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(54) Title: INFRARED-TRANSPARENT, POLYMER FIBER-BASED WOVEN TEXTILES FOR HUMAN BODY COOLING

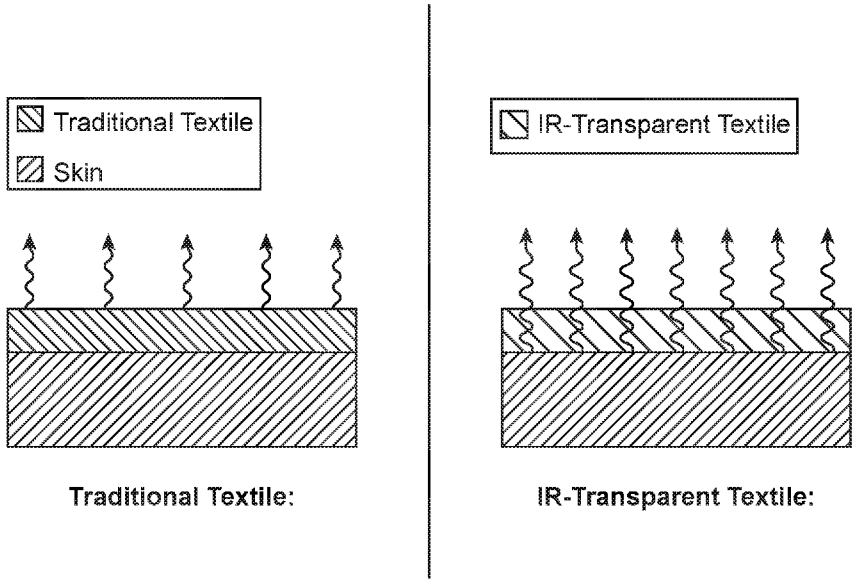


FIG. 1

(57) Abstract: A fiber includes an elongated member and refractive index contrast domains dispersed within the elongated member. The elongated member includes at least one polymer having a transmittance of infrared radiation at a wavelength of 9.5 μπι of at least about 40%.

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INFRARED-TRANSPARENT, POLYMER FIBER-BASED WOVEN TEXTILES FOR HUMAN BODY COOLING

Cross-Reference to Related Application

[0001] This application claims the benefit of U.S. Provisional Application No. 62/399,974, filed September 26, 2016, the contents of which are incorporated herein by reference in their entirety.

Statement Regarding Federally Sponsored Research or Development

[0002] This invention was made with Government support under contract DE-AR0000533 awarded by the Department of Energy. The Government has certain rights in the invention.

Background

[0003] Indoor heating, ventilation, and air conditioning (HVAC) contributes about one-third of the global energy consumption. Reducing usage of HVAC can benefit both the economy and the environment. For example, expanding a setpoint range of HVAC by about +/- 4 °F can save more than about 30% of energy consumption of buildings. Human body heat dissipation has three forms: conduction, convection, and radiation. Among these dissipation routes, radiation accounts for greater than about 50% of the total heat loss under normal skin conditions, but traditional textiles are not designed to control radiative heat loss. Traditional textiles trap air around the human body to change convection or conduction dissipation rates. However, the heat dissipation from radiation typically is not adequately controlled by traditional textiles. It is desirable to provide a textile material that is infrared (IR)-transparent and can tune its thermal property by radiation control.

[0004] It is against this background that a need arose to develop embodiments of this disclosure.

Summary

[0005] In some embodiments, a fiber includes an elongated member and refractive index contrast domains dispersed within the elongated member. The elongated member includes at least one polymer having a transmittance of infrared radiation at a wavelength of 9.5 μm of at least about 40%.

[0006] In some embodiments of the fiber, the elongated member includes at least one polyolefin.

[0007] In some embodiments of the fiber, the elongated member includes at least one of polyethylene or polypropylene.

[0008] In some embodiments of the fiber, the elongated member includes a blend of polyethylene and polypropylene, and a weight percentage of polypropylene relative to a combined weight of polyethylene and polypropylene is in a range of about 1% to about 50%. In some embodiments of the fiber, the elongated member includes a blend of polyethylene and polypropylene, and a weight percentage of polyethylene relative to a combined weight of polyethylene and polypropylene is in a range of about 1% to about 50%.

[0009] In some embodiments of the fiber, the refractive index contrast domains are pores. In some embodiments, the pores have an average pore size in a range of about 50 nm to about 1000 nm. In some embodiments, a volume percentage of the pores within the elongated member is at least about 10%.

[0010] In some embodiments of the fiber, the refractive index contrast domains are particulate fillers. In some embodiments, the fillers have an average particle size in a range of about 50 nm to about 1000 nm. In some embodiments, a volume percentage of the fillers within the elongated member is at least about 10%. In some embodiments, the fillers include an inorganic material.

[0011] In some embodiments of the fiber, a difference in refractive index between the refractive index contrast domains and the elongated member is at least about ±1% with respect to a refractive index of the elongated member.

[0012] In some embodiments of the fiber, the elongated member is a first elongated member, and further comprising a second elongated member combined with the first elongated member to form a body of the fiber.

[0013] In some embodiments, a woven textile includes the fiber of any one of the foregoing embodiments. In some embodiments, the woven textile has a transmittance of infrared radiation at a wavelength of 9.5 μm of at least about 40%. In some embodiments, the woven textile has an opacity to visible light over a wavelength range of 400-700 nm of at least about 40%.

[0014] In some embodiments, a cloth includes at least one layer including a woven textile including the fiber of any one of the foregoing embodiments.

[0015] In some embodiments, a method of regulating a temperature of a human body is provided. The method includes placing a woven textile adjacent to the human body, wherein the woven textile includes the fiber of any one of the foregoing embodiments.

[0016] In some embodiments, a method of forming a porous polymer fiber is provided. The method includes forming a mixture of a solvent and at least one polymer, extruding the mixture to form a polymer fiber including the solvent dispersed within the polymer fiber, and extracting the solvent from the polymer fiber to form the porous polymer fiber.

[0017] In some embodiments of the method, a volume percentage of the solvent in the mixture is at least about 10%.

[0018] In some embodiments of the method, the mixture includes at least one polyolefin.

[0019] In some embodiments of the method, the mixture includes at least one of polyethylene or polypropylene.

[0020] In some embodiments of the method, the mixture includes polyethylene and polypropylene.

[0021] Other aspects and embodiments of this disclosure are also contemplated. The foregoing summary and the following detailed description are not meant to restrict this disclosure to any particular embodiment but are merely meant to describe some embodiments of this disclosure.

Brief Description of the Drawings

[0022] For a better understanding of the nature and objects of some embodiments of this disclosure, reference should be made to the following detailed description taken in conjunction with the accompanying drawings.

[0023] Figure 1. Schematics showing a traditional textile and an IR-transparent textile.

[0024] Figure 2. Schematic showing a perspective, cross-sectional view of a polymer fiber.

[0025] Figure 3. Schematic showing a cross-sectional view of a polymer fiber.

[0026] Figure 4. Schematic showing a cross-sectional view of a polymer fiber.

[0027] Figure 5. Schematic showing a cross-sectional view of a polymer fiber.

[0028] Figure 6. Process flow for forming nanoporous polyethylene (PE) fibers.

[0029] Figure 7. Schematic diagram of an extrusion device for forming nanoporous PE fibers.

[0030] Figure 8. Scanning electron microscope (SEM) images of nanoporous PE fibers, at various levels of magnification.

[0031] Figure 9(a). Process flow for forming a woven textile from nanoporous PE fibers.

[0032] Figure 9(b). Image of a resulting textile.

[0033] Figure 9(c). Transmittance/reflectance of a textile over a range of wavelengths.

[0034] Figure 10(a). Process flow for forming a woven textile from nanoporous PE fibers.

[0035] Figure 10(b). Image of a resulting textile.

[0036] Figure 10(c). Transmittance/reflectance of a textile over a range of wavelengths.

[0037] Figure 11. Evaluation results of mechanical strength of resulting fibers, in terms of their maximum elongation at break.

[0038] Figure 12. Transmittance/reflectance of a textile (about 10% of polypropylene (PP)) on the left compared with transmittance/reflectance of a textile formed from a single-fiber yarn of nanoporous PE fibers (0% of PP) on the right.

Description

[0039] Some embodiments of this disclosure are directed to an IR-transparent, polymer fiber-based woven textile for wearers to reduce indoor HVAC usage, while providing comfort and breathability. In some embodiments, the IR-transparent textile increases IR radiation dissipation of a human body. As the result, a cooling effect is achieved and less HVAC energy can be consumed to maintain a comfortable body temperature. Also, the IR-transparent textile is a woven textile, which ensures its comfort and breathability, and renders it desirable for use as a next-to-skin textile in an article of clothing.

[0040] Unlike traditional textiles, an IR-transparent textile of some embodiments has a low absorption of IR radiation emitted by a human body, so the IR radiation can be transmitted freely into an environment and result in a wearer feeling cooler. Meanwhile, polymer fibers included in the textile are provided with refractive index contrast domains dispersed within the fibers, which serve to scatter visible light and render the textile opaque to visible light. In some embodiments, the refractive index contrast domains are pores, which are sized to primarily scatter visible light rather than IR radiation. These pores can be interconnected, and can render the textile breathable and increase heat dissipation via conduction and convection. Also, its fiber-based woven structure provides comfort for a human body, and allows the textile to be used as a next-to-skin textile. Polymer fibers provided with pores (or other refractive index contrast domains) can be formed at a large scale by a process such as extrusion and solvent extraction, and woven textiles can be formed from such fibers at a large scale by a process such as weaving. The result is an IR-transparent and visibly opaque polymer fiber-based woven textile, which maintains comfort when used as a next-to-skin textile and also can be realized at a large scale.

[0041] By way of overview and referring to Figure 1, a traditional textile mainly focuses on improving convection or conduction heat dissipation to achieve a cooling effect, but there is little control for radiation heat dissipation. At normal skin temperature of about 34 °C, the

human body can emit about 7-14 μm mid-IR radiation with a peak at about 9.5 μm. The traditional textile has a high absorption of IR radiation emitted by the human body, so the IR radiation is largely blocked from being transmitted into an environment. In contrast, an IR-transparent textile has a low absorption of IR radiation emitted by the human body, so the IR radiation can be transmitted largely unblocked into the environment and thereby can achieve a greater cooling effect. In addition, the provision of refractive index contrast domains within polymer fibers of the IR-transparent textile serves to scatter visible light and render the textile visibly opaque but still IR-transparent. Furthermore, a fiber-based woven structure of the IR-transparent textile provides comfort as well as benefits such as washability and greater strength and durability.

[0042] Polymer Fibers

[0043] Figure 2 is a schematic showing a perspective, cross-sectional view of a polymer fiber 200 according to some embodiments of this disclosure. The fiber 200 includes an elongated member 202 and refractive index contrast domains 204 dispersed within the elongated member 202.

[0044] The elongated member 202 includes a single polymer or a blend of two or more different polymers. To impart IR transparency in some embodiments, a polymer or a blend of polymers having a low absorption of IR radiation can be used. In such embodiments, suitable polymers include polyolefins, such as polyethylene (PE), polypropylene (PP), and other thermoplastic polyolefins or polyolefin elastomers. In the case of PE, suitable molecular weights can range from low density PE (LDPE), high density PE (HDPE), and ultra-high molecular weight PE (UHMWPE). PE can be blended or at least partially replaced with other polymers, such as PP, polyvinyl chloride (PVC), vinylon, polyacrylonitrile (PAN), polyamide (e.g., nylon), polyethylene terephthalate (PET), polyester, polyvinyl fluoride (PVF), copolymers, other thermoplastic polymers, natural polymers, and so forth. For example, a blend of PE and PP (or more generally a blend of two or more different polyolefins) can be used to impart improved mechanical strength while maintaining IR transparency, such as where a weight percentage of PP relative to a combined weight of PE and PP is in a range of about 1% to about 60%, about 1% to about 50%, about 5% to about 45%, about 5% to about 40%, about 5% to about 35%, about 5% to about 30%, about 5% to about 25%, about 5% to about 20%, or about 10%. In place of, or in combination with, polyolefins, other polymers having a low absorption of IR radiation can be used, such as polymers substantially devoid of one or more of the following functional groups: C–O; C–N; aromatic C–H; and S=O, and such as polymers with a content of no greater than about 1 mmole/g, no greater than about

0.1 mmole/g, no greater than about 0.01 mmole/g, no greater than about 0.001 mmole/g, or no greater than about 0.0001 mmole/g of one or more of these functional groups. In some embodiments, suitable polymers have a transmittance of IR radiation at a wavelength of 9.5 μm of at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, or at least about 80%, and up to about 90%, up to about 95%, up to about 98%, or more. In some embodiments, suitable polymers have a weighted average transmittance of IR radiation over a wavelength range of 7-14 μm of at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, or at least about 80%, and up to about 90%, up to about 95%, or more. During formation of the fiber 200 shown in Figure 2, one or more additives can be included, such as anti-oxidants, anti-microbials, colorants or dyes, water wicking agents (e.g., cotton), metals, wood, silk, wool, and so forth. The one or more additives can be dispersed within a polymer or a blend of polymers included in the elongated member 202.

[0045] The refractive index contrast domains 204 provide a contrast in refractive index relative to the polymer or the blend of polymers included in the elongated member 202 to scatter visible light and render the fiber 200 (and a resulting woven textile) visibly opaque. In some embodiments, a relative difference in refractive index between the domains 204 and the elongated member 202 is at least about ±1% with respect to a refractive index of the polymer or the blend of polymers included in the elongated member 202 (e.g., for visible light measured at 589 nm), such as at least about ±5%, at least about ±8%, at least about ±10%, at least about ±15%, at least about ±20%, at least about ±25%, at least about ±30%, at least about ±35%, at least about ±40%, at least about ±45%, or at least about ±50%. In some embodiments, an absolute difference in refractive index between the domains 204 and the elongated member 202 is at least about ±0.01 with respect to the refractive index of the polymer or the blend of polymers included in the elongated member 202 (e.g., for visible light measured at 589 nm), such as at least about ±0.05, at least about ±0.1, at least about ±0.15, at least about ±0.2, at least about ±0.25, at least about ±0.3, at least about ±0.35, at least about ±0.4, at least about ±0.45, at least about ±0.5, or at least about ±0.55. A refractive index of the domains 204 can be higher or lower than the refractive index of the polymer or the blend of polymers included in the elongated member 202.

[0046] In some embodiments, the refractive index contrast domains 204 are pores, which provide a contrast in refractive index due to, for example, the presence of air contained within the pores. The pores are sized to primarily scatter visible light instead of IR radiation. For example, the pores can be nano-sized (e.g., as nanopores) so as to be comparable to

wavelengths of visible light and below wavelengths of IR radiation, or below wavelengths of mid-IR radiation. In some embodiments, the pores have an average pore size in a range of about 50 nm to about 1000 nm, about 50 nm to about 900 nm, about 50 nm to about 800 nm, about 50 nm to about 700 nm, about 50 nm to about 600 nm, about 50 nm to about 500 nm, about 50 nm to about 400 nm, about 100 nm to about 400 nm, or about 500 nm and about 1000 nm, although larger pores having an average pore size up to about 2 μm or up to about 3 μm are also contemplated. In some embodiments, a distribution of pore sizes can be controlled to impart a desired coloration to the fiber 200 (and a resulting woven textile). For example, the pores can be relatively uniform in size, such as where a standard deviation of pore sizes is no greater than about 50%, no greater than about 45%, no greater than about 40%, no greater than about 35%, no greater than about 30%, no greater than about 25%, or no greater than about 20% of a mean pore size. A pore size can be determined using, for example, the Barret-Joyner-Halenda model. In some embodiments, a volume percentage of the pores within the elongated member 202 is at least about 10%, at least about 15%, at least about 20%, at least about 25%, at least about 30%, at least about 35%, or at least about 40%, and up to about 60%, up to about 70%, or more. In some embodiments, at least some of the pores can be interconnected to increase air permeability and increase conduction and convection heat dissipation through the interconnected pores. The pores can be regularly or irregularly shaped, and can have aspect ratios of about 3 or less, or greater than about 3.

[0047] In some embodiments, the refractive index contrast domains 204 are particulate fillers, which provide a contrast in refractive index due to a material of the fillers. Examples of suitable materials of the fillers include inorganic materials that have a low absorption of IR radiation, such as metalloids (e.g., silicon and germanium), metal oxides, metalloid oxides (e.g., silicon oxide), metal halides, and so forth. Polymers and other organic materials that have a low absorption of IR radiation and can provide a suitable contrast in refractive index also can be used for the fillers. In some embodiments, suitable materials for the fillers have a transmittance of IR radiation at a wavelength of 9.5 μm of at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, or at least about 80%, and up to about 90%, up to about 95%, up to about 98%, or more. In some embodiments, suitable materials for the fillers have a weighted average transmittance of IR radiation over a wavelength range of 7-14 μm of at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, or at least about 80%, and up to about 90%, up to about 95%, or more. The fillers are sized to primarily scatter visible light instead of IR radiation. For example, the fillers can be nano-sized (e.g., as nanoparticles) so as to be comparable to

wavelengths of visible light and below wavelengths of IR radiation, or below wavelengths of mid-IR radiation. In some embodiments, the fillers have an average particle size in a range of about 50 nm to about 1000 nm, about 50 nm to about 900 nm, about 50 nm to about 800 nm, about 50 nm to about 700 nm, about 50 nm to about 600 nm, about 50 nm to about 500 nm, about 50 nm to about 400 nm, about 100 nm to about 400 nm, or about 500 nm and about 1000 nm, although larger fillers having an average particle size up to about 2 μm or up to about 3 μm or up to about 5 μm are also contemplated. In some embodiments, a distribution of particle sizes can be controlled to impart a desired coloration to the fiber 200 (and a resulting woven textile). For example, the fillers can be relatively uniform in size, such as where a standard deviation of particle sizes is no greater than about 50%, no greater than about 45%, no greater than about 40%, no greater than about 35%, no greater than about 30%, no greater than about 25%, or no greater than about 20% of a mean particle size. In some embodiments, a volume percentage of the fillers within the elongated member 202 is at least about 10%, at least about 15%, at least about 20%, at least about 25%, at least about 30%, at least about 35%, or at least about 40%, and up to about 60%, up to about 70%, or more. The fillers can be regularly or irregularly shaped, and can have aspect ratios of about 3 or less, or greater than about 3.

[0048] In some embodiments, a lateral dimension (e.g., a diameter) of the fiber 200 is about 5 μm or greater, about 10 μm or greater, or about 20 μm or greater, and up to about 150 μm, up to about 200 μm, up to about 300 μm, or more. Larger dimensioned fibers can impart greater strength and greater ease of forming the fibers, such as during an extrusion process, while smaller dimensioned fibers can impart greater comfort to a human body. While Figure 2 illustrates the fiber 200 with a circular cross-sectional shape, fibers with a variety of other regular or irregular cross-sectional shapes are contemplated, such as multi-lobal, octagonal, oval, pentagonal, rectangular, square-shaped, trapezoidal, triangular, wedge-shaped, and so forth. A surface of the fiber 200 can be chemically or physically modified to impart additional properties, such as hydrophilicity, anti-microbial property, coloration, texturing, and so forth. For example, although not shown in Figure 2, a coating can be applied over the surface of the fiber 200 to impart hydrophilicity, such as a coating of polydopamine (PDA) as a hydrophilic agent.

[0049] Other embodiments of a polymer fiber are contemplated. In some embodiments, a polymer fiber includes multiple (e.g., two or more) elongated members that are joined or otherwise combined to form an unitary body of the fiber. At least one of the elongated members includes refractive index contrast domains dispersed therein, and the elongated

members can include the same polymer (or the same blend of polymers) or different polymers (or different blends of polymers). The elongated members can be arranged in a variety of configurations. For example, the elongated members can be arranged in a core-sheath configuration, an island-in-sea configuration, a matrix or checkerboard configuration, a segmented-pie configuration, a side-by-side configuration, a striped configuration, and so forth. Further embodiments of a polymer fiber can be realized so as to have a hollow structure, a block structure, a grafted structure, and so forth.

[0050] Figure 3 is a schematic showing a cross-sectional view of a polymer fiber 300 according to some embodiments of this disclosure. The fiber 300 includes multiple elongated members arranged in a core-sheath configuration, including a first elongated member 302 (shown shaded in Figure 3) forming a core of the fiber 300, and a second elongated member 304 (shown unshaded in Figure 3) forming a sheath of the fiber 300 and surrounding the core. The first elongated member 302 can include refractive index contrast domains dispersed therein, while the second elongated member 304 can be substantially devoid of refractive index contrast domains, or vice versa. It is also contemplated that refractive index contrast domains can be dispersed within both elongated members 302 and 304. The elongated members 302 and 304 can include the same polymer (or the same blend of polymers) or different polymers (or different blends of polymers). While Figure 3 illustrates the fiber 300 with a circular cross-sectional shape, other regular or irregular cross-sectional shapes are contemplated, such as multi-lobal, octagonal, oval, pentagonal, rectangular, square-shaped, trapezoidal, triangular, wedge-shaped, and so forth. A surface of the fiber 300 can be chemically or physically modified to impart additional properties, such as a coating to impart hydrophilicity, anti-microbial property, coloration, texturing, and so forth.

[0051] Figure 4 is a schematic showing a cross-sectional view of a polymer fiber 400 according to some embodiments of this disclosure. The fiber 400 includes multiple elongated members arranged in a core-sheath configuration, including a first elongated member 402 (shown shaded in Figure 4) forming a core of the fiber 400, a second elongated member 404 (shown dotted in Figure 4) forming an intermediate sheath of the fiber 400 and surrounding the core, and a third elongated member 406 (shown unshaded in Figure 4) forming an outer sheath of the fiber 400 and surrounding the intermediate sheath. At least one of the elongated members 402, 404, and 406 includes refractive index contrast domains dispersed therein, while at least another of the elongated members 402, 404, and 406 is substantially devoid of refractive index contrast domains. It is also contemplated that refractive index contrast domains can be dispersed within each of the elongated members 402, 404, and 406. The

elongated members 402, 404, and 406 can include the same polymer (or the same blend of polymers) or different polymers (or different blends of polymers). While Figure 4 illustrates the fiber 400 with a circular cross-sectional shape, other regular or irregular cross-sectional shapes are contemplated, such as multi-lobal, octagonal, oval, pentagonal, rectangular, square-shaped, trapezoidal, triangular, wedge-shaped, and so forth. A surface of the fiber 400 can be chemically or physically modified to impart additional properties, such as a coating to impart hydrophilicity, anti-microbial property, coloration, texturing, and so forth.

[0052] Figure 5 is a schematic showing a cross-sectional view of a polymer fiber 500 according to some embodiments of this disclosure. The fiber 500 includes multiple elongated members arranged in an island-in-sea configuration, including a first set of elongated members 502 (shown shaded in Figure 5) and a second elongated member 504 (shown unshaded in Figure 5). The first set of elongated members 502 are positioned within and surrounded by the second elongated member 504, thereby forming "islands" within a "sea" of the second elongated member 504. The first set of elongated members 502 can include refractive index contrast domains dispersed therein, while the second elongated member 504 can be substantially devoid of refractive index contrast domains, or vice versa. It is also contemplated that refractive index contrast domains can be dispersed within each of the elongated members 502 and 504. The elongated members 502 and 504 can include the same polymer (or the same blend of polymers) or different polymers (or different blends of polymers). In some embodiments, the elongated members 502 have an average cross-sectional dimension (e.g., a diameter) of up to about 0.5 μm, or up to about 1 μm, or up to about 2 μm, or up to about 3 μm, or up to about 5 μm, although larger elongated members having an average cross-sectional dimension up to about 10 μm are also contemplated. While Figure 5 illustrates the fiber 500 with a circular cross-sectional shape, other regular or irregular cross-sectional shapes are contemplated, such as multi-lobal, octagonal, oval, pentagonal, rectangular, square-shaped, trapezoidal, triangular, wedge-shaped, and so forth. A surface of the fiber 500 can be chemically or physically modified to impart additional properties, such as a coating to impart hydrophilicity, anti-microbial property, coloration, texturing, and so forth.

[0053] Formation of Polymer Fibers and Woven Textiles from Polymer Fibers

[0054] In some embodiments, a nanoporous polymer fiber is formed by a process of extrusion and solvent extraction. In particular, a polymer or a blend of polymers can be dissolved in a solvent, such as paraffin oil, to form a mixture. A volume percentage of the solvent in the mixture can be selected to obtain a desired volume percentage of pores within a

resulting fiber after solvent extraction, such as at least about 10%, at least about 15%, at least about 20%, at least about 25%, at least about 30%, at least about 35%, or at least about 40%, and up to about 60%, up to about 70%, or more. In place of, or in combination with, paraffin oil, other suitable liquid solvents or solids can be used, such as solid wax, mineral oil, and so forth. Also, one or more additives can be included in the mixture, such as water wicking agents, colorants, and so forth. The mixture can then be extruded through an extrusion device (e.g., a spinneret or a syringe) to form polymer fibers including the solvent dispersed in the fibers, and the solvent is extracted from the fibers, leaving nanopores in the polymer fibers. Extraction of the solvent can be performed by immersion in a chemical bath of an extraction agent, such as methylene chloride, although other manners of extraction are contemplated, such as evaporation.

[0055] In some embodiments, a polymer fiber including particulate fillers is formed by a process of extrusion. In particular, a polymer or a blend of polymers can be combined with particulate fillers to form a mixture. A volume percentage of the fillers in the mixture can be selected to obtain a desired volume percentage of the fillers within a resulting fiber, such as at least about 10%, at least about 15%, at least about 20%, at least about 25%, at least about 30%, at least about 35%, or at least about 40%, and up to about 60%, up to about 70%, or more. The polymer or the blend of polymers can be combined with the fillers in a molten state or a dissolved state. Also, one or more additives can be included in the mixture, such as water wicking agents, colorants, and so forth. The mixture can then be extruded through an extrusion device (e.g., a spinneret or a syringe) to form polymer fibers including the fillers dispersed in the fibers.

[0056] Once formed, polymers fibers of some embodiments are subjected to spinning, twisting, winding, or braiding to form a yarn. In general, a resulting yarn includes multiple (e.g., two or more) fibers that are twisted or otherwise combined, and the fibers can be the same or different. In some embodiments, at least one fiber in a yarn is a polymer fiber including refractive index contrast domains. For example, the yarn can include two or more twisted nanoporous polymer fibers, or two or more twisted polymers fibers including particulate fillers, or a nanoporous polymer fiber twisted with a polymer fiber including particulate fillers. As another example, the yarn can include a polymer fiber including refractive index contrast domains twisted with another fiber, such as another polymer fiber substantially devoid of refractive index contrast domains (e.g., a fiber formed of a thermoplastic polymer or a natural polymer), or a metallic fiber. An adhesive can be used during a process of forming a yarn to durably secure fibers together. A resulting yarn is used

to form a woven textile of some embodiments. In other embodiments, polymers fibers are directly used to form a woven textile, without undergoing a process of spinning, twisting, winding, or braiding to form a multi-fiber yarn.

[0057] A variety of processes can be used to form a woven textile from polymers fibers of some embodiments, either as individual fibers or as included in a multi-fiber yarn. Examples include weaving, knitting, felting, braiding, plaiting, and so forth. Depending on a process used, a variety of woven structures can be attained, including weaving patterns such as plain, basket, twill, satin, herringbone, and houndstooth, and knitting patterns such as Jersey, Rib, Purl, Interlock, Tricot, and Raschel. Polymer fibers of some embodiments can be subjected to weaving in combination with other fibers (e.g., other fibers formed of a thermoplastic polymer or a natural polymer) to form a woven textile.

[0058] A resulting IR-transparent woven textile of some embodiments can exhibit various benefits. In some embodiments, the textile has a transmittance of IR radiation at a wavelength of 9.5 μm of at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, or at least about 80%, and up to about 90%, up to about 95%, up to about 98%, or more. In some embodiments, the textile has a weighted average transmittance of IR radiation over a wavelength range of 7-14 μm of at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, or at least about 80%, and up to about 90%, up to about 95%, or more. In some embodiments, the textile has an opacity (expressed as a percentage as [100 – transmittance]) to visible light over a wavelength range of 400-700 nm of at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, or at least about 80%, and up to about 90%, up to about 95%, up to about 99%, or more. In some embodiments, the textile has a water vapor transmission rate of at least about 0.005 $g/cm^2 \cdot hr$, at least about 0.008 $g/cm^2 \cdot hr$, at least about 0.01 $g/cm^2 \cdot hr$, at least about 0.012 $g/cm^2 \cdot hr$, at least about 0.014 $g/cm^2 \cdot hr$, or least about 0.016 $g/cm^2 \cdot hr$, and up to about 0.02 $g/cm^2 \cdot hr$ or more. In some embodiments, the textile has an air permeability of at least about 10 $cm^3/sec \cdot cm^2 \cdot Pa$, at least about 20 $cm^3/sec \cdot cm^2 \cdot Pa$, at least about 30 $cm^3/sec \cdot cm^2 \cdot Pa$, at least about 40 $cm^3/sec \cdot cm^2 \cdot Pa$, at least about 50 $cm^3/sec \cdot cm^2 \cdot Pa$, or at least about 60 $cm^3/sec \cdot cm^2 \cdot Pa$, and up to about 80 $cm^3/sec \cdot cm^2 \cdot Pa$ or more. In some embodiments, the textile has a tensile strength of at least about 10 N, at least about 20 N, at least about 30 N, or at least about 40 N, and up to about 60 N or more.

[0059] An IR-transparent woven textile of some embodiments can be incorporated into a cloth, either as a single layer in a single-layered cloth, or among multiple (e.g., two or more) layers of a multi-layered cloth. In the case of a multi-layered cloth, an IR-transparent woven

textile can be laminated or otherwise combined with one or more additional layers, such as one or more layers of other textile materials (e.g., cotton or polyester). A resulting cloth can be used in a variety of articles of clothing, such as apparel and footwear, as well as other products, such as medical products.

Examples

[0060] The following examples describe specific aspects of some embodiments of this disclosure to illustrate and provide a description for those of ordinary skill in the art. The examples should not be construed as limiting this disclosure, as the examples merely provide specific methodology useful in understanding and practicing some embodiments of this disclosure.

Example 1

Formation of Nanoporous Polyethylene Fibers

[0061] Figure 6 is a process flow for forming nanoporous polyethylene (PE) fibers. PE is dissolved in paraffin oil under heating and agitation and then cooled to form a (solid) mixture of PE and paraffin oil. Referring to Figure 6, a weight-to-volume ratio of PE and paraffin oil is about 1 g to 3.5 mL, although other ratios can be used, such as from about 1 g to 0.5 mL to about 1 g to 10 mL or from about 1 g to 2 mL to about 1 g to 4.5 mL. The mixture of PE and paraffin oil is then extruded under heating to form PE fibers including paraffin oil dispersed in the fibers, and paraffin oil is extracted from the PE fibers by immersion in methylene chloride, leaving nanopores in the PE fibers and forming nanoporous PE fibers.

[0062] Figure 7 is a schematic diagram of an extrusion device for forming nanoporous PE fibers. A mixture of PE and paraffin oil is loaded inside a syringe, and the mixture is subjected to heating under control by a temperature controller through a heating tape and a thermocouple. A syringe pump compresses the mixture inside the syringe such that a PE fiber including paraffin oil is extruded from a tip of the syringe. The PE fiber is collected by a roller under control by a controller.

[0063] Figure 8 are scanning electron microscope (SEM) images of nanoporous PE fibers, at various levels of magnification. As shown in Figure 8, the fibers have interconnected nanopores. The nanopores can provide improved air and water vapor permeability, in addition to opacity towards visible light.

Example 2

Formation of Textiles from Nanoporous Polyethylene Fibers

[0064] Nanoporous PE fibers can be spun into yarns and then woven into textiles. Figure 9(a) is a process flow for forming a woven textile from nanoporous PE fibers. Figure 9(b) is an image of a resulting textile, and Figure 9(c) shows transmittance/reflectance of the textile over a range of wavelengths. At normal skin temperature of about 34 °C, the human body can emit about 7-14 μm mid-IR radiation with a peak at about 9.5 μm. Referring to Figure 9(c), the textile has a relatively high transmittance of IR radiation (including over 7-14 μm), and its relatively narrow absorption peaks are away from the peak of human body radiation.

Example 3

Formation of Textiles from Nanoporous Polyethylene Fibers – Improvement in Transmittance

[0065] Figure 10(a) is a process flow for forming a woven textile from nanoporous PE fibers. Instead of using a multi-fiber yarn, resulting nanoporous PE fibers, as a single-fiber yarn, are directly woven into a textile. Figure 10(b) is an image of a resulting textile, and Figure 10(c) shows transmittance/reflectance of the textile over a range of wavelengths. Referring to Figure 10(c), the textile has a higher transmittance of IR radiation (including over 7-14 μm) compared with a textile woven from a multi-fiber yarn, and its relatively narrow absorption peaks are away from the peak of human body radiation. No noticeable scattering of IR radiation is observed to result from gaps among fibers in the textile, and a thickness of the textile also can be reduced compared with the use of multi-fiber yarns.

Example 4

Formation of Nanoporous Fibers of Blends of Polymers – Improvement in Mechanical Strength

[0066] A combination of different polymers can be subjected to a similar process flow as shown in Figure 6 for forming nanoporous fibers of a blend of the polymers. In particular, a combination of PE and polypropylene (PP), at various weight percentages of PP relative to a total weight of the combination, are dissolved in paraffin oil under heating and agitation and then cooled to form a (solid) mixture of PE, PP, and paraffin oil. Weight percentages of PP

evaluated include 0% of PP, about 10% of PP, about 35% of PP, about 60% of PP, about 85% of PP, and 100% of PP. The mixture of PE, PP, and paraffin oil is then extruded under heating to form fibers including paraffin oil dispersed in the fibers, and paraffin oil is extracted from the fibers, forming nanoporous fibers of a blend of PE and PP. Figure 11 shows evaluation results of the mechanical strength of resulting fibers, in terms of their maximum elongation at break. As can be observed, maximum elongation at break varies depending on weight percentages of PP, with the inclusion of about 10% of PP (maximum elongation at break of about 110%) and about 35% of PP (maximum elongation at break of about 70%) yielding fibers with improved mechanical strength compared to 0% of PP (namely PE alone) and 100% of PP (namely PP alone).

Example 5

Formation of Textiles from Nanoporous Fibers of Blends of Polymers

[0067] Nanoporous fibers of a blend of PE and PP (including a weight percentage of PP of about 10%) are woven into a textile. Figure 12 shows transmittance/reflectance of the textile (about 10% of PP) on the left compared with transmittance/reflectance of a textile formed from a single-fiber yarn of nanoporous PE fibers (0% of PP) on the right. Both textiles have a high transmittance of IR radiation, with comparable weighted averaged transmittance over wavelengths of human body radiation (2 μm to 20 μm) of about 73.1% (blend of PE and PP) and about 74.7% (PE alone).

[0068] As used herein, the singular terms "a," "an," and "the" may include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to an object may include multiple objects unless the context clearly dictates otherwise.

[0069] As used herein, the terms "substantially," "substantial," and "about" are used to describe and account for small variations. When used in conjunction with an event or circumstance, the terms can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close approximation. For example, when used in conjunction with a numerical value, the terms can encompass a range of variation of less than or equal to ±10% of that numerical value, such as less than or equal to ±5%, less than or equal to ±4%, less than or equal to ±3%, less than or equal to ±2%, less than or equal to ±1%, less than or equal to ±0.5%, less than or equal to ±0.1%, or less than or equal to ±0.05%.

[0070] As used herein, the term "size" refers to a characteristic dimension of an object. Thus, for example, a size of an object that is spherical can refer to a diameter of the object. In the case of an object that is non-spherical, a size of the non-spherical object can refer to a diameter of a corresponding spherical object, where the corresponding spherical object exhibits or has a particular set of derivable or measurable properties that are substantially the same as those of the non-spherical object. When referring to a set of objects as having a particular size, it is contemplated that the objects can have a distribution of sizes around the particular size. Thus, as used herein, a size of a set of objects can refer to a typical size of a distribution of sizes, such as an average size, a median size, or a peak size.

[0071] Additionally, amounts, ratios, and other numerical values are sometimes presented herein in a range format. It is to be understood that such range format is used for convenience and brevity and should be understood flexibly to include numerical values explicitly specified as limits of a range, but also to include all individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly specified. For example, a range of about 1 to about 200 should be understood to include the explicitly recited limits of about 1 and about 200, but also to include individual values such as about 2, about 3, and about 4, and sub-ranges such as about 10 to about 50, about 20 to about 100, and so forth.

[0072] While this disclosure has been described with reference to the specific embodiments thereof, it should be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the true spirit and scope of this disclosure as defined by the appended claims. In addition, many modifications may be made to adapt a particular situation, material, composition of matter, method, operation or operations, to the objective, spirit and scope of this disclosure. All such modifications are intended to be within the scope of the claims appended hereto. In particular, while certain methods may have been described with reference to particular operations performed in a particular order, it will be understood that these operations may be combined, sub-divided, or re-ordered to form an equivalent method without departing from the teachings of this disclosure. Accordingly, unless specifically indicated herein, the order and grouping of the operations are not a limitation of this disclosure.

What is claimed is:

1. A fiber comprising:

an elongated member; and

refractive index contrast domains dispersed within the elongated member,

wherein the elongated member includes at least one polymer having a transmittance of infrared radiation at a wavelength of 9.5 μm of at least 40%.

2. The fiber of claim 1, wherein the elongated member includes at least one polyolefin.

3. The fiber of claim 1, wherein the elongated member includes at least one of polyethylene or polypropylene.

4. The fiber of claim 1, wherein:

the elongated member includes a blend of polyethylene and polypropylene, and a weight percentage of polypropylene relative to a combined weight of polyethylene and polypropylene is in a range of 1% to 50%; or

the elongated member includes a blend of polyethylene and polypropylene, and a weight percentage of polyethylene relative to a combined weight of polyethylene and polypropylene is in a range of 1% to 50%.

5. The fiber of claim 1, wherein the refractive index contrast domains are pores.

6. The fiber of claim 5, wherein the pores have an average pore size in a range of 50 nm to 1000 nm.

7. The fiber of claim 5, wherein a volume percentage of the pores within the elongated member is at least 10%.

8. The fiber of claim 1, wherein the refractive index contrast domains are particulate fillers.

9. The fiber of claim 8, wherein the fillers have an average particle size in a range of 50 nm to 1000 nm.

10. The fiber of claim 8, wherein a volume percentage of the fillers within the elongated member is at least 10%.

11. The fiber of claim 8, wherein the fillers include an inorganic material.

12. The fiber of claim 1, wherein a difference in refractive index between the refractive index contrast domains and the elongated member is at least ±1% with respect to a refractive index of the elongated member.

13. The fiber of claim 1, wherein the elongated member is a first elongated member, and further comprising a second elongated member combined with the first elongated member to form a body of the fiber.

14. The fiber of claim 13, wherein a cross-sectional dimension of at least one of the first elongated member or the second elongated member is up to about 5 μm.

15. A woven textile including the fiber of any one of claims 1-14.

16. The woven textile of claim 15, having a transmittance of infrared radiation at a wavelength of 9.5 μm of at least 40%.

17. The woven textile of claim 15, having an opacity to visible light over a wavelength range of 400-700 nm of at least 40%.

18. A cloth comprising:

at least one layer including a woven textile including the fiber of any one of claims 1-14.

19. A method of regulating a temperature of a human body, comprising:

placing a woven textile adjacent to the human body, wherein the woven textile includes the fiber of any one of claims 1-14.

20. A method of forming a porous polymer fiber, comprising:

forming a mixture of a solvent and at least one polymer;

extruding the mixture to form a polymer fiber including the solvent dispersed within the polymer fiber; and

extracting the solvent from the polymer fiber to form the porous polymer fiber.

21. The method of claim 20, wherein a volume percentage of the solvent in the mixture is at least 10%.

22. The method of claim 20, wherein the mixture includes at least one polyolefin.

23. The method of claim 20, wherein the mixture includes at least one of polyethylene or polypropylene.

24. The method of claim 20, wherein the mixture includes polyethylene and polypropylene.

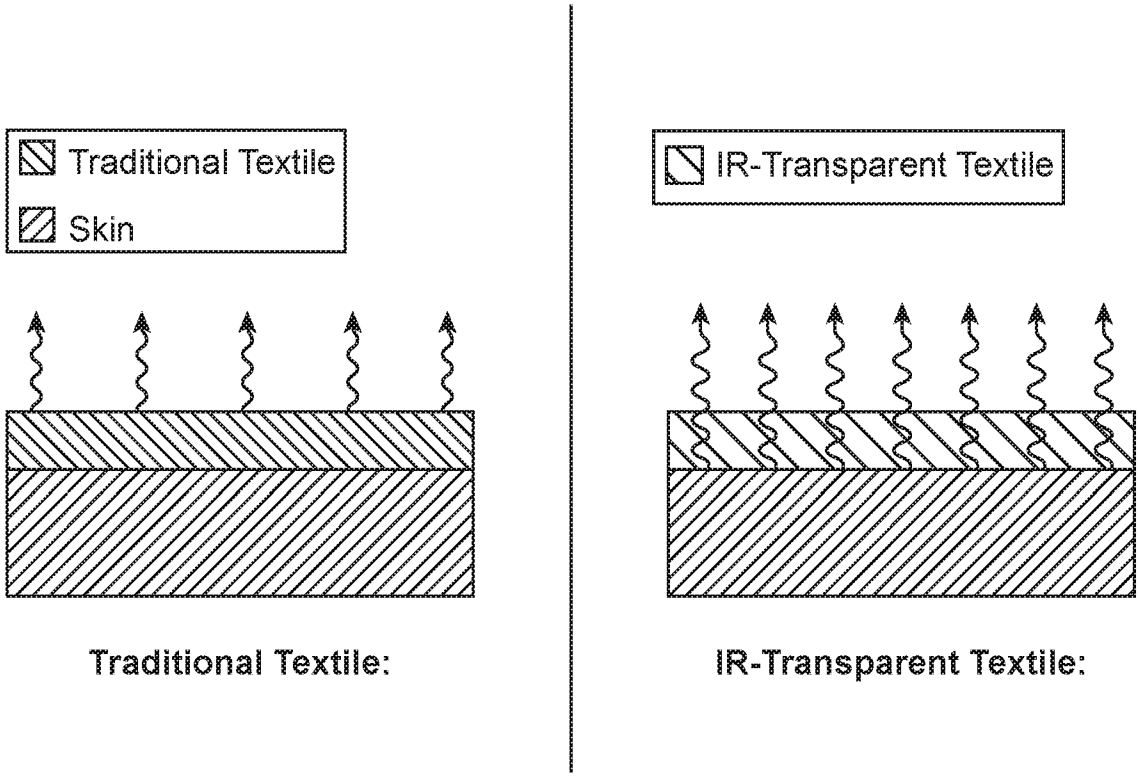

Traditional Textile
Skin
IR-Transparent Textile
Traditional Textile:
IR-Transparent Textile:

FIG. 1

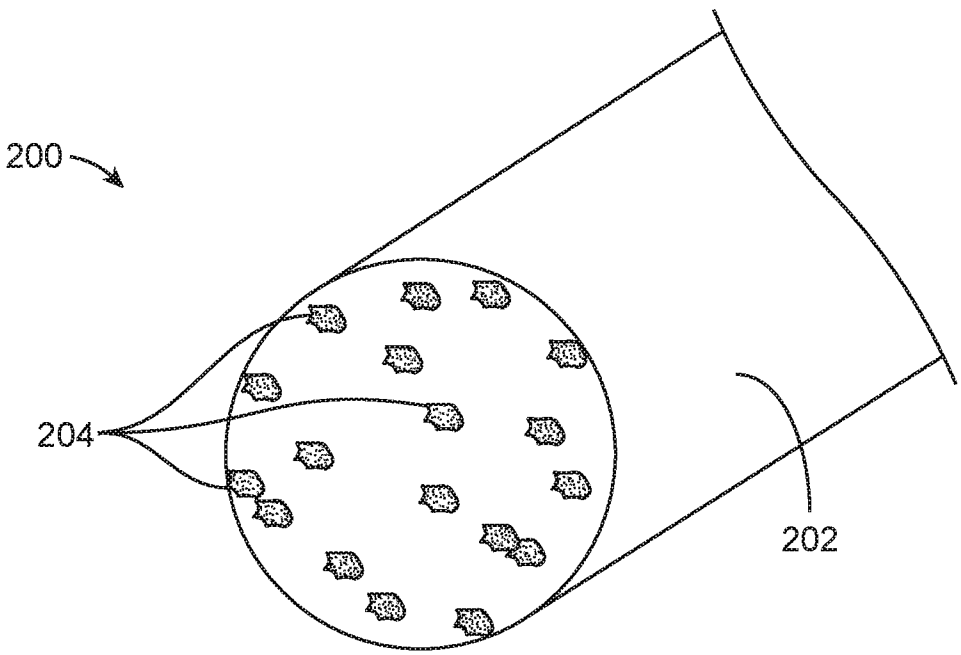

200
204
202

FIG. 2

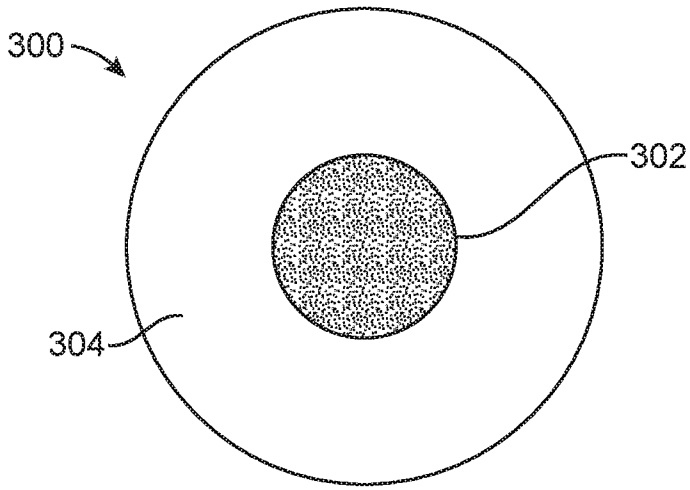


FIG. 3

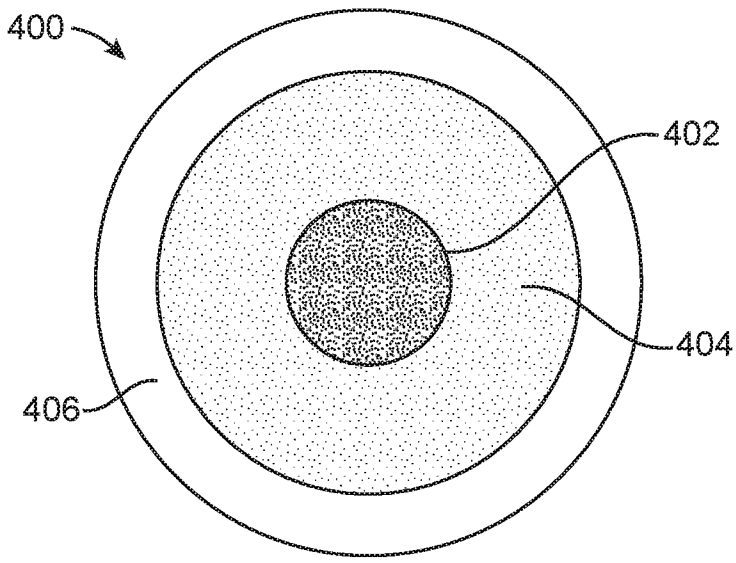


FIG. 4

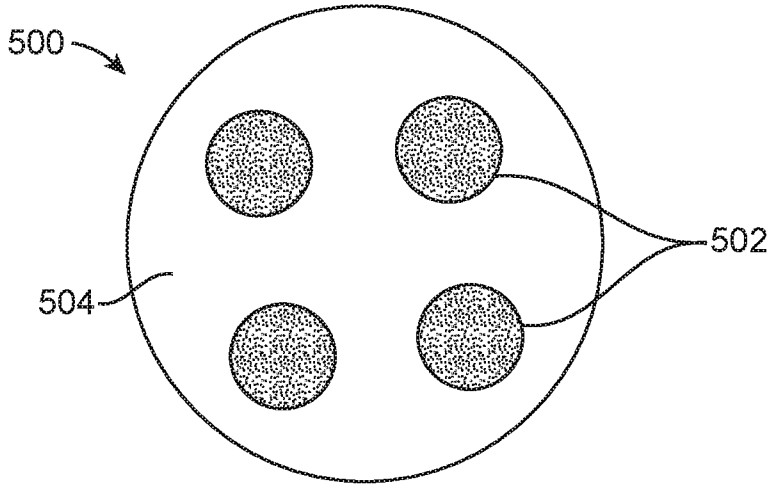

500
502
504

FIG. 5

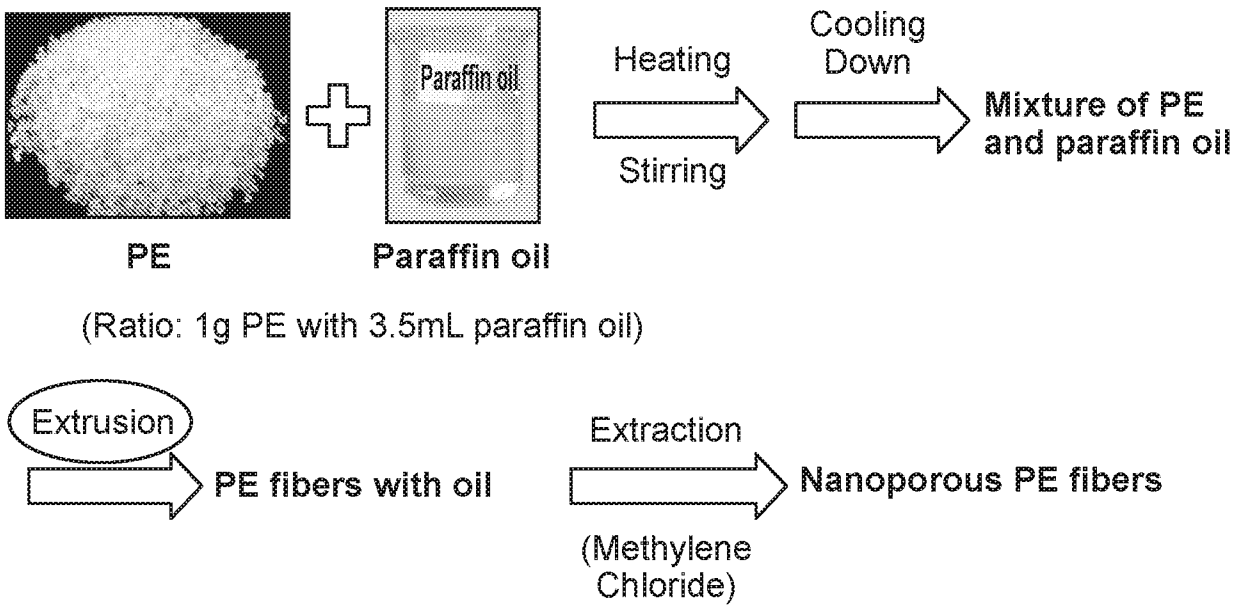

Paraffin oil
Heating
Stirring
Cooling
Down
Mixture of PE
and paraffin oil
PE
Paraffin oil
(Ratio: 1g PE with 3.5mL paraffin oil)
Extrusion
PE fibers with oil
Extraction
(Methylene
Chloride)
Nanoporous PE fibers

FIG. 6

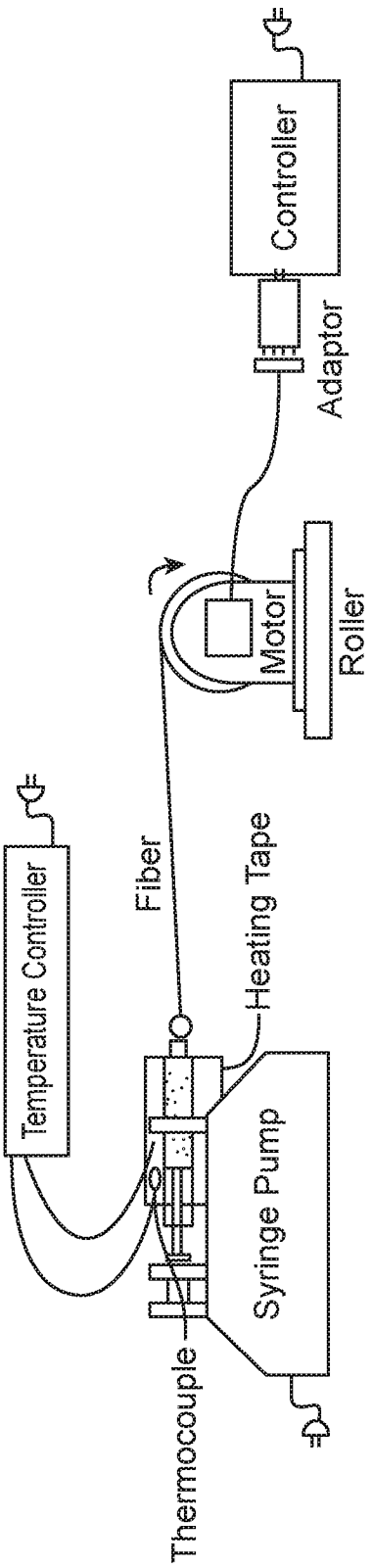

Temperature Controller
Fiber
Heating Tape
Syringe Pump
Thermocouple
Motor
Roller
Adaptor
Controller

FIG. 7

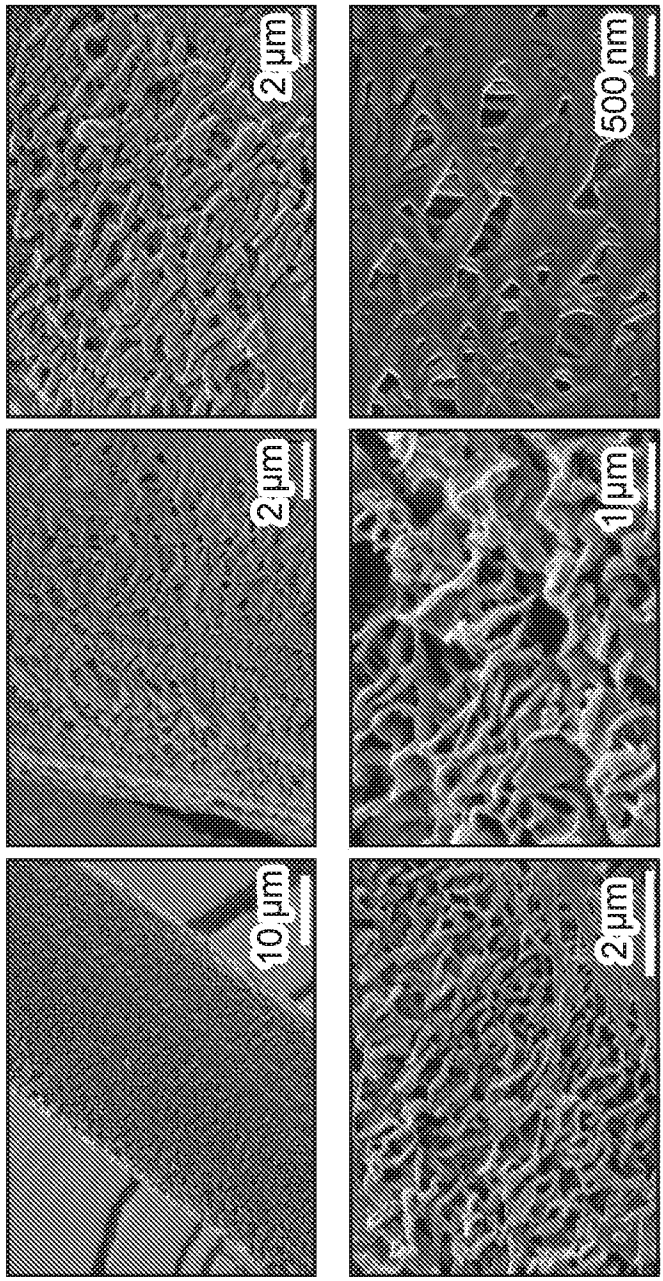

2 µm
2 µm
500 nm
10 µm
1 µm
2 µm

FIG. 8

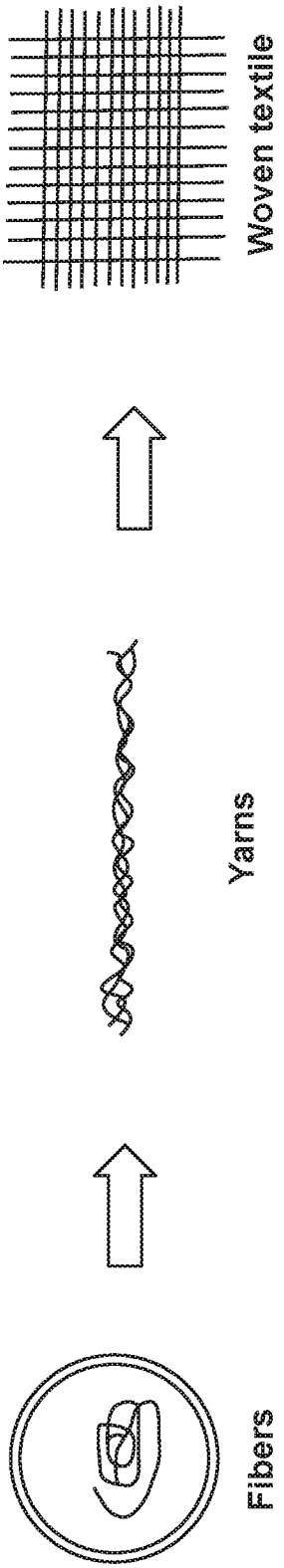


FIG. 9A

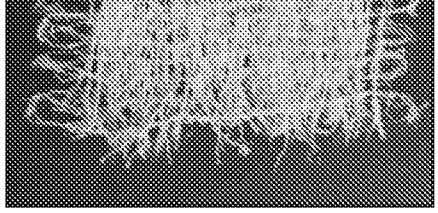


FIG. 9B

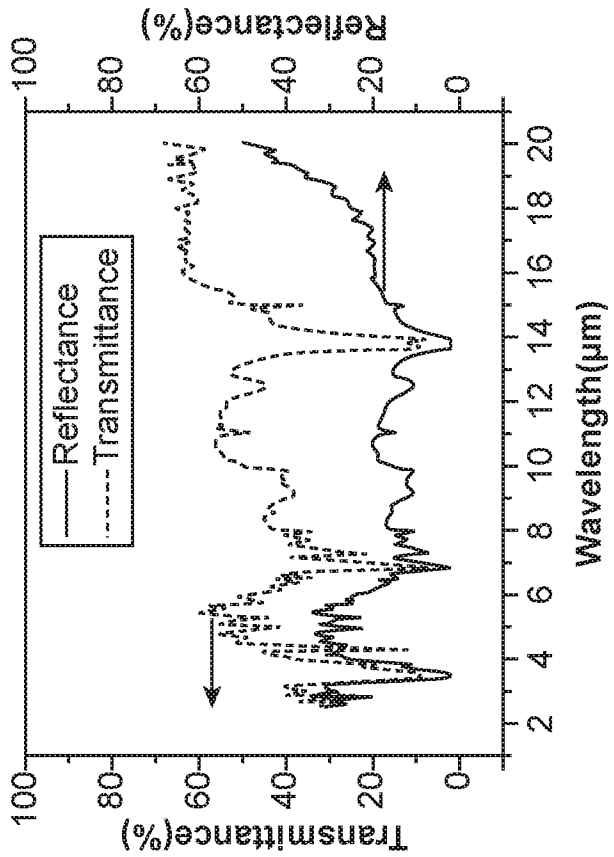


FIG. 9C

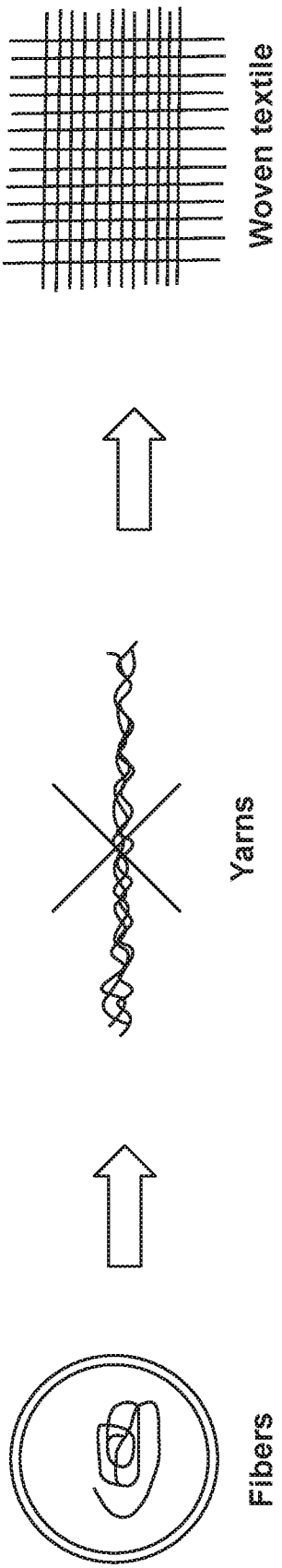


FIG. 10A

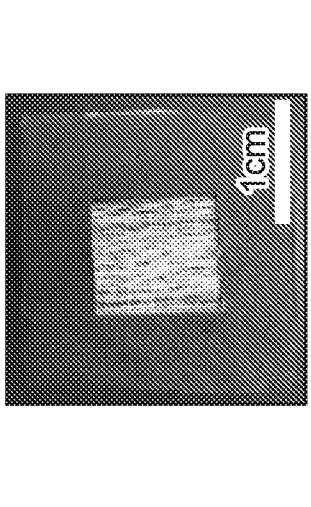


FIG. 10B

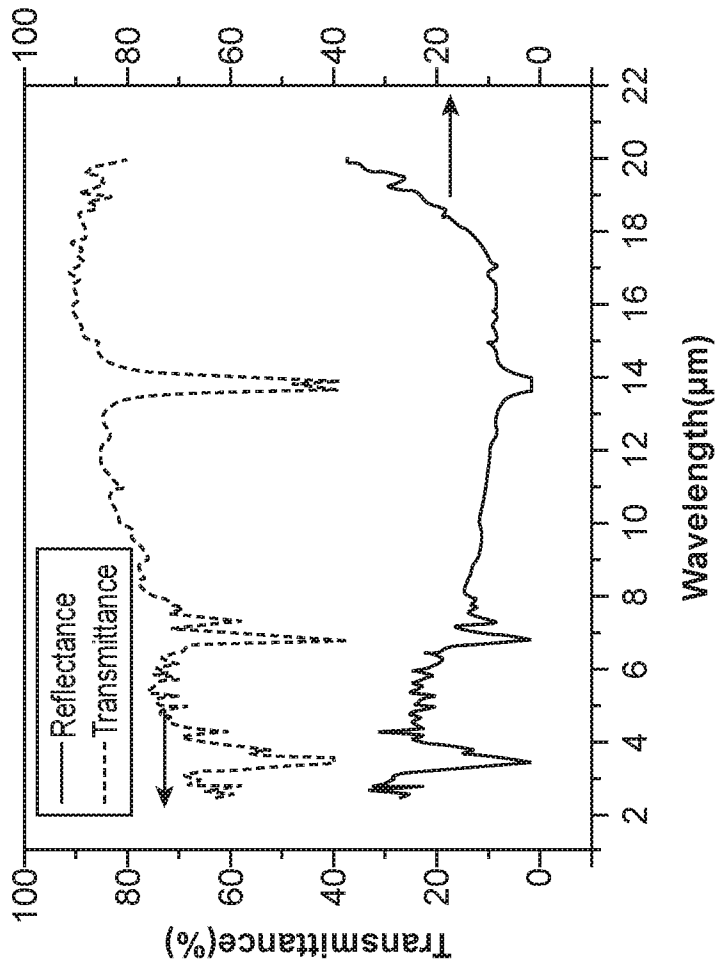


FIG. 10C

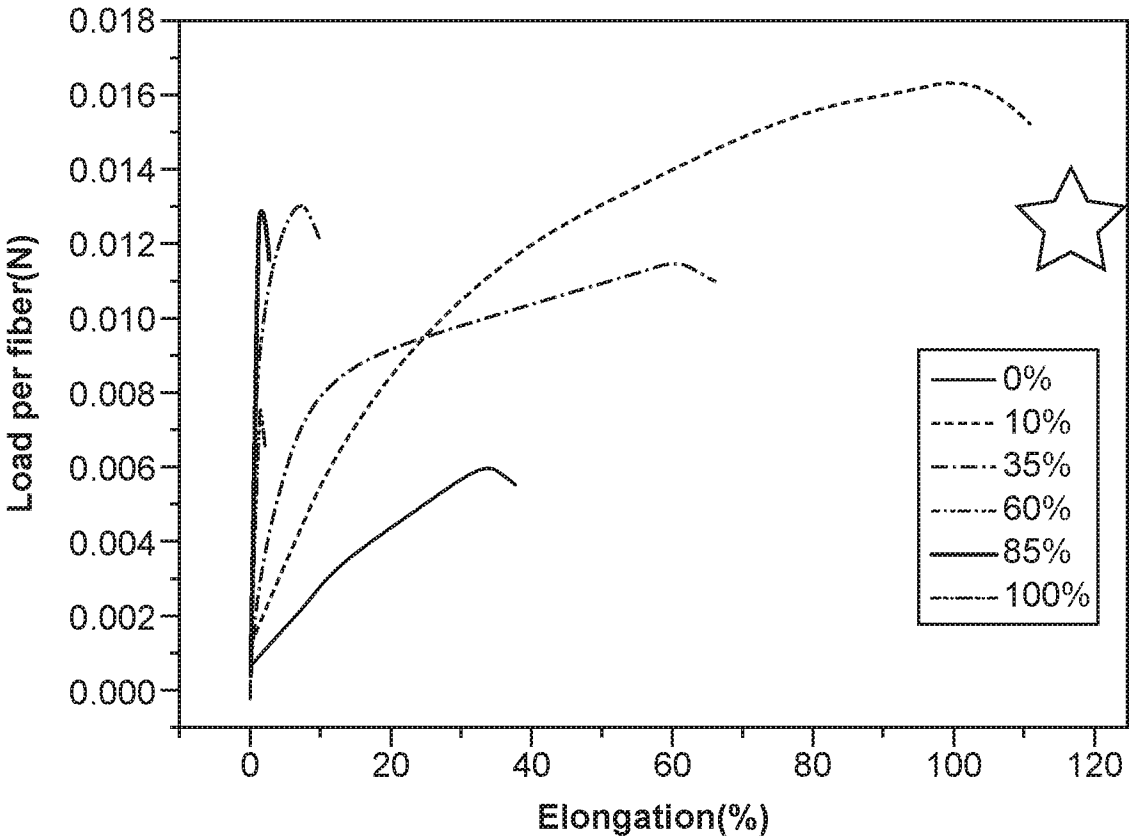
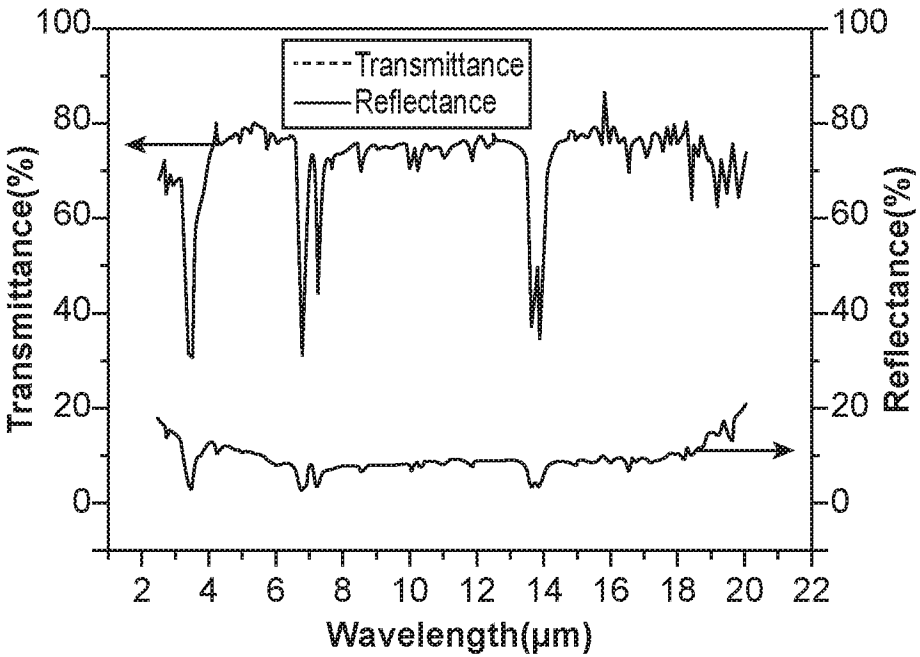
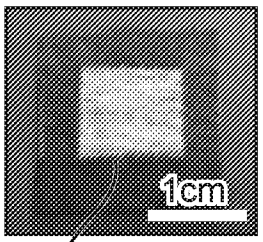

Load per fiber(N)
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
20
40
60
80
100
120
Elongation(%)
0%
10%
35%
60%
85%
100%

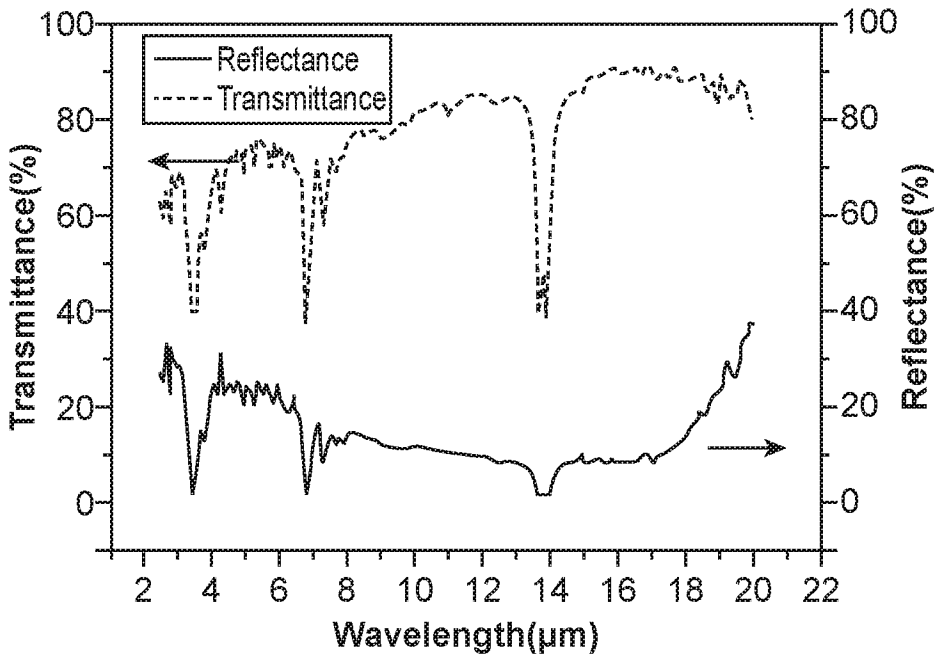
FIG. 11

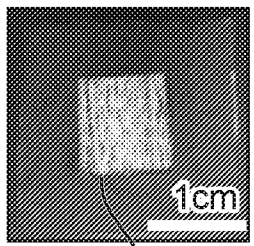




Weighted average transmittance based on human body radiation: **73.1%**

Nanoporous PP/ PE (10/90) blending fibers





Weighted average transmittance based on human body radiation: **74.7%**

Nanoporous PE fibers

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/053305

A. CLASSIFICATION OF SUBJECT MATTER

D02G 3/36(2006.01)i, D02G 3/02(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
D02G 3/36; C08K 3/30; B29C 67/20; A61L 15/22; C08L 23/00; B32B 27/08; D02G 3/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: infrared, transmittance, polyolefin, porous, filler, sheath-core, garment

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HSU, PO-CHUN et al. Radiative human body cooling by nanoporous polyethylene textile. Science, 02 September 2016, vol. 353, pp. 1019-1023 See abstract; page 1019, right column, lines 28-29; page 1020, left column, line 6 - middle column, line 1; page 1020, right column, line 11 - page 1021, line 2; page 1022, left column, lines 2-4; and figures 1-2.	1-7,15-19
Y		8-14
A		20-24
Y	US 2009-0156727 A1 (BENSASON, SELIM et al.) 18 June 2009 See paragraph [0015]; and claims 1, 7, 9.	8-14
X	US 5643511 A (PLUYTER, PIETER BOUDEWIJN et al.) 01 July 1997 See column 1, lines 20-22; claim 1; and example 2.	1-7,20-24
A	US 2014-0065092 A1 (CORDEIRO BASTOS, TARCIS et al.) 06 March 2014 See the entire document.	1-24
A	US 2006-0024520 A1 (KONG, DAN-CHENG et al.) 02 February 2006 See the entire document.	1-24

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 January 2018 (09.01.2018)	**10 January 2018 (10.01.2018)**

Name and mailing address of the ISA/KR
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2017/053305

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2009-0156727 A1	18/06/2009	AT 484614 T	15/10/2010
		AU 2005-311588 A1	08/06/2006
		BR PI0518081 A	28/10/2008
		BR PI0518081 B1	05/04/2016
		CA 2587334 A1	08/06/2006
		CN 101068960 A	07/11/2007
		CN 101068960 B	11/05/2011
		EP 1825035 A1	29/08/2007
		EP 1825035 B1	13/10/2010
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