperature range.

[0060] Other than achieving cooling effect, the multi-layer thermal-regulating surface coating 100 may be modified such that the outer layer 102 in the wet state can generate heat under sunlight for heating purposes during cold weather or in cold regions.

[0061] Depending on the weather condition, the multi-layer thermal-regulating surface coating 100 can operate in one of three modes – a cooling mode, a balance mode, or a transition mode.

[0062] Figure 3 is a schematic representation of the multi-layer thermal-regulating surface coating 100 of Figure 1 in a cooling mode 300. During sunny weather, a surrounding environment or ambient temperature is high with strong solar radiation. Under this condition, the multi-layer thermal-regulating surface coating 100 can operate in the cooling mode. Thermal regulation can be achieved via solar reflection, thermal infrared radiation, and reduction of thermal convection or thermal isolation in this mode.

[0063] In this mode, the outer layer 102 can be dry and portray a white colour appearance, exhibiting relatively high solar reflectance. In this manner, direct solar heating on surfaces of buildings and/or structures is reduced. Further, thermal convection between the surfaces of buildings and/or structures and surrounding air is reduced mainly by the inner layer 106. Direct thermal conduction from the hot surrounding air to the surfaces of buildings and/or structures is also reduced. With solar reflection and thermal isolation achieved by the multi-layer thermal-regulating surface coating 100, the surfaces of buildings and/or structures can be at a temperature close to that of the surrounding air. In addition, the multi-layer thermal-regulating surface coating 100 may exhibit high emissivity within the atmospheric window, hence thermal infrared is emitted through the atmosphere. With a relatively higher emissivity, buildings and/or structures beneficially emit more thermal infrared and thus achieve

passive cooling. In this manner, the surfaces of the buildings and/or structures can be cooler than the surrounding air.

[0064] Figure 4 is a schematic representation of the multi-layer thermal-regulating surface coating 100 of Figure 1 in a balance mode 400. Under cloudy or rainy weather conditions, the surrounding air is relatively cold. Further, rainwater on the surfaces of buildings and/or structures removes heat from the surfaces. There may be a drop in indoor temperature, which can reduce comfort levels. The multi-layer thermal-regulating surface coating 100 beneficially regulates and balances the indoor temperature by achieving a smaller temperature drop. In the balance mode, the outer layer 102 may be in a wet state and portray a transparent appearance. Under cloudy or rainy weather conditions, clouds narrow or close the atmospheric space, thereby reducing or completely suppressing passive thermal infrared radiation. Accordingly, a cooling effect is also suppressed. The inner layer 106 further reduces heat loss due to a continuous flow of rainwater down the surfaces of buildings and/or structures due to its relatively greater thickness. Heat loss is also suppressed through reduction in thermal convection which reduces heat exchange between the surfaces of buildings and/or structures and the surrounding cold air.

[0065] Figure 5A is a schematic representation 500 of the multi-layer thermal-regulating surface coating 100 of Figure 1 at a beginning of a transition mode. Figure 5B is a schematic representation 500 of the multi-layer thermal-regulating surface coating 100 of Figure 1 at an end of the transition mode. Transition mode may be activated when the cloudy or rainy weather condition begins to change to a sunny weather condition. In the transition mode, the multi-layer thermal-regulating surface coating 100 may transit from the balance mode to the cooling mode. In the balance mode, water may be retained in the structure of the multi-layer thermal-regulating

surface coating 100. The retained water may need to be evaporated to change to the cooling mode. As shown in Figure 5A, sunlight can directly pass through the transparent outer layer 102 in the wet state. The middle layer 104 can absorb solar power for heat generation, hence water evaporation is accelerated. Thermal infrared radiation re-occurs as clouds disappear. In this manner, the outer layer 102 may be dried and portray an opaque appearance. The middle layer 104 may then stop generating heat. Hence, the multi-layer thermal-regulating surface coating 100 may enter the cooling mode (the end of the transition mode) as shown in Figure 5B.

[0066] Figure 6 600 illustrates optical switching properties of the outer layer 102. Figure 6(a) shows an opaque outer layer 102 of the multi-layer thermal-regulating surface coating 100 of Figure 2A in the dry state. Figure 6(b) shows a transparent outer layer 102 of the multi-layer thermal-regulating surface coating 100 of Figure 2B in the wet state. The difference in appearance of the outer layer 102 indicates optical switching ability. The outer layer 102 in the dry state may block more than 80% of incoming solar energy through Mie scattering in the porous structure.

[0067] Figure 6(c) is a graph showing solar transmittance of the outer layer 102 of the multi-layer thermal-regulating surface coating 100 of Figure 1 in the dry state and the wet state. As can be seen, overall solar transmittance of the outer layer 102 in the wet state reaches 91%, thereby direct permeation of sunlight to the middle layer 104 occurs.

[0068] Figure 6(d) is a graph showing long wavelength infrared (LWIR) emittance of the outer layer 102 of the multi-layer thermal-regulating surface coating 100 of Figure 1 in the dry state. It can be seen that the outer layer 102 exhibits strong thermal radiation of approximately 96% LWIR emittance rate within the atmospheric window.

[0069] Figure 7 illustrates solar absorbance properties of the middle layer 104. Figure 7(a) shows an image 700 of the middle layer 104 of the multi-layer thermal-regulating

surface coating 100 of Figure 1 when the outer layer 102 is in the wet state. As mentioned above, the middle layer 104 can exhibit photo-thermal properties when the outer layer 102 is in the wet state. The black colour middle layer 104 as shown is due to dispersed black photo-thermal material(s) or nanoparticles within its polymeric structure.

[0070] Figure 7(b) shows an infrared image 700 of the middle layer 104 of the multi-layer thermal-regulating surface coating 100 of Figure 1 after being exposed to direct sunlight for approximately five minutes. After exposure to direct sunlight (e.g. 1 Sun power density), the photo-thermal material(s) in the middle layer 104 converts solar energy into heat, hence temperature is increased as shown.

[0071] Figure 8 shows a prototype of a two-layer surface coating 800 comprising the outer layer 102 and the middle layer 104 of the multi-layer thermal-regulating surface coating 100 of Figure 1, whereby a 300 μm thick outer layer 102 is applied on the middle layer 104 to form the two-layer structure. As shown, the two layers are self-adhered. Further, as shown, the left portion of the prototype of the two-layer surface coating 800 is in a dry state and portrays a white and opaque appearance while the right portion is in a wet or moist state and portrays a grey and translucent appearance. A colour contrast between the dry and wet or moist parts of the two-layer surface coating 800 indicates a transition of states.

[0072] Figure 9(a) shows an image 900 of concrete blocks with no surface coating and applied with different surface coatings. As shown, the leftmost concrete block has no surface coating, the middle concrete block has a conventional surface coat (Nippon Solareflect Si) and rightmost concrete block has an outer layer 102 in the dry state. The three concrete blocks are placed under direct sunlight.

[0073] Figure 9(b) shows an infrared image 900 of the concrete blocks of Figure 9(a) after being exposed to direct sunlight. It can be seen that the concrete block with an outer layer 102 in the dry state exhibits a lowest temperature as compared to the other two concrete blocks. This shows that the outer layer 102 has the best cooling property.

[0074] Figure 9(c) shows graphs 900 illustrating temperature profile of the concrete blocks of Figure 9(a) under solar irradiance over a period of time, such as from noon to nighttime under sunny weather. Solar irradiance and relative humidity (RH) during the period of time are also shown. Continuous temperature recording shows a maximum of 5°C difference between the concrete blocks with the conventional surface coat and with the outer layer 102 at noon time. The temperature difference is due to a difference in solar reflectance of the conventional surface coat and the outer layer 102. It can also be seen that the concrete block with the outer layer 102 has a lowest temperature throughout the time period.

[0075] Figure 10 is a flowchart 1000 illustrating a method for fabricating a multi-layer thermal-regulating surface coating, according to an example embodiment. At step 1002, an outer layer comprising a material having a porous structure is fabricated. In a dry state, a first refractive index of the material mismatches a second refractive index of air in pores of the porous structure to exhibit a first solar transmittance. In a wet state, the first refractive index of the material matches a third refractive index of water in the pores of the porous structure to exhibit a second solar transmittance. The method for fabricating a multi-layer thermal-regulating surface coating may further comprise fabricating a middle layer as shown at step 1004. The middle layer may be disposed adjacent an inner surface of the outer layer and may comprise a photo-thermal material. The photo-thermal material may comprise a MXene compound and/or carbon. The method for fabricating a multi-layer thermal-regulating surface coating may further

comprise fabricating an inner layer as shown at step 1006. The inner layer may be disposed adjacent an inner surface of the middle layer. The material of the outer layer may comprise a polymeric structure of an organic material. Each of the middle layer and the inner layer may also comprise the polymeric structure of the organic material. A thickness of the outer layer and a thickness of the middle layer may each be smaller than a thickness of the inner layer. The organic material may comprise cellulose acetate (CA) and/or polyvinylidene fluoride (PVDF). It will be appreciated that the method for fabricating the multi-layer thermal-regulating surface coating can be in the sequence of step 1006, followed by step 1004 and followed by step 1002. In other words, an inner layer can be fabricated, followed by a middle layer, and followed by an outer layer.

[0076] Thus, it can be seen that methods and multi-layer thermal regulating surface coatings have been provided that address the drawbacks of prior art methods and surface coatings. The method for fabricating a multi-layer thermal-regulating surface coating may further comprise disposing less than 10 mg/cm^3 of the photo-thermal material in the polymeric structure of the organic material of the middle layer. The thickness of the inner layer may be greater than 1 mm.

[0077] The method for fabricating a multi-layer thermal-regulating surface coating may further comprise disposing a fire-retardant material in the polymeric structure of the organic material of the outer layer, the middle layer and the inner layer. The fire-retardant material may comprise bromide.

[0078] In some implementations, the material of the outer layer may further comprise a hydrophilic structure. The first solar transmittance of the outer layer in the dry state may be lower than the second solar transmittance of the outer layer in the wet state.

[0079] The method for fabricating a multi-layer thermal-regulating surface coating may further comprise disposing (e.g. depositing or incorporating) a viral-phobic and/or

bacterial-phobic nanomaterial on an outer surface of the outer layer. The viral-phobic and/or bacterial-phobic nanomaterial may comprise nanoparticles of TiO_2 and/or nanoparticles of Ag.

[0080] Embodiments of the invention may also provide a method comprising applying the inner layer on a surface, applying the middle layer on the inner layer, and applying the outer layer on the middle layer.

[0081] Embodiments of the invention may also provide a method comprising applying the multi-layer thermal-regulating surface coating which may comprise the inner layer, the middle layer and the outer layer on a surface.

[0082] It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. For example, parameters such as thickness of each of the layers in the multi-layer thermal-regulating surface coating may vary depending on the application for optimizing performance. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

What is claimed is:

1. A multi-layer thermal-regulating surface coating, comprising:
an outer layer comprising a material having a porous structure, wherein:
in a dry state, a first refractive index of the material mismatches a second refractive index of air in pores of the porous structure to exhibit a first solar transmittance; and
in a wet state, the first refractive index of the material matches a third refractive index of water in the pores of the porous structure to exhibit a second solar transmittance; and
a middle layer disposed adjacent an inner surface of the outer layer, wherein the middle layer comprises a photo-thermal material comprising a MXene compound.
2. The surface coating of claim 1, wherein the photo-thermal material also comprises carbon.
3. The surface coating of claim 1 or 2, further comprising an inner layer disposed adjacent an inner surface of the middle layer, wherein:
the material of the outer layer comprises a polymeric structure of an organic material;
each of the middle layer and the inner layer also comprise the polymeric structure of the organic material; and
a thickness of the outer layer and a thickness of the middle layer are each smaller than a thickness of the inner layer.
4. The surface coating of claim 3, wherein the organic material comprises cellulose acetate (CA) and/or polyvinylidene fluoride (PVDF).
5. The surface coating of claim 3 or 4, wherein the middle layer comprises less than 10 mg/cm³ of the photo-thermal material disposed in the polymeric structure of the organic material.

6. The surface coating of any one of claims 3 to 5, wherein the thickness of the inner layer is greater than 1 mm.
7. The surface coating of any one of claims 3 to 6, wherein the outer layer, the middle layer and the inner layer comprise a fire-retardant material disposed in the polymeric structure of the organic material.
8. The surface coating of claim 7, wherein the fire-retardant material comprises bromide.
9. The surface coating of any one of the preceding claims, wherein the material of the outer layer further comprises a hydrophilic structure.
10. The surface coating of any one of the preceding claims, wherein the first solar transmittance of the outer layer in the dry state is lower than the second solar transmittance of the outer layer in the wet state.
11. The surface coating of any one of the preceding claims, wherein the outer layer further comprises a viral-phobic and/or bacterial-phobic nanomaterial disposed on an outer surface of the outer layer.
12. The surface coating of claim 11, wherein the viral-phobic and/or bacterial-phobic nanomaterial comprises nanoparticles of TiO_2 and/or nanoparticles of Ag.
13. A method for fabricating a multi-layer thermal-regulating surface coating, comprising:
 - fabricating an outer layer comprising a material having a porous structure, wherein:
 - in a dry state, a first refractive index of the material mismatches a second refractive index of air in pores of the porous structure to exhibit a first solar transmittance; and
 - in a wet state, the first refractive index of the material matches a third refractive index of water in the pores of the porous structure to exhibit a second solar transmittance; and

fabricating a middle layer, wherein the middle layer is disposed adjacent an inner surface of the outer layer, and wherein the middle layer comprises a photo-thermal material comprising a MXene compound.

14. The method of claim 13, wherein fabricating the middle layer comprising the photo-thermal material comprises fabricating the middle layer comprising a photo-thermal material comprising the MXene compound and carbon.

15. The method of claim 13 or 14, further comprising fabricating an inner layer adjacent an inner surface of the middle layer, wherein:

fabricating the outer layer comprises fabricating the outer layer of a material comprising a polymeric structure of an organic material and fabricating the outer layer to have a thickness smaller than a thickness of the inner layer;

fabricating the inner layer comprises fabricating the inner layer of a material having the same polymeric structure of the organic material as the material of the outer layer; and

fabricating the middle layer comprises fabricating the middle layer of a material having the same polymeric structure of the organic material as the material of the outer layer and fabricating the middle layer to have a thickness smaller than the thickness of the inner layer.

16. The method of claim 15, wherein fabricating the middle layer further comprises disposing less than 10 mg/cm^3 of the photo-thermal material in the polymeric structure of the organic material of the middle layer.

17. The method of claim 15 or 16, wherein fabricating the outer layer, fabricating the middle layer and fabricating the inner layer each further comprise disposing a fire-retardant material in the polymeric structure of the organic material of the outer layer, the middle layer and the inner layer.

18. The method of any one of claims 13 to 17, wherein fabricating the outer layer further comprises fabricating a hydrophilic structure in the material of the outer layer.

19. The method of any one of claims 13 to 18, further comprising disposing a viral-phobic and/or bacterial-phobic nanomaterial on an outer surface of the outer layer.
20. The method of any one of claims 15 to 17 comprising:
applying the inner layer on a surface;
applying the middle layer on the inner layer; and
applying the outer layer on the middle layer.
21. The method of any one of claims 15 to 17 further comprising applying the multi-layer thermal-regulating surface coating comprising the inner layer, the middle layer and the outer layer on a surface.