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(54) Title: COMPRESSED NANOFIBER COMPOSITE MEDIA

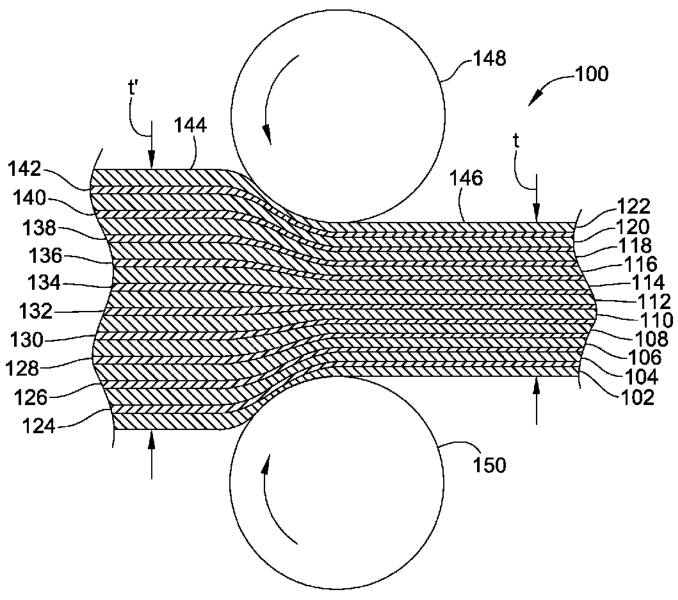

FIG. 2

(57) Abstract: A coalescing media includes a compressed composite filter media comprising substrate layers and hydrophilic fine fiber layers for separating free water emulsified in fuels.

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COMPRESSED NANOFIBER COMPOSITE MEDIA

FIELD OF THE INVENTION

[0001] This invention generally relates to a filter media, and in particular to a compressed composite media comprising a substrate and fine fibers, and method of making the same.

BACKGROUND OF THE INVENTION

[0002] Hydrocarbon fuels, such as diesel fuel, jet fuel, and gasoline, can entrain small amount of water. The water may be introduced in the hydrocarbon fuels, for example, by leakage, accidental contamination, or atmospheric condensation. The hydrocarbon fuels can dissolve about 75 to 150 parts per million (ppm) of water at room temperature. Water solubility can increase about 1 ppm per 1° F rise in temperature, and decrease about 1 ppm per 1° F fall in temperature. Excess water or undissolved water may accumulate in lower parts of a fuel handling system as a result of temperature changes over a period of time.

[0003] Undissolved water can be harmful to engines. Diesel engine injectors may be damaged by steam formation, jet turbine engines may flame-out, and gasoline engines may suffer ignition problems. Many water separation devices and filters have been developed to remove undissolved or free water from the fuel and prevent such engine problems. Simple mechanical devices base on gravity or centrifugal force separation are sufficient if free water is present as a discrete second phase. However, free water is often emulsified by pumps and valves, may remain as a stable emulsion, especially in diesel or jet fuel. Two stage coalescer/separators are designed to remove water emulsions. The coalescer breaks the emulsion by preferential wetting of fibrous materials such as fiber glass. The water is accumulated into large droplets and is removed by gravity separation against a hydrophobic separator material such as PTFE coated wire cloth or silicone impregnated paper. The presence of wetting agents or surfactants may interfere with the coalescence of water emulsions, especially in diesel fuel or jet fuel. A coalescer including hydrophobic fluoropolymer fine fibers to capture and remove water from fuel emulsions is disclosed in

Fluoropolymer Fine Fiber, U.S. Patent Application Publication No. 2009/0032475, to Ferrer et al.

[0004] Filter media including fine fibers formed using an electrostatic spinning process is also known. Such prior art includes Filter Material Construction and Method, U.S. Patent No. 5,672,399; Cellulosic/Polyamide Composite, U.S. Patent Publication No. 2007/0163217; Filtration Medias, Fine Fibers Under 100 Nanometers, And Methods, U.S. Provisional Patent Application No. 60/989,218; Integrated Nanofiber Filter Media, U.S. Provision Patent Application No. 61/047,459; Filter Media Having Bi-Component Nanofiber Layer, U.S. Provisional Patent No. 61,047,455, the entire disclosures of which are incorporated herein by reference thereto. As shown in these references nanofibers are commonly laid upon a finished preformed filtration media substrate.

[0005] The invention provides improved coalescing medias and method of making the coalescing media. These and other advantages of the invention, as well as additional inventive features, will be apparent from the description of the invention provided herein.

BRIEF SUMMARY OF THE INVENTION

[0006] A compressed nanofiber composite filter media according to various embodiments of the present invention includes at least one substrate and fine fibers carried thereby. Preferably, the compressed filter media includes multiple substrate layers, each of which carrying fine fibers. The multiple substrate and fine fiber layers are compressed together to form the compressed composite filter media. The compressed filter media according to various embodiments of the present invention is particularly well suited for a coalescing media to coalesce water in various hydrocarbon fuels. However, the compressed filter media can also be used in other filtration applications. For example, the compressed filter media can make a very efficient water filter element.

[0007] Preferably, the substrate layers employed are relative open materials with coarse fibers to provide support while at the same time not being overly restrictive to fluid flow especially as layers are stacked and/or compressed. This structure spaces nano-fibers apart and affords the ability to provide for a much heavier total coverage of nano-fibers per square unit of area while at the same time not being overly restrictive. Further, a relatively thin substrate may be used (and compression used), such that the fine fibers throughout the media is spaced relatively close and close enough to facilitate coalescing; and thickness of the media as a whole is suitable for coalescing filtration applications and filter element arrangement. Many embodiments also employ hydrophilic fine fibers that attract as opposed to repelling water. By using multiple layers of fine fibers at sufficient coverage, water molecules or fine droplets grow within this structure and are effectively coalesced out of a fluid stream.

[0008] The multiple substrate layers and the fine fibers may and preferably are compressed together to form a coalescing filter media. As such, the coalescing filter media is compacted and high in solidity and includes a sufficient fine fiber coverage to provide a sufficient fiber surface area to coalesce emulsified water in a hydrocarbon fuel stream. The fine fibers are preferably electrospun nanofibers formed of a hydrophilic material, such as polyamide-6. The hydrophilic fine fibers further facilitate formation and growth of water droplets.

[0009] In one embodiment and inventive aspect of the present invention, a method of forming a coalescing filter media is provided. The method comprises steps of electrostatically spinning fine fibers having an average diameter of less than 1 micron, applying the fine fibers to a substrate comprising coarse fibers having an average diameter greater than 1 micron, and compacting the fine fibers and the coarse fibers together. The method further includes steps of generating sufficient fine fiber coverage and tightness through the compacting process to coalesce water droplets from a fluid stream, and structuring the coarse fibers and the fine fibers into a coalescing filter media that is operable to remove water from a fluid stream.

[0010] In some embodiments, the substrate comprise a fiber entanglement that is bonded together, wherein the fine fibers are deposited onto the substrate during the step of applying the fine fibers. The substrate can be a scrim formed of bi-component fibers comprising a high melt component and a low melt component, wherein the fine fibers are deposited on a surface of the scrim and carried by the scrim.

[0011] The step of compacting can involve laminating multiple layers of the scrim carrying the fine fibers, and compressing the multiple layers of the scrim and the fine fibers using a set of calendering rollers. The multiple layers of the scrim and the fine fibers can be heated to or near a melting temperature of the low melt component, wherein the low melt component melts or softens to act as a bonding agent to bond layers together.

[0012] In some embodiments, the multiple layers are heated before being compressed. For example, the multiple layers can be heated in an oven and compressed subsequently via a set of calendering rollers. In such embodiments, a thickness of the laminated multiple layers may increase as the scrims expand and loft during heating. The subsequent compression of the lofted multiple layers reduces the lofted thickness, however, the final thickness of the compressed multiple layers may be less, equal, or greater than the original thickness of the laminated multiple layers before heating. In other embodiments, the multiple layers are heated and compressed simultaneously. For example, the multiple layers can be heated and compressed using a set of heated calendering rollers. Yet in other embodiments, the multiple layers can be compressed first then heated, wherein the thickness of the compressed multiple layers may increase during heating. Further, some embodiments can including more than one heating steps. For example, the multiple layers can be heated before compressing, and further heated during compressing via the set of heated calendering rollers.

[0013] In an embodiment, 10 layers of the scrim, each of which carrying fine fibers, are laminated and compressed together. Each scrim layer carries the fine fibers having a relatively heavy fine fiber coverage between about 0.075 g/m^2 and .225 g/m^2. When assembled to a stacked configuration with overlapping fine fiber coverage, a total fine fiber coverage of the coalescing filter media can be between about 0.75 g/m^2 and 2.25 g/m^2. The layers of the scrim and the fine fibers are compressed together to form a coalescing filter media having a thickness to between about 3/16" and ½".

[0014] In some embodiments, the scrim carrying the fine fibers is folded into multiple folds and compressed to form a coalescing filter media. In such embodiments, the coalescing filter media can include a fine fiber to fine fiber laminated surface and a scrim to scrim laminated surface.

[0015] Yet in another embodiment, the substrate is a web of coarse fibers comprising a loose entanglement of the coarse fibers, wherein the fine fibers are applied to the loose entanglement of the coarse fibers during the step of applying the fine fibers. The web of coarse fibers applied with the fine fibers can be folded into multiple folds and compressed together, wherein the fine fibers and the coarse fibers are integrated to form a single integrated coalescing media.

[0016] A method of forming a coalescing filter media according to a different embodiment includes steps of electrostatically spinning a web of fine fibers having an average diameter of less than 1 micron, applying the fine fibers to a substrate formed of coarse fibers having an average fiber diameter greater than 1 micron that are bonded together, and lapping the combination of the fine fiber applied substrate such that the fine fibers overlap. The method can further include a step of unwinding a roll of substrate from an unwind station and transferring the substrate to an electrospinning station, wherein the substrate is kept afloat via a line tension. In such embodiment, the substrate can be a scrim comprising bi-component fibers. The bi-component fibers can include a high melt polyester core and a low melt polyester sheath.

[0017] The step of applying the fine fibers can provide a fine fiber coverage between about 0.03 g/m^2 and 0.25 g/m^2, preferably between about 0.075 g/m^2 and .225 g/m^2, wherein the fine fibers are carried by the scrim. Further, the step of lapping can involve folding the scrim carrying the fine fibers into 2-20 folds, wherein the folding provides a fine fiber to fine fiber laminated surface and a scrim to scrim laminated surface, wherein the folded layers are heated and compressed to form a coalescing media. In such heating and compressing process, a thickness of the folded layers can be adjusted from the original thickness (thickness of each layer x number of layers) by about 50% to 300%, preferably about 70% to 200%, and more preferably about 80% to 150%. (The thickness can increase after heating than reduced during compressing. In some cases, the increase in thickness during heating can be so great that the final thickness may be still greater than the original thickness even after compressing.) Two or more folded or unfolded scrims may also be employed in a stacked combination to achieve heavy fine fiber coverage per area.

[0018] In one embodiment, the coalescing media is formed to have a total fine fiber coverage between about 0.09 g/m^2 and 5.25 g/m^2, preferably between about 0.75 g/m^2 and 2.25 g/m^2. Further, the step of electrostatically spinning fine fibers preferably involves spinning fine fibers from a solution including a polyamide-6.

[0019] In another embodiment of the present invention, a coalescing filter media is provided. The coalescing filter media includes at least one substrate containing coarse fibers having an average fiber diameter of greater than 1 micron, and fine fibers carried by the substrate. The fine fibers are hydrophilic fibers having an average fiber diameter of less than 1 micron and provide a sufficient fiber surface area to coalesce emulsified water in a hydrocarbon fuel. In such embodiment, the hydrophilic fibers facilitate formation and growth of water droplets. The coalescing filter media can further include a drainage layer arranged on a downstream surface of the coalescing filter media. Such drainage layer can facilitate growth of the water droplet size. In one embodiment, the drainage layer is formed of a cellulous material or a fiber glass material.

[0020] The fine fibers are preferably electrospun nanofibers formed of a hydrophilic polymer, such as polyamide-6. In one embodiment, the coalescing filter media includes the fine fibers having a total fine fiber coverage between about 0.09 g/m^2 and 5.25 g/m^2, preferably between about 0.75 g/m^2 and 2.25 g/m^2.

[0021] The substrate is preferably a scrim comprising bi-component fibers, which includes a high melt component and a low melt component. For example, the bi-component fibers can include a high melt polyester core and a low melt polyester sheath. In such embodiments, the substrate layers and the fine fibers are heated and compressed together to form a coalescing media, wherein the low melt polyester sheath melts or softens to bond the coarse fibers and the fine fibers.

[0022] The coalescing filter media can include multiple layers of substrate, wherein each of the multiple substrate layers carry a layer of fine fibers having a fine fiber coverage between about 0.075 g/m^2 and .225 g/m^2. In one embodiment, each of the fine fiber layer is sandwiched between the substrate layers and or a media layer. In other embodiment, the coalescing filter media can include a fine fiber to fine fiber laminated surface and a substrate to substrate laminated surface.

[0023] In one embodiment, the coalescing filter media includes 10 layers of substrate. Each of the substrate layer is formed of a scrim comprising bi-component fibers and carries fine fibers. The fine fibers on each substrate layer is formed of electrospun polyamide-6 nanofibers. The fine fibers carried by the 10 substrate layers provide a total fine fiber coverage between about 0.75 g/m^2 and 2.25 g/m^2. The coalescing filter media can further including a drainage layer arranged on a downstream surface of the coalescing filter media formed of a fiber glass mat. In such embodiment, the coalescing filter media can have a total thickness between about 3/16" and ½".

[0024] In another embodiment of the present invention, a coalescing filter media including at least one substrate containing coarser fibers having an average fiber diameter of greater than 1 micron and fine fibers carried by the substrate is provided. The fine fibers have an average fiber diameter of less than 1 micron, and at least some of the fine fibers are embedded at least partially within the coarse fibers in a compressed state. In many of the embodiments, at least some of the fine fibers can form a three dimensional matrix of fine fibers extending into the substrate as opposed to a planar layer. Further, at least some of the fine fibers can be generally sandwiched between layers of the substrate.

[0025] In one embodiment, the fine fibers have a melting point higher than a melting point of at least one component of the coarse fibers, and the fine fibers are permanently affixed and oriented. Further, the at least one substrate and the fine fibers are calendered together to form the compressed state.

[0026] Other aspects, objectives and advantages of the invention will become more apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] The accompanying drawings incorporated in and forming a part of the specification illustrate several aspects of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

[0028] FIG. 1 is a schematic cross-sectional view (e.g. relative illustrated thickness not to scale) of a filter media including tightly compacted multiple scrim layers carrying fine fibers according to an embodiment of the present invention;

[0029] FIG. 2 is a schematic cross-sectional view of the coalescing filter media of FIG. 1 in a pre-compressed state, which is compressed to a compressed state;

[0030] FIG. 3 is a schematic illustration of a concentric sheath/core type bi-component fiber of a substrate according to an embodiment of the present invention;

[0031] FIG. 4 is a schematic illustration of an eccentric sheath/core type bi-component fiber of a substrate according to an embodiment of the present invention;

[0032] FIG. 5 is a schematic illustration of a side-by-side type bi-component fiber of a substrate according to an embodiment of the present invention;

[0033] FIG. 6 is a schematic illustration of a pie wedge type bi-component fiber of a substrate according to an embodiment of the present invention;

[0034] FIG. 7 is a schematic illustration of a hollow pie wedge type bi-component fiber of a substrate according to an embodiment of the present invention;

[0035] FIG. 8 is a schematic illustration of an islands/sea type bi-component fiber of a substrate according to an embodiment of the present invention;

[0036] FIG. 9 is a schematic illustration of a trilobal type bi-component fiber of a substrate according to an embodiment of the present invention;

[0037] FIG. 10 is a schematic illustration of tipped typed bi-component fiber of a substrate according to an embodiment of the present invention;

[0038] FIG. 11 is a schematic cross-sectional view of a coalescing filter media including tightly compressed multiple scrim layers and fine fibers and a downstream porous layer according to an embodiment of the present invention;

[0039] FIG. 12 is a schematic illustration of a system for making a coalescing filter media according to an embodiment of the present invention;

[0040] FIG. 13 is a schematic illustration of a system for making a coalescing filter media according to a different embodiment of the present invention;

[0041] FIG. 14 is a schematic illustration of a system for making a coalescing filter media according to yet another embodiment of the present invention;

[0042] FIG. 15(A) is a Scanning Electron Microscopic image showing bi-component fibers and the fine fibers of a composite media produced using the system of FIG. 12 taken at a magnification level x300;

[0043] FIG. 15(B) is a Scanning Electron Microscopic image showing bi-component fibers and the fine fibers of a composite media produced using the system of FIG. 12 taken at a magnification level x1,000;

[0044] FIG. 15(C) is a Scanning Electron Microscopic image showing bonding between bi-component fibers and the fine fibers of a composite media produced using the system of FIG. 12 taken at a magnification level x2,000;

[0045] FIG. 15(D) is a Scanning Electron Microscopic image showing bonding between bi-component fibers and the fine fibers of a composite media produced using the system of FIG. 12 at a magnification level x10,000; and

[0046] FIG. 16 is a schematic cross-sectional view (e.g. relative illustrated thickness not to scale) of a coalescing filter element including an expanded nanofiber composite media and a compressed nanofiber composite coalescing media according to an embodiment of the present invention.

[0047] While the invention will be described in connection with certain preferred embodiments, there is no intent to limit it to those embodiments. On the contrary, the intent is to cover all alternatives, modifications and equivalents as included within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

[0048] Prior to turning to the details, some lexicography will be developed to assist in understanding the present invention. As used herein, the term "substrate" is meant to be broad in nature and meant to include any structure upon which fine fibers are carried or deposited. "Substrate" may include conventional formed filter medias such as scrims and the like that may be unwound from media rolls. Such filter medias have a fiber entanglement that typically bonded or secured together mechanically, chemically, adhesively and/or otherwise and thereby have strength such that they cannot be easily torn manually (e.g. a 1 square foot sheet typically holds up to application of tension of 5 lbs force) and have filtrations properties. "Substrate" may also include looser fiber entanglements that may not be bonded together or secured together (e.g. a 1 square foot sheet may fall apart upon application of tension of 5 lbs force). A "scrim" used as herein refers to woven or non-woven fiber entanglement, wherein the fibers are bonded and compressed into a planar formed media.

[0049] FIG. 1 is a schematic cross-sectional view of a filter media 100 according to an embodiment of the present invention. It is schematic in the sense that in reality the fine fiber layer has virtually no thickness, but for illustration and understanding, thickness is illustrated in FIG. 1 and other schematic illustrations. The filter media 100 is configured to coalesce water in hydrocarbon fuels, such as diesel fuel, jet fuel, and gasoline. The filter media 100 can also capture solids in a hydrocarbon fuel stream. The filter media 100 is also referred to as a coalescer, a coalescing media, a coalescing filter media, or other similar terms in the present application. In preferred embodiments, the filter media 100 includes at least two different fibers, for example, electrospun nanofibers and a substrate of coarser fibers carrying the nanofibers. As such, the filter media 100 is also referred to as a composite filter media, a composite media, or other like terms in this application. Although, the filter media 100 is particularly well suited for coalescing applications, the filter media 100 may be used in other filtration applications.

[0050] In the embodiment shown in FIG. 1, the filter media 100 comprises 10 layers of substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120, each of which carrying fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142, and a media 122 on top of the fine fibers 142. The substrate, 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 and the media 122 are formed of fibers having an average fiber diameter typically larger than that of the fine fibers. The substrate layers 102, 104, 106, 108, 110, 112, 114, 116, 118, 120, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142, and the media 122 are laminated and tightly compressed together to increase fiber surface area per volume to provide a sufficient fiber surface area for water emulsified in a hydrocarbon fuel, such as a diesel fuel, to coalesce. Further, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 are formed of a hydrophilic material, for example nylon-6, to attract water and to enhance formation and growth of water droplets, facilitating separation of water from a hydrocarbon fuel stream. Although this embodiment is shown with the media layer 122, this media layer is optional, and thus, the filter media 100 according to other embodiments may not include this media layer 122.

[0051] The filter media of FIG. 1 may be formed using the process shown in FIG. 2. FIG. 2 illustrates the filter media 100 in a pre-compressed state 144 and a compressed state 146. As shown, the filter media 100 in the pre-compressed state 144 has an initial thickness t' (also referred herein as an original thickness.) The filter media 100 in the pre-compressed state 144 is compressed into the compressed state 146 using a set of calendering rollers 148 (or progressive sets of rolls), 150, wherein the initial thickness t' is reduced to a final thickness t.

[0052] In some embodiments, the filter media 100 in the pre-compressed state 144 is heated before compressing. In certain preferred embodiments, fibers of the substrate relax and reorient to increase an average distance between the fibers during heating (such as a scrim that has been at least partially compressed during the scrim production process.) As such, the substrate layers expand and loft, wherein the thickness of each of the substrate layer increases. Further, as the fibers proximate the surface of the substrate relax and reorient, the fine fibers which are carried by these fibers move and reorient with the fibers. Thus, fine fibers are extended, pushed and pulled with the larger fibers. In such embodiments, the initial thickness t' of the pre-compressed state 144 can increase by at least 1.5 times, 2 times, 3 times or even more via heating. In such embodiments, the final thickness t of the filter media 100 after subsequent compression of the lofted filter media 100 can be either less than, or equal to, or greater than the initial thickness t', depending on the amount of expansion during heating and the amount of reduction during compression. In other embodiments, the filter media 100 in the pre-compressed state 144 can be heated and compressed simultaneously via a set of heated calendering rollers. In such embodiments, there may not be any expansion or a very slight increase in the initial thickness t' prior to the thickness reduction to the final thickness t. In yet different embodiments, the compressed filter media 100 having the final thickness t can be heated post compression, wherein the thickness t' may be increased. In some embodiments, the filter media 100 can be heated more than once. For example, the filter media 100 can be heated before compression, then heated again during compression.

[0053] In one embodiment, the final thickness t can be between about 50% and 300% of the initial thickness t', preferably between about 70% and 200% of the initial thickness t', and more preferably between 80% and 150% of the initial thickness t'. As the filter media 100 in the pre-compressed state 144 is pressed down to the final compressed state 146, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 become more integrated with the coarse fibers of the adjacent substrate layers 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 and form 3 dimensional fine fiber matrix within the filter media 100. The filter media 100 in the compressed state 146 has characteristics sufficient for a coalescing media. Although, the filter media 100 in this embodiment includes 10 layers of substrate carrying fine fibers, other embodiments can include more or less substrate layers carrying fine fibers.

[0054] The substrate layers 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 can be formed of any suitable porous material. Each of the substrate layer can be formed of a same type of porous material or different types of porous material. In one embodiment, each layer of the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 comprises a formed filter media. The formed filter media comprises fibers that are bonded together. For example, the fibers of the formed filter media may be bonded together by solvent bonding, thermal bonding, and/or pressure bonding. The formed filter media can carry fine fibers and provide a structural support. The formed filter media typically can be independently used as a filter media, such as an air filter media, without being laminated or supported by other media or structure. The formed filter media is also referred to as a substrate filter media, a filter media substrate, a substrate, a filter media, or other like terms in the present application.

[0055] Alternatively, the substrate may comprise one or more webs of fibers which are loosely tangled together in a highly fluffed thick state and may not be bonded together as in the case of a formed filter media. Thus, the web of coarse fibers can easily be pulled apart with very little manual effort and has little structural integrity such that it is not considered a formed filter media in the conventional sense. The fibers of the web of fibers typically have a larger average fiber diameter than an average fiber diameter of the fine fibers. As such, the web of fibers is also referred to as a web of coarse fibers or other like terms in this application. A composite filter media including fine fibers integrated with such web of coarse fibers is described in Integrated Nanofiber Filter Media, US Patent Application Publication No. 2009/0266759, which is assigned to the assignee of the present application, the entire disclosures of which are incorporated herein by reference thereto.

[0056] Preferably, the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 is a multi-component filter media. As used herein, the term "multi-component filter media", "multi-component media", "multi-component fiber media" and other similar terms can be used interchangeably to refer to filter medias including at least two different materials. For example, a multi-component filter media can comprise fibers formed of a first material and fibers formed of a second material, wherein the first material and the second material are different materials. Alternatively, a multi-component filter media can be formed of fibers including at least two different materials, such as fibers including a core formed of the first material and a sheath formed of the second material, as described in detail below. A multi-component filter media including two different materials is refer to herein as "bi-component filter media", "bi-component media", and like terms.

[0057] In one preferred embodiment, each of the substrate layers 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 comprises a scrim formed of bi-component fibers including two different materials having different melting points. A composite filter media comprising fine fibers and a substrate formed of such multi-component fibers are described in Multi-Component Filter Media with Nanofiber Attachment, PCT Patent Application No. PCT/US09/50392, which is assigned to the assignee of the present application, the entire disclosure of which are incorporated herein by reference thereto.

[0058] In this embodiment, one component of the bi-component fibers of the scrim has a lower melting point than the other component. The low melt component can be any suitable polymer such as polypropylene, polyethylene, or polyester. The other component may be a polymer having a higher melting point than the low melt component, or other suitable fiber materials such as glass and/or cellulose. The bi-component fibers are bonded together and/or compressed together to form a scrim or a substrate filter media having a certain thickness.

[0059] The bi-component fibers of the scrim used as the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 can include a high melt polymer component and a low melt polymer component. For example the bi-component may comprise a high-melt polyester and a low-melt polyester, in which one has a higher melting temperature than the other. FIG. 3 schematically illustrates a bi-component fiber 22 according to one embodiment. As shown, the bi-component 22 is a concentric sheath/core type, wherein a core 24 is formed of a high melt polymeric component and a sheath 26 is formed of a low melt polymeric component.

[0060] The high melt polymer component is formed of a polymer having a higher melting temperature than the low melt polymer component. Suitable high melt polymers include, but are not limited to, polyester and polyamide. Suitable low polymers include polypropylene, polyethylene, co-polyester, or any other suitable polymers having a lower melting temperature than the selected high melt polymer. For example, bi-component fibers may be formed of a polyester core and a polypropylene sheath. In this embodiment, the bi-component fibers are formed of two different types of polyesters, one having a higher melting point than the other.

[0061] Other types of bi-component fibers may be used to form the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 in other embodiments. Some examples of different types of bi-component fibers are schematically illustrated in FIGS. 4-10. An eccentric sheath/core type bi-component fiber 28 comprising a core 30 and a sheath 32 is shown in FIG. 4. This fiber is similar to the concentric sheath core fiber 22, but with the core 30 shifted off-center. The different shrinkage rates of the two polymer components can cause the fiber to curl into a helix when heated. This allows an otherwise flat fiber to develop crimp and bulk, and can result in different fiber reorientation, expansion and/or undulation of surface under heat.

[0062] FIG. 5 schematically illustrates a side-by-side type bi-component fiber 34 including a first polymer component 36 and a second polymer component 38. Depending on an application, the first polymer component may be a higher or lower melt polymer than the second polymer component. This is a further extension of the eccentric sheath/core fiber, in which both polymers occupy a part of the fiber surface. With proper polymer selection, this fiber can develop higher levels of latent crimp than the eccentric sheath/core fiber 28.

[0063] A pie wedge type bi-component fiber 40 is schematically illustrated in FIG. 6. The pie wedge fiber 40 comprises a plurality of adjacent wedges formed of a first polymer component 42 and a second polymer component 44. Each of the first polymer component 42 has a second polymer component 44 on either side. The first polymer component 42 may be a higher or lower melt polymer than the second polymer component 44. These fibers are designed to be split into the component wedges by mechanical agitation (typically hydroentangling), yielding microfibers of 0.1 to 0.2 denier in the filter media.

[0064] FIG. 7 is a schematic illustration of a hollow pie wedge type bi-component fiber 46 comprising first polymer wedges 48 and second polymer wedges 50. Again, depending on an application, the first polymer wedges 48 may be formed of a higher or lower melt polymer than the second polymer wedges 50. The hollow pie wedge fiber 46 is similar to the pie wedge fiber 40 but with a hollow center 52 core that prevents the inner tips of the wedges from joining, thus making splitting easier.

[0065] FIG. 8 is a schematic illustration of a islands/sea type bi-component fiber 54. This fiber is also known as the "pepperoni pizza" configuration where a first polymer component 56 is the pepperoni and a second polymer component 58 is the cheese. In some embodiments, the first polymer component 56 is formed of a higher melt polymer than the second polymer component 58, or the second polymer component 58 is formed of a soluble polymer. In such embodiments, this fiber allows the placement of many fine strands of high melt polymer 56 within a matrix of low melt or soluble polymer 58 that is subsequently melted or dissolved away. This allows the production of a media made of fine microfiber because the fibers are easier to process in the "pizza" form rather than as individual "pepperonis." Staple fibers can be made of 37 pepperonis on each pizza, producing fibers about 0.04 denier (about 2 microns diameter), or even finer.

[0066] The bi-component fibers may be formed into different shapes. For example, some bi-component fibers may not have a cylindrical shape with a circular cross section as the bi-component fibers described above. FIGS. 9 and 10 illustrate some examples of bi-component fibers with irregular shapes. Although, these fibers do not have a circular cross section, each has a diameter in context of the present invention. The diameter of the fibers having a non-circular cross section is measured from the outer perimeter of the fiber. FIG. 9 is a schematic illustration of a trilobal type bi-component fibers 60, 62. Each of the trilobal fibers 60, 62 comprises a first polymer component 64, 66 and a second polymer component 68, 70. Each of the trilobal fibers 60, 62 are measured by its diameter 72, 74. In some embodiments, the first polymer component 64, 66 is formed of a higher melt or lower melt polymer than the second polymer component 68, 70.

[0067] FIG. 10 is a schematic illustration of a tipped type bi-component fibers 78, 80. The fiber 78 is a tipped trilobal bi-component fiber with a first polymer center 82 and second polymer tips 84. The fiber 80 is a tipped cross bi-component fiber with a first polymer center 86 and second polymer tips 88. Preferably, the first polymer center 82, 86 is formed of a higher melt polymer than the second polymer tips 84, 88.

[0068] The fibers of the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 are formed to have a larger average fiber diameter than that of the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142. For example, the fibers of the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 can have an average fiber diameter of greater than about 1 micron, preferably greater than about 2 micron, and more preferably, greater than 5 micron. In one embodiment, an average diameter of the bi-component fibers of the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 are between about 1 micron and about 40 micron.

[0069] The coarse fibers are compressed and/or heated, for example via a set of calendering rollers and/or an oven, to form the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120, wherein any of the substrate layers has a thickness between about 0.05 and 1.0 mm, preferably between about 0.1 and 0.5 mm. Such substrate can provide a structural support necessary for the fine fibers. Bi-component scrims of various thicknesses suitable for use as any of the substrate layers 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 are commercially available through various suppliers, such as HDK Industries, Inc. of Rogersville, TN, or other filter media suppliers. Thus, the substrate can be selected from such off the shelf bi-component medias.

[0070] In one embodiment, each layer of the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 and the media 122 comprise a scrim formed of bi-component staple fibers having a high melt polyester core and a low melt polyester sheath. The bi-component staple fibers are compressed together to form the scrim, wherein the bi-component staple fibers are bonded together chemically, mechanically and/or thermally. For example, the bi-component staple fibers are heated to or near the melting temperature of the low melt polyester and compressed together, wherein the sheath formed of the low melt polyester melts or softens and acts as a bonding agent to bond fibers together.

[0071] The fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 can be deposited directly on the corresponding substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 as they are formed. Alternatively, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 may be separately prepared as a web of fine fibers, then laminated with the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120. Although, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 may comprise fibers having various fiber diameters, preferably, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 are nanofibers having very fine fiber diameter. Such fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 can be formed by electrospinning or other suitable processes. In one embodiment, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 are electrospun nanofibers having an average fiber diameter less than about 1 micron, preferably less than 0.5 micron, and more preferably between 0.01 and 0.3 microns. Such small diameter fine fibers can pack more fibers together in a given volume to provide an increased fiber surface area in a coalescing filter media for formation of water droplets.

[0072] The fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 may be formed by various suitable polymeric materials. To avoid destruction of the fine fibers during heating and/or compressing of the filter media 100, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 are typically formed of a material having a higher melt temperature than at least the low-melt component of the bi-component fibers of the substrate. In preferred embodiments of water coalescing applications, the fine fibers are formed of a hydrophilic material such as polyamides. Other suitable hydrophilic polymers include, but not limited to, poly(acrylic acid), polyalkylene glycols, polyvinyl alcohol, polyvinyl acetate, polyalkylene glycols, copolymers of methylvinyl ether and maleic acid, maleic anhydride polymers, polylkylene oxides, poly(meth)acrylamides, hydrophilic polyurethanes, polyethyleneimines, methyl cellulose, hydroxylmethyl cellulose, hydroxyethyl cellulose, polyvinylsulfonic acid, poly(saccharides) such as chitosan and many other polymers or copolymers with enough –OH, -COOH, and/or -NH2 groups.

[0073] In one embodiment, the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 are formed of nylon-6 (polyamide-6, also referred to as "PA-6" herein) via electrospinning, wherein the electrospun fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 are deposited directly on the substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120. In this embodiment, the fine fibers 124 are generated electrostatically from a solution containing nylon-6 and deposited on a surface of the substrate 102. The fine fibers 126 can be similarly generated and deposited on the substrate layer 104, and so on. The substrate layers 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 coated with the electrospun nanofibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 are then laminated together with the media 122, such that each layer of the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 is sandwiched between the adjacent substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 and/or the media 122 to create the filter media 100 in the pre-compressed state 144 as shown in FIG. 2. As discussed above, the filter media 100 in the pre-compressed state 144 is then compressed to form the coalescing filter media 100 in its final compressed state 146 as shown in FIGS. 1 and 2. In preferred embodiments, the coalescing filter media 100 is heated before, during, and/or after the compression. For example, the filter media 100 in the pre-compressed state 144 is heated prior to passing through the set of calendering rollers 148, 150. Further, the set of calendering rollers 148, 150 can be heated to further heat the filter media 100 during the compression.

[0074] The bonding between the fine fibers 124, 126, 128, 130, 132, 134, 136, 138, 140, 142 and the adjacent coarser fibers of substrate 102, 104, 106, 108, 110, 112, 114, 116, 118, 120 and/or media 122 may involve solvent bonding, pressure bonding, and/or thermal bonding. For example, as the fine fibers are electrostatically generated from a polymer solution containing a solvent, the solvent remaining on the surface of the fine fibers can effectuate a solvent bonding as the fiber fibers come in contact with the coarse fibers of the substrate. Further, the low melt component of the bi-component fibers of the substrate can be used to enhance bonding between the fine fibers and the adjacent coarse fibers of the substrate. In such embodiment, the filter media 100 is heated to or near the melting point of the low melt component and compressed, wherein the low melt component of the bi-component coarse fibers melts or softens, which allows the adjacent fine fibers to embed into the low melt component as they are compressed together, thereby enhancing the bonding between the coarse fibers and the fine fibers (via pressure bonding and thermal bonding.)

[0075] In the embodiment shown in FIG. 11, the coalescing filter media 500 includes 10 layers of substrate 502, 504, 506, 508, 510, 512, 514, 516, 518, 520, each of which carrying fine fibers 524, 526, 528, 530, 532, 534, 536, 538, 540, 542, and a media 522, all of which are tightly compressed together similar to the filter media 100. In addition, the coalescing filter media 500 includes a porous layer 544 on the downstream surface 548. The porous layer 544 is also referred herein as a "drainage layer". Although this embodiment is shown with the media layer 522 and the porous layer 544, these layers are optional, and thus, the filter media 500 according to other embodiments may not include the media layer 522 and the porous layer 544.

[0076] In this embodiment, the media 522 and each layer of the substrate 502, 504, 506, 508, 510, 512, 514, 516, 518, 520 are formed of a bi-component fiber scrim having an average fiber diameter between about 1 and 40 microns and a base weight between about 0.5 and 15 oz/yd^2. The bi-component fibers comprise a high-melt polyester core and a low melt polyester sheath. The fine fibers 524, 526, 528, 530, 532, 534, 536, 538, 540, 542 are electrospun nanofibers formed of nylon-6. The fine fibers have an average fiber diameter between about 0.01 and 0.5 microns, wherein each layer of the fine fibers 524, 526, 528, 530, 532, 534, 536, 538, 540, 542 has fine fiber coverage between about 0.075 g/m^2 and .225 g/m^2, providing total fine fiber coverage between 0.75 g/m^2 and 2.25 g/m^2.

[0077] The porous layer 544 (also referred herein as a drainage layer) can be formed of various materials such as a cellulous material or fiber glass. In this embodiment, the porous layer 544 is formed of a fiber glass, and has a pore size greater than or equal the bi-component fiber scrim. The porous layer 544 allows continual growth of water droplet that are coalesced through the compacted substrate layers and fine fiber layers, and allows the water droplets to pass through the porous layer 544 for subsequent collection of water droplets. Further, the porous layer 544 can provide additional structural support for the compacted substrate and fine fiber layers. The media 522, the substrate layers 502, 504, 506, 508, 510, 512, 514, 516, 518, 520, the fine fibers 524, 526, 528, 530, 532, 534, 536, 538, 540, 542, and the porous layer 544 are laminated and compressed together to form the tightly packed coalescing filter media 500 having a total thickness between about 3/16" to ½".

[0078] In some embodiments the drainage layer 544 is formed of a siliconized cellulous material. In such embodiments, the drainage layer 544 is not continuously bonded to the substrate layer 502, but may be partially secured to the substrate layer 502 to prevent sliding movements when the coalescing filter media 500 is subsequently pleated or formed into various filter elements. In these embodiments, the compacted substrate and fine fiber layers coalesce water droplets into a size sufficient to be captured by the drainage layer 544 that is formed of the hydrophobic siliconized cellulous material. The hydrophobic drainage layer 544 acts as a water barrier preventing the water droplets from flowing through the pore of the hydrophobic drainage layer 544. Instead, the water droplets flow along the hydrophobic inner surface of the drainage layer 544 and run down between the substrate layer 502 and the drainage layer 544. The water droplets are then collected off line, allowing only fuel to enter the engine.

[0079] In this embodiment, a hydrocarbon fuel stream enters the coalescing filter media 500 from the upstream surface 546, flows through the layers of substrate and fine fibers, and exits through the porous layer 544 on the downstream surface 548. As the hydrocarbon fuel stream passes through the layers of substrate and fine fibers, water emulsified in the hydrocarbon fuel stream coalesces due to the large fiber surface area provides by the fine fibers. Further, the hydrophilic fine fibers attract water, enhancing formation of water droplets. The coalesced water droplets further grow in size as they pass through large pores of the porous layer 544 and are separated from the hydrocarbon fuel. Further, solids and/or contaminants in the hydrocarbon fuel system can be captured within pores of the coalescing filter media 500, thereby providing added filtration capacity.

[0080] In other embodiments, the substrate layers 502, 504, 506, 508, 510, 512, 514, 516, 518, 520 comprise different medias. For example, some of the substrate layers may be formed of a thicker scrim or filter media than other layers, or may have different pore sizes than other layers. Further, the fine fiber layers 524, 526, 528, 530, 532, 534, 536, 538, 540, 542 may have a same fine fiber coverage or different fine fiber coverage. For example, some of the fine fiber layers can have a fine fiber coverage of about 0.08 g/m^2, while other fine fiber layers have a fine fiber coverage of about 0.2 g/m^2. Further, the fine fiber coverage of each layer can be configured according to characteristics of a hydrocarbon fuel stream and water content to optimize the coalescing process.

[0081] FIG. 12 schematically illustrates a representative process of making a coalescing filter media according to a processing embodiment of the present invention. Although this embodiment includes downstream process steps for making the coalescing filter media 500 of FIG. 11, the process can produce filter medias according to other embodiments of the present invention with minor modifications. A system 200 shown in FIG. 12 includes an upstream system 201 for making a composite media including a substrate and fine fibers deposited thereon, and a downstream system 203 for laminating and compressing multiple layers of composite media and other additional layers to make a coalescing filter media.

[0082] The upstream system 201 includes an unwinding station 202, an electrospinning station 204, an optional oven 206, an optional set of calendering rollers 207 and a rewinding station 208. In this embodiment, a roll of scrim 210, which is used here as a substrate layer, is unwound from the unwinding station 202. The scrim 212 unwound from the roll of scrim 210 travels in a machine direction 214 toward the electrospinning station 204. In the electrospinning station 204, fine fibers 216 are formed and deposited on one surface of the scrim 212 to form a composite media 218 comprising the scrim carrying the fine fibers 216. The composite media 218 may be heated and compressed in the optional oven 206 and the optional set of calendering rollers 207 before being wound into a roll of composite media 230 on the rewound station 208.

[0083] The scrim may be formed in an upstream process of the system 200 (either part of a continuous line process or interrupted line process) or may be purchased in a roll form from a supplier such as HDK or other suitable media supplier such as H&V or Ahlstrom or the like. The scrim can be formed of various suitable materials, such as bi-component fibers of FIGS. 3-10 as discussed above. For example, the scrim can be formed of high melt polyester core/low melt polyester sheath bi-component staple fibers, which are compressed and/or heated to form the roll of scrim 210 having a desired thickness and solidity. Alternatively, the substrate layer may be other single component media that may be compressed and held in place via a solvent bond, heat bond or the like.

[0084] In the case of a bi-component, for example, the concentric sheath/core type bi-component fibers may be coextruded using a high melt polyester as the core and a low melt polyester as the sheath. Such bi-component fibers can then be used to form a scrim or a filter media. In one embodiment, the bi-component fibers are used as staple fibers to form a multi-component filter media or a scrim via conventional dry laying or air laying process. The staple fibers used in this process are relatively short and discontinuous but long enough to be handled by conventional equipment. Bales of the bi-component fibers can be fed through a chute feed and separated into individual fibers in a carding device, which are then air laid into a web of fibers (which itself for purposes of the present disclosure may be used as a substrate.) The web of fibers is then compressed using a set of calendering rollers to form the roll of scrim 210 (which can also be used as a substrate.) The web of the fibers may optionally be heated before entering the set of calendering rollers. Since the scrim 210 of this embodiment comprises bi-component fibers, including a high melt component and a low melt component, it is also referred to as a bi-component filter media. In some embodiments, the web of fibers are folded before being calendered to form a thicker bi-component filter media.

[0085] In a different embodiment, a web comprising high melt polymer fibers such as polyester fibers and a web comprising low melt polymer fibers such as polypropylene fibers can be formed, separated and laminated together to form the roll of bi-component filter media or scrim. In such embodiment, the fine fibers 216 are deposited on the low melt side of the scrim 212. In this embodiment, the low melt web is substantially thinner than the high melt web, such that the low melt component does not clog the surface of the high melt web when heated and melted.

[0086] In another embodiment, the bi-component fiber scrim can be formed via a melt blowing process. For example, molten polyester and molten polypropylene can be extruded and drawn with heated, high velocity air to form coarse fibers. The fibers can be collected as a web on a moving screen to form a bi-component scrim 210.

[0087] The multi-component fiber filter media or scrim may also be spun-bounded using at least two different polymeric materials. In a typical spun-bounding process, a molten polymeric material passes through a plurality of extrusion orifices to form a multifilamentary spinline. The multifilamentary spinline is drawn in order to increase its tenacity and passed through a quench zone wherein solidification occurs which is collected on a support such as a moving screen. The spun-bounding process is similar to the melt blowing process, but melt blown fibers are usually finer than spun-bounded fibers.

[0088] In yet another embodiment, the multi-component filter media is wet-laid. In a wet laying process, high melt fibers and low melt fibers are dispersed on a conveying belt, and the fibers are spread in a uniform web while still wet. Wet-laid operations typically use ¼" to ¾" long fibers, but sometimes longer if the fiber is stiff or thick. The above discussed fibers, according to various embodiments, are compressed to form a scrim 210 or a filter media having a desired thickness.

[0089] Referring back to FIG. 12, the scrim 212 enters the electrospinning station 204, wherein the fine fibers 216 are formed and deposited on one surface of the scrim 212. In the electrospinning station 204, the fine fibers 216 are electrospun from eletrospinning cells 222 and deposited on the web of scrim 212. The electrospinning process of the system 200 can be substantially similar to the electrospinning process disclosed in Fine Fibers Under 100 Nanometers, And Methods, U.S. Patent Application Publication No. U.S. 2009/0199717, assigned to the assignee of the present application, the entire disclosure of which has been incorporated herein by reference thereto. Alternatively, nozzle banks or other electrospinning equipment can be utilized to form the fine fibers. Such alternative electrospinning devices or rerouting of chain electrodes of the cells 222 can permit the fibers to be deposited in any orientation desired (e.g. upwardly is shown although fibers can also be spun downwardly, horizontally or diagonally onto a conveyor carrying coarser fibers).

[0090] The electrospinning process produces synthetic fibers of small diameter, which are also known as nanofibers. The basic process of electrostatic spinning involves the introduction or electrostatic charge to a stream of polymer melt or solution in the presence of a strong electric field, such as a high voltage gradient. Introduction of electrostatic charge to polymeric fluid in the electrospinning cells 222 results in formation of a jet of charged fluid. The charged jet accelerates and thins in the electrostatic field, attracted toward a ground collector. In such process, viscoelastic forces of polymeric fluids stabilize the jet, forming small diameter filaments. An average diameter of fibers may be controlled by the design of eletrospinning cells 222 and formulation of polymeric solutions.

[0091] The polymeric solutions used to form the fine fibers can comprise various polymeric materials and solvents. Examples of polymeric materials include polyvinyl chloride (PVC), polyolefin, polyacetal, polyester, cellulous ether, polyalkylene sulfide, polyarylene oxide, polysulfone, modified polysulfone polymers and polyvinyl alcohol, polyamide, polystyrene, polyacrylonitrile, polyvinylidene chloride, polymethyl methacrylate, polyvinylidene fluoride. Solvents for making polymeric solution for electrostatic spinning may include acetic acid, formic acid, m-cresol, tri-fluoro ethanol, hexafluoro isopropanol chlorinated solvents, alcohols, water, ethanol, isopropanol, acetone, and N-methyl pyrrolidone, and methanol. The solvent and the polymer can be matched for appropriated use based on sufficient solubility of the polymer in a given solvent and/or solvent mixture (both of which may be referred to as "solvent".) For example, formic acid may be chosen for nylon-6. Reference can be had to the aforementioned patents for further details on electrospinning of fine fibers.

[0092] In the electrospinning station 204, an electrostatic field is generated between electrodes in the electrospinning cells 222 and a vacuum collector conveyor 224, provided by a high voltage supply generating a high voltage differential. As shown in FIG. 12, there may be multiple electrospinning cells 222, wherein fine fibers 216 are formed. The fine fibers 216 formed at the electrodes of the electrospinning cells 222 are drawn toward the vacuum collector conveyor 224 by the force provided by the electrostatic field. The vacuum collector conveyor 224 also holds and transfers the scrim 212 in the machine direction 214. As configured, the scrim 212 is positioned between the electrospinning cells 222 and the vacuum collector conveyor 224, such that the fine fibers 216 are deposited on the scrim 212. In embodiments, wherein the scrim 212 is a multi-component filter media including a low melt component on one surface and a high melt component on the other surface, the multi-component scrim 212 is positioned between the electrospinning cells 222 and the vacuum collector conveyor 224, such that the low melt component surface of the multi-component scrim faces the electrospinning cells 222.

[0093] In one preferred embodiment, the electrospinning cells 222 contain a polymeric solution comprising polyamide-6 (PA-6) and a suitable solvent consisting of 2/3 acetic acid and 1/3 formic acid. In such a solvent, both acetic acid and formic acid act as a dissolving agent to dissolve PA-6, and acetic acid controls conductivity and surface tension of the polymeric solution. The electrospinning cells 222 generate fine fibers formed of PA-6, which are deposited onto a surface of the scrim 212. As the fine fibers 216 are deposited on the surface of the scrim 212, some fine fibers 216 entangle with coarse fibers of the scrim proximate the surface facing the electrospinning cells 222. When some fine fibers 216 entangle with some coarse fibers, solvent remaining in the fine fibers 216 from the electrospinning process can effectuate a solvent bonding between the fine fibers 216 and the coarse fibers of the scrim 212.

[0094] The bonding between bi-component fibers of the scrim 212 and the fine fibers 216 may be enhanced via thermal bonding and pressure bonding by the optional oven 206 and the optional set of calendering rollers 207. As the composite media 218 is heated in the oven 206, the low melt polymer component of the bi-component fibers softens or melts and allowing the fine fibers 216 to embed into the low melt polymer component. Thus, during the heat treatment, the composite filter media 218 is heated to at least above the glass transition temperature of the low melt component, and more preferably to or near the melting temperature of the low melt component. For example, the composite media 218 is heated to or near the melt point of low melt polyester, such that the outer low melt polyester layer of the bi-component fibers melts and bonds with the fine fibers 216 formed of PA-6. In such embodiments, PA-6 fine fibers 216 and the high melt polyester core of the bi-component fibers do not melt, since PA-6 and the high melt polyester have a significantly higher melting temperature than that of the low melt polyester. The low melt polyester, which has the lowest melting temperature, melts or softens, and adjacent PA-6 fine fibers 216 are embedded in the softened or melted low melt polyester, thereby bonding the fine fibers 216 and the scrim 212 together. Thus, the low melt polyester acts as a bonding agent between the bi-component fiber scrim 212 and the fine fibers 216. The bonding between the fine fibers 216 and the scrim 212 can further be enhanced through pressure bonding via the set of calendering rollers 207. As the composite media passes through the calendering rollers 207, the fine fibers 216 and the scrim 212 are compressed together, wherein the fine fibers are further embedded into the fibers of the scrim 212. Further, the compression reduces voids in the composite media to form a composite media 220 with an increased solidity.

[0095] FIGS. 15(A)-15(D) are Scanning Electron Microscopic (SEM) images of the bi-component fibers of the scrim 212 and the fine fibers 216 proximate the surface of the scrim 212 taken at various magnification levels. As shown in the SEM images taken at magnification levels x300 and x1000 of FIGS. 15(A) and 15(B), the fine fibers 216 deposited on the web of scrim 212 form a spider web like fiber structure between the coarser bi-component fibers that are located proximate the surface of the scrim 212. The SEM images taken at higher magnifications (FIG. 15(C) at x2,000 and FIG. 15(D) at x10,000) show the bonding between the fine fibers 216 and the bi-component fibers. As shown clearly in FIG. 15(D), the fine fibers 216 are embedded on the low melt polyester surface of the bi-component fibers.

[0096] The roll of composite media 230 including the bi-component scrim 212 and the fine fibers 216 is laminated with other composite medias 232, 234, 236, 238, 240, 242, 244, 246, 248, and a media 250 in the downstream system 203. Each of the composite media rolls 230, 232, 234, 236, 238, 240, 242, 244, 246, 248, and a roll of the media 250 are unwound from unwind stations 252, 254, 256, 258, 260, 262, 264, 266, 268, 270, 272, and laminated together by a set of rollers 274. The set of rollers may be a calendering rollers to apply a significant pressure to laminate and significantly reduce a thickness of the layers of composite medias. Alternatively, the set of rollers 274 may apply a small pressure to laminate and reduce the thickness of the laminated layers just enough to fit through an oven 276. In such embodiment, the laminated layers 280 is heated in the oven 276 and compressed via a set of calendering rollers, wherein the laminated layers 280 is compressed together into a compressed state having a desired thickness and solidity.

[0097] In this embodiment, each roll of the composite media 232, 234, 236, 238, 240, 242, 244, 246, 248 is prepared similarly as the roll of the composite media 230. Therefore, each of the roll of the composite media 232, 234, 236, 238, 240, 242, 244, 246, 248 includes a substrate formed of a bi-component fiber scrim 284, 286, 288, 290, 292, 294, 296, 298, 300, and electrospun nanofibers 302, 304, 306, 308, 310, 312, 314, 316, 318, carried by the bi-component fiber scrim 284, 286, 288, 290, 292, 294, 296, 298, 300.

[0098] In one embodiment, each of the substrates 212, 284, 286, 288, 290, 292, 294, 296, 298, 300 and the media 250 are formed of a same bi-component fiber scrim having a thickness between about 0.05 mm and 1.0 mm. Each layer of the fine fibers 216, 302, 304, 306, 308, 310, 312, 314, 316, 318, is formed by electrospinning PA-6 polymer solution to produce a fine fiber coverage between about 0.075 g/m^2 and .225 g/m^2. In other embodiments, the substrates may be formed of different types of filter media or scrim, and each of the fine fibers layer may have different fine fiber coverage.

[0100] The composite media 280 is heated in the oven 276 to or near a melting temperature of the low melt polyester component of the bi-component fiber scrim. During heating the substrates can relax and expand in thicknesses. Thus, the lofted composite media 281 can have a thickness that is at least 1.5 times, 2 times, 3 times or even greater than the thickness of the composite media 280 before being heated in the oven 276. The lofted composite media 281 is then compressed via the set of calendering rollers 282 into the compressed state 320. The composite media is compressed, such that the thickness of the composite media 280 is reduced between about 50% and 300%, preferably between about 70% and 200%, and more preferably between about 80% and 150% of the original thickness of the composite media 280 prior to heating ((total thickness of 10 scrim layers carrying 10 fine fiber layers + thickness of media - thickness of the composite media in the compressed state 320)/(total thickness of 10 scrim layers carrying 10 fine fiber layers + thickness of media).) The thickness reduction will depend on the amount of lofting during heating. Thus, when the lofting from heating is large, the final thickness of the composite media after compression may be greater than the initial thickness of the composite media before heating. The composite media in the compressed state 320 is then laminated with a drainage layer 322 and wound into a roll of coalescing media 324.

[0101] In this embodiment, the rolls of the composite media 230, 232, 234, 236, 238, 240, 242, 244, 246, 248. and the media 250 are laminated together, such that each of the fine fiber layers 216, 302, 304, 306, 308, 310, 312, 314, 316, 318 is sandwiched between adjacent substrate layer and/or media. However, in other embodiments, the composite media layers may be laminated such that some of the fine fiber layers face each other to form fine fiber to fine fiber or substrate to substrate bonding within the final composite media 320.

[0102] FIG. 13 schematically illustrates a system and a process of making a coalescing filter media according to a different embodiment of the present invention. A system 400 generally includes an unwinding station 402, an electrospinning station 404, a folding station 406, a set of rollers 408, an oven 410, and a set of calendering rollers 412 and a rewinding station 414.

[0103] In this embodiment a roll of substrate 416 is unwound from the unwinding station 402 and transferred to the electrospinning station 404, wherein fine fibers are formed and deposited on a surface of the substrate 416. The electrospinning station 404 and the process are similar to the electrospinning station 204 and the process described above. In this embodiment, the substrate 416 is a scrim formed of bi-component fibers including a high melt polyester core and a low melt polyester sheath. The fine fibers 418 are formed of PA-6.

[0104] The composite media 420 comprising the substrate 416 and fine fibers 418 is folded in the folding station 406. The composite media 420 can be folded to 2-20 folds thick depending on desired characteristics of the final coalescing media. As shown, the folding creates fine fiber to fine fiber laminated surfaces and substrate to substrate laminated surfaces. The folding station 406 in this embodiment is shown as folding the composite media 420 in a line direction, such that the folds are pointing toward the set of the rollers 408. However, in other embodiments, the composite media 402 may be folded such that the folds are pointing toward the electrospinning station 404, or folded in cross-line directions. The folded composite media 422 is then compressed to a thickness appropriate to pass through an oven 410. As the composite media 424 is heated, the low melt polyester sheath melts or softens to effectuate thermal bonding between layers. After exiting the oven 410, the composite media 424 passes through the set of calendering rollers 412. The calendering rollers 412 are spaced apart from each other according to a desired final thickness of the coalescing media. The composite media 424 is pressed down into a compressed state having a desired thickness as it passes through the set of calendering rollers 412.

[0105] Further, a media layer 426 and a porous layer 428 are laminated on each surface of the coalescing media 430 and wound into a roll in the rewinding station 414. A expanded cross sectional view of a coalescing filter media 432 including the coalescing media 430, the media layer 426, and the porous layer 428 is shown in FIG. 13. As shown, the coalescing media 430 includes multiple layers of substrate 416 and multiple layers of fine fibers 418 in a slanted orientation from the folding process. The media layer 426 can be formed of any suitable media, but in this embodiment, the media layer 426 is formed of the same bi-component fiber scrim used for the substrate 416. The porous layer 428 can also be formed of various porous material, but in this embodiment, the porous layer 428 is a fiber glass material.

[0106] FIG. 14 shows yet a different embodiment of a system and a process of making a coalescing media. A system 600 is similar to the system 400 but the fine fibers in this embodiment are not deposited on a substrate. Rather, the fine fibers are formed and deposited onto a web of loosely entangled coarse fibers. The system 600 generally includes a chute 602, a carding device 603, an electrospinning station 604, a folding station 606, a set of rollers 608, an oven 610, and a set of calendering rollers 612 and a rewinding station 614.

[0107] In the system 600, the web of coarse fibers 616 is formed from staple fibers using a dry laying or air laying process. The staple fibers of this embodiment are bi-component fibers comprising a high melt polyester core and a low-melt polyester sheath. The bi-component staple fibers are relatively short and discontinuous, but long enough to be handled by conventional equipment. Bales of staple fibers are fed through the chute feed 602. In the carding device 603, the bi-component staple fibers are separated into individual fibers and air laid to form the web of coarse fiber 616. At this point, the web of coarse fiber 616 can be loosely tangled together in a highly fluffed thick state and may not be bonded together. The web of coarse fiber 616 can be easily pulled apart with very little manual effort and has little structural integrity at this point such that it is not considered a filter media or substrate in the conventional sense.

[0108] The web of coarse fiber 616 is transferred via a conveyor belt 617 toward the electrospinning station 604, wherein the fine fibers 618 are formed and deposited on a surface of the web of coarse fiber 616. As the fine fibers 618 are deposited on the web of coarse fiber 616, the fibers 618 are integrated with the coarse fibers of the web of coarse fiber 616 much more than in the previous embodiment with the substrate 416, as the web of coarse fiber 616 are much more porous and less dense to allow deeper integration of the fine fibers 616.

[0109] The web of coarse fiber 616 integrated with the fine fibers 618 are then folded into 10-30 folds in the folding station 606 and compressed via the set of rollers 608, which is heated in the oven 610 and compressed again via the set of calendering rollers 612 as it was with the system 400. The coalescing media 630 is then laminated with a media layer 626 and a porous layer 628 to from a coalescing filter media 632. The coarse bi-component fibers and the fine fibers of the coalescing media 630 of this embodiment are much more integrated. Thus, a cross sectional view of the coalescing media 630 does not show multiple layers, but rather appears more like a single integrated media 630. The coalescing media 630 has a sufficient fine fiber coverage and tightness to provide coalescing of water droplets from a fluid stream, such as a hydrocarbon fuel stream. Further, the coalescing filter media 632 is configured to remove water from such fluid stream.

[0110] The coalescing media according to various embodiments of the present invention can be configured into various shapes and sizes for various applications. For example, the coalescing media can be used in spin-on filter applications, large fuel filtration vessels, aviation filter systems, hydraulic filter elements, and bio-fuel systems. The coalescing media can be pleated or gathered into a fluted filter, a pleated filter, or other such typical filter element arrangements. Although the coalescing media works particularly well in coalescing applications, the coalescing media can also work effectively in other filtration applications such as filtering particulates from water.

[0111] A typical coalescing filter element may include a pre-filter element and a coalescing element. The pre-filter media is typically a separate structure from the coalescing element and configured to filter out particulates from a fuel stream before the fuel stream enters the coalescing element to prevent particulates from blocking coalescing media pores. In one embodiment, the coalescing filter element is constructed to include an expanded nanofiber composite media and a compressed coalescing filter media. Such coalescing filter element can filter particulates and coalesce water to eliminate the need of the pre-filter element.

[0112] FIG. 16 shows a coalescing filter element 700 that includes an expanded nanofiber composite media 702, a compressed coalescing media 704, and a drainage layer 706. As shown, a fuel stream 708 enters the coalescing filter media 700 via the expanded nanofiber composite media 702 and flows though the compressed coalescing media 704 and exits out through the drainage layer 706. Such expanded nanofiber composite media is disclosed in US Provisional Patent Application No. 61/308,488, Expanded Composite Filter

Media Including Nanofiber Matrix and Method, assigned to the assignee of the present application, entire disclosure of which is incorporated herein by reference thereto.

[0113] In this embodiment, the expanded nanofiber composite media 702 includes three layers of substrate 710, 712, 714, wherein the substrate layers 712 and 714 carry nanofibers 726, 728. The compressed nanofiber composite media 704 includes five layers of substrate 716, 718, 720, 722, 724, each of which carries nanofibers 730, 732, 734, 736, 738. Each of the substrate layers 710, 712, 714, 716, 718, 720, 722, 724 can be formed of a same or different porous material. In this embodiment, each of the substrate layers are formed of a scrim comprising bi-component fibers as described above with regard to other embodiments of the coalescing media. The nanofibers 726, 728, 730, 732, 734, 736, 738 are deposited on the corresponding substrate layers via electrospinning similar to other embodiments described above.

[0114] The expanded nanofiber composite media 702 is constructed by laminating the nanofiber 726, 728 deposited scrim layers 712, 714 with the scrim layer 710 and heating the laminated layers in an oven to reorient and loft fibers of scrim layers. As the scrim layers 710, 712, 714 reorient and loft, nanofibers 726, 728 also reorient and extend with the fibers of scrim layers. As a result, a volumetric coverage of nanofibers can increase (more volumetric coverage for a same basis weight application – as the expansion can open up and expand the nanofibers into a 3D matrix); a pressure drop can be reduced due to expansion; and/or a pressure drop increase with dust loading can be slowed. Thus, the expanded nanofiber composite media 702 layer can effectively filter out particulates in the fuel stream before it enters the subsequent compressed coalescing media layer 704.

[0115] The compressed coalescing media 704 can be constructed similarly as the coalescing filter media 100 or 500 as described in detail above. The nanofiber deposited scrim layers are laminated, heated and compressed to form the compressed coalescing media to coalesce water in the fuel stream. The drainage layer 706 can be any porous media described above. In this embodiment, the drainage layer 706 is a hydrophobic siliconized cellulous material. This drainage layer 706 is not continuously attached to the substrate layer 738, but secured to the substrate layer in several spots along sides. The hydrophobic drainage layer 706 prevents coalesced water droplets from passing through its pores. Rather, the coalesced water droplets flow along the inner surface 725 of the drainage layer 706 and are collected. As such, only the fuel stream without the coalesced water droplets are allowed to pass through the drainage layer to enter an engine system.

[0116] All references, including publications, patent applications, and patents cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

[0117] The use of the terms “a” and “an” and “the” and similar referents in the context of describing the invention (especially in the context of the following claims) is to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms “comprising,” “having,” “including,” and “containing” are to be construed as open-ended terms (i.e., meaning “including, but not limited to,”) unless otherwise noted. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., “such as”) provided herein, is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[0118] Preferred embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

WHAT IS CLAIMED IS:

1. A method of forming a coalescing filter media, comprising steps of:

electrostatically spinning fine fibers having an average diameter of less than 1 micron;

applying the fine fibers to at least one substrate comprising coarse fibers having an average diameter greater than 1 micron;

compacting the fine fibers and the coarse fibers together;

generating sufficient fine fiber coverage and tightness through said compacting to provide coalescing of water droplets from a fluid stream; and

structuring the coarse fibers and the fine fibers into a coalescing filter media that is operable to remove water from a fluid stream.

2. The method of claim 1, wherein the at least one substrate comprises a fiber entanglement that is bonded together into a formed filter media prior to said applying, the fine fibers deposited onto the formed filter media during said step of applying the fine fibers.

3. The method of claim 2, wherein the at least one substrate comprises at least one scrim formed of bi-component fibers comprising a high melt component and a low melt component, wherein the fine fibers are deposited on a surface of the at least one scrim and carried by the at least one scrim.

4. The method of claim 1, further comprising generating multiple layers of substrate with nanofibers carried on multiple individual layers either by feeding multiple discrete substrate layers or lapping one or more individual substrate layers, thereby spacing fine fibers within the thickness of the coalescing filter media by the multiple layers of substrate, wherein said compacting comprises laminating multiple layers of the substrate carrying the fine fibers, and compressing the multiple layers of the substrate carrying the fine fibers to form a composite filter media.

5. The method of claim 4, further comprising permanently bonding the multiple layers of substrate carrying the fine fibers together to form an integrated composite filter media layer.

6. The method of claim 1, wherein each substrate individually carries the fine fibers along one surface thereof having a fine fiber coverage between about 0.075 g/m^2 and .225 g/m^2, and collectively providing a total fine fiber coverage in the composite filter media between about 0.75 g/m^2 and 2.25 g/m^2 in the coalescing filter media and thereby providing said sufficient fine fiber coverage and tightness.

7. The method of claim 6, wherein the layers are compressed together to reduce a thickness to between about 3/16" and ½".

8. The method of claim 4, further comprising laminating a drainage filter layer on or proximate a downstream side of the coalescing filter media, the drainage layer arranged to collect and grow water droplets coalesced by fine fibers.

9. The method of claim 5, wherein the at least one substrate comprises at least one scrim formed of bi-component fibers comprising a high melt component and a low melt component, wherein the fine fibers are deposited on a surface of the at least one scrim and carried by the at least one scrim; further including heating the multiple layers of the scrim carrying the fine fibers to or near a melting temperature of the low melt component, wherein the low melt component melts or softens to act as a bonding agent to bond layers together.

10. The method of claim 5, the scrim carrying the fine fibers are folded into multiple folds and compressed together, wherein the folding creates a fine fiber to fine fiber laminated surface and a scrim to scrim laminated surface.

11. The method of claim 1, wherein the substrate is a web of coarse fibers comprising a loose entanglement of the coarse fibers, the fine fibers being applied to the loose entanglement of the coarse fibers during the said step of applying the fine fibers, and wherein the web of coarse fibers applied with the fine fibers are folded into multiple folds

and compressed together, wherein the fine fibers and the coarse fibers are integrated to form a single integrated coalescing media.

12. The method of claim 1, wherein said electrostatically spinning fine fibers comprises spinning fine fibers from a solution including a hydrophilic polymer.

13. A method of forming a compressed filter media, comprising steps of:

electrostatically spinning a web of fine fibers having an average diameter of less than 1 micron;

applying the fine fibers to a substrate, the substrate comprising coarse fibers that are bonded together to form a filter media, wherein the coarse fibers have an average fiber diameter greater than 1 micron; and

lapping the combination of the fine fiber applied substrate such that the fine fibers overlap.

14. The method of claim 13, further comprising unwinding a roll of filter media from an unwind station and transferring the filter media to an electrospinning station, wherein the filter media is kept afloat via a line tension.

15. The method of claim 13, wherein the substrate is a scrim comprising bi-component fibers, the bi-component fibers comprising a high melt polyester core and a low melt polyester sheath.

16. The method of claim 13, wherein the step of applying the fine fibers provide a fine fiber coverage between about 0.075 g/m^2 and .225 g/m^2, wherein the fine fibers are carried by a scrim.

17. The method of claim 13, wherein the step of lapping comprises folding the substrate carrying the fine fibers into 2-20 folds, wherein the folding provides a fine fiber to fine fiber laminated surface and a substrate to substrate laminated surface, wherein the folded layers are heated and compressed to form a compressed media, wherein a thickness is adjusted by between about 50% and 300% via heating and compressing.

18. The method of claim 17, wherein the compressed media is formed to have a total fine fiber coverage between about 0.09 g/m^2 and 5.25 g/m^2.

19. The method of claim 13, wherein the step of electrostatically spinning fine fibers comprises spinning fine fibers from a solution including a polyamide-6.

20. A coalescing filter media, comprising:

at least one substrate comprising at least one filter media including coarse fibers having an average fiber diameter of greater than 1 micron;

fine fibers carried by the substrate, the fine fibers comprising hydrophilic fibers having an average fiber diameter of less than 1 micron, the fine fibers providing a sufficient fiber surface area to coalesce emulsified water in a hydrocarbon fuel, wherein the hydrophilic fibers facilitate formation and growth of water droplets.

21. The coalescing filter media of claim 20, further including a drainage layer arranged on a downstream surface of the coalescing filter media, wherein the drainage layer is formed of a hydrophobic porous material.

22. The coalescing filter media of claim 21, wherein the drainage layer is formed of a cellulous material or a fiber glass material.

23. The coalescing filter media of claim 20, wherein the fine fibers are electrospun nanofibers formed of a hydrophilic polymer.

24. The coalescing filter media of claim 23, wherein the fine fibers are formed of a polyamide-6.

25. The coalescing filter media of claim 24, wherein the fine fibers have a total fine fiber coverage between about 0.09 g/m^2 and 5.25 g/m^2.

26. The coalescing filter media of claim 20, wherein the substrate is a scrim comprising bi-component fibers, the bi-component fibers having a high melt component and a low melt component.

27. The coalescing filter media of claim 26, wherein the bi-component fibers comprise a high melt polyester core and a low melt polyester sheath, wherein the at least one substrate and the fine fibers are heated and compressed together to form a coalescing media, wherein the low melt polyester sheath melts or softens to bond the coarse fibers and the fine fibers.

28. The coalescing filter media of claim 20, wherein the coalescing filter media includes multiple layers of filter media, each of the multiple filter media layers carrying a layer of fine fibers having a fine fiber coverage between about 0.075 g/m^2 and .225 g/m^2.

29. The coalescing filter media of claim 28, wherein each of the fine fiber layer is sandwiched between the substrate layers and/or a media layer.

30. The coalescing filter media of claim 29, wherein the coalescing filter media includes a fine fiber to fine fiber laminated surface and a substrate to substrate laminated surface.

31. The coalescing filter media of claim 28, wherein the coalescing filter media includes 10 layers of substrate, wherein each of the substrate layer is formed of a scrim comprising bi-component fibers, wherein each of the fine fiber layers comprises electrospun polyamide-6 nanofibers, wherein 10 layers of fine fibers provide a total fine fiber coverage between about 0.75 g/m^2 and 2.25 g/m^2.

32. The coalescing filter media of claim 31, further including a drainage layer arranged on a downstream surface of the coalescing filter media, the drainage layer formed of a fiber glass mat, wherein the coalescing filter media has a total thickness between about 3/16" and ½".

33. A compressed filter media, comprising:

at least one substrate, the at least one substrate comprising coarse fibers having an average fiber diameter of greater than 1 micron;

fine fibers carried by the at least one substrate, the fine fibers having an average fiber diameter of less than 1 micron, at least some of the fine fibers being embedded at least partially within the coarse fibers in a compressed state.

34. The compressed filter media of claim 33, wherein at least some of the fine fibers form a dimensional matrix of fine fibers as opposed to a planar layer.

35. The compressed filter media of claim 33, wherein at least some of the fine fibers are generally sandwiched between layers of the substrate.

36. The compressed filter media of claim 33, wherein the fine fibers have a melting point higher than a melting point of at least one component of the coarse fibers, and wherein the fine fibers are permanently affixed and oriented

37. The compressed filter media of claim 33, wherein the at least one substrate carrying the fine fibers are calendered together in the compressed state.

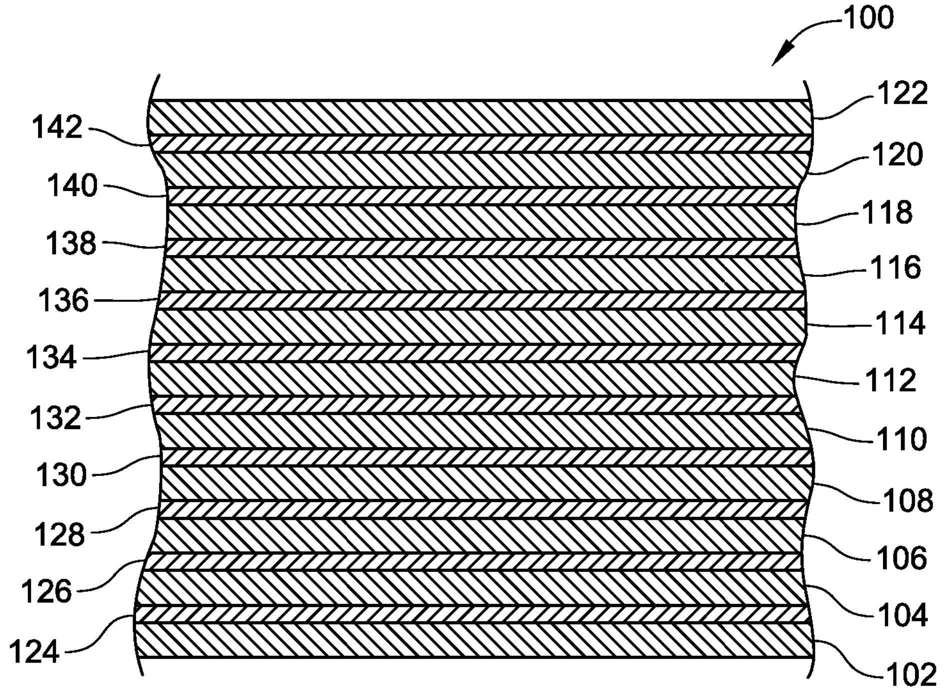
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FIG. 1

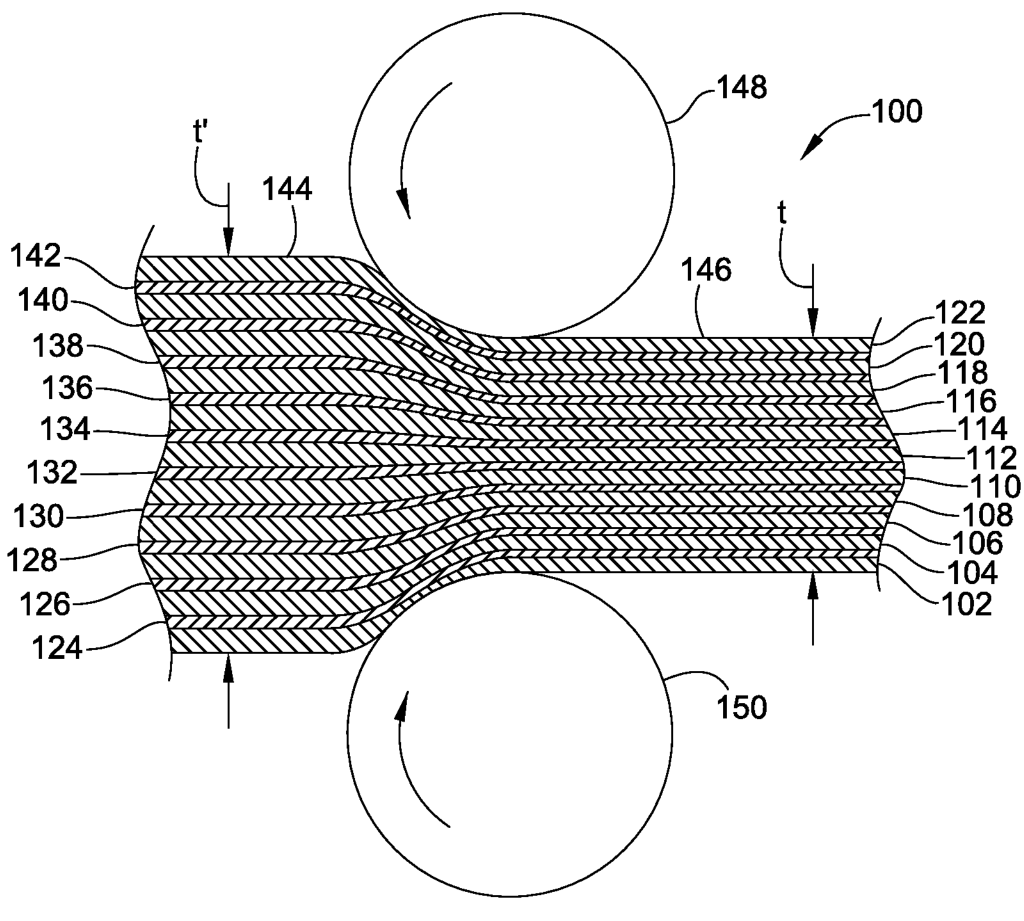
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FIG. 2

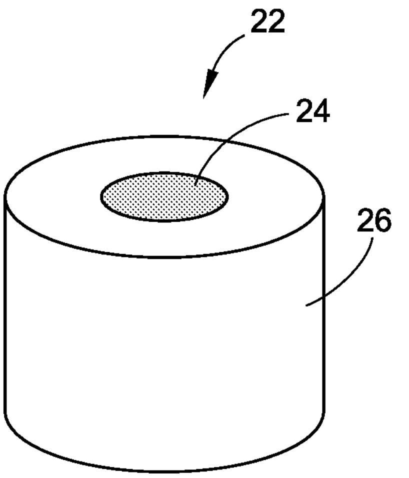

FIG. 3

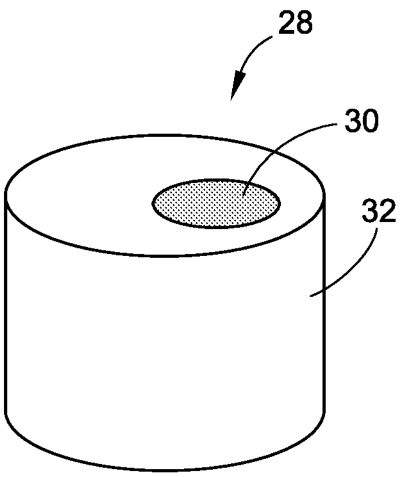

FIG. 4

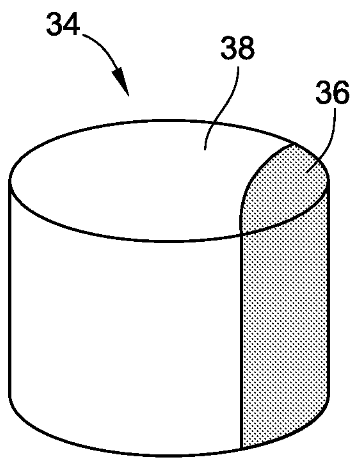

FIG. 5

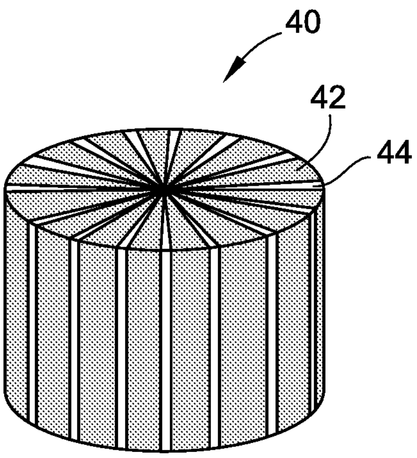

FIG. 6

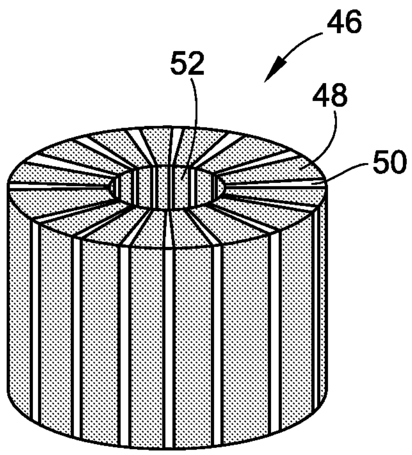

FIG. 7

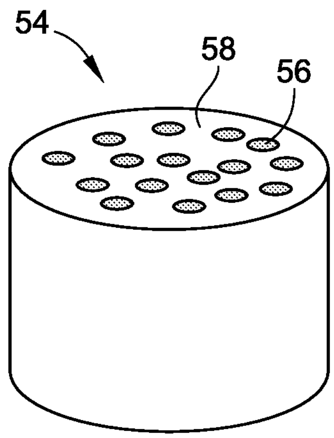

FIG. 8

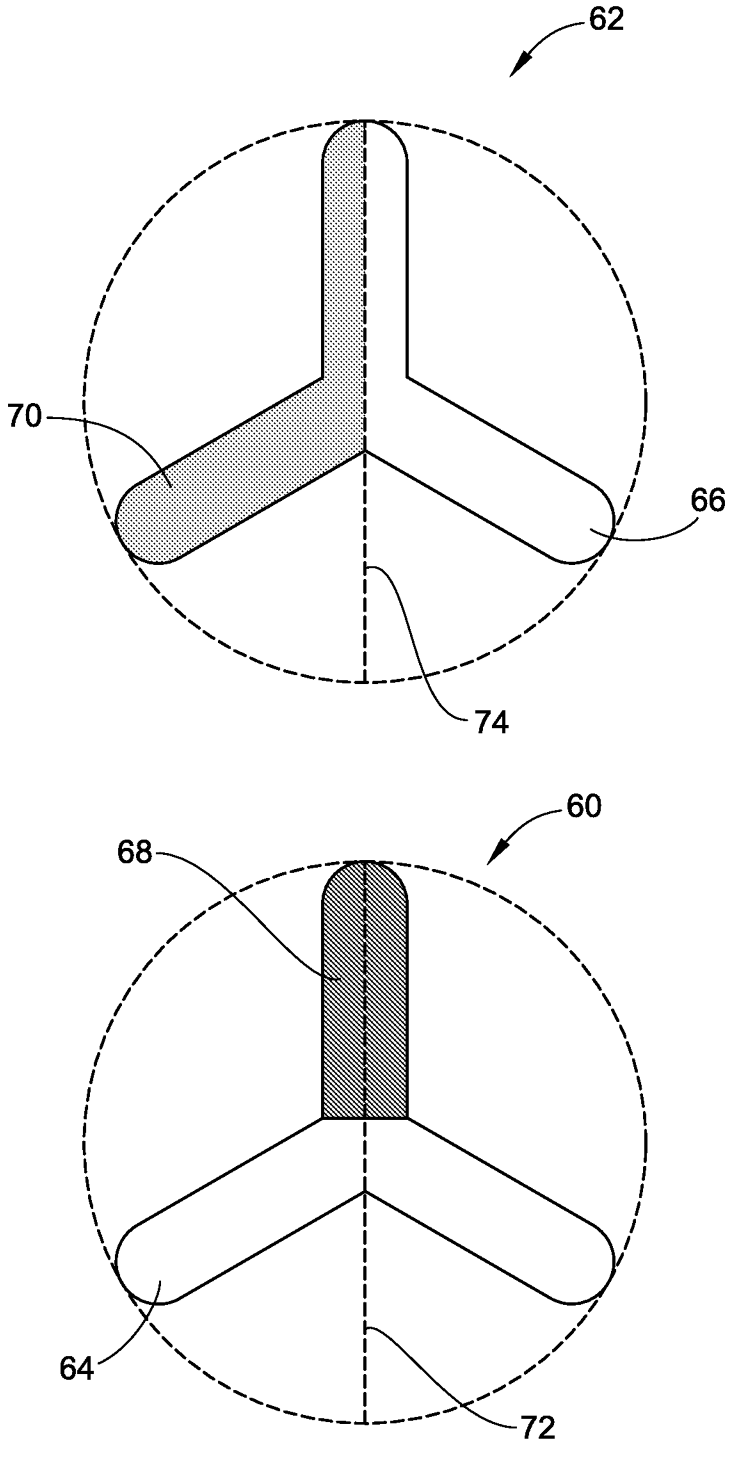

FIG. 9

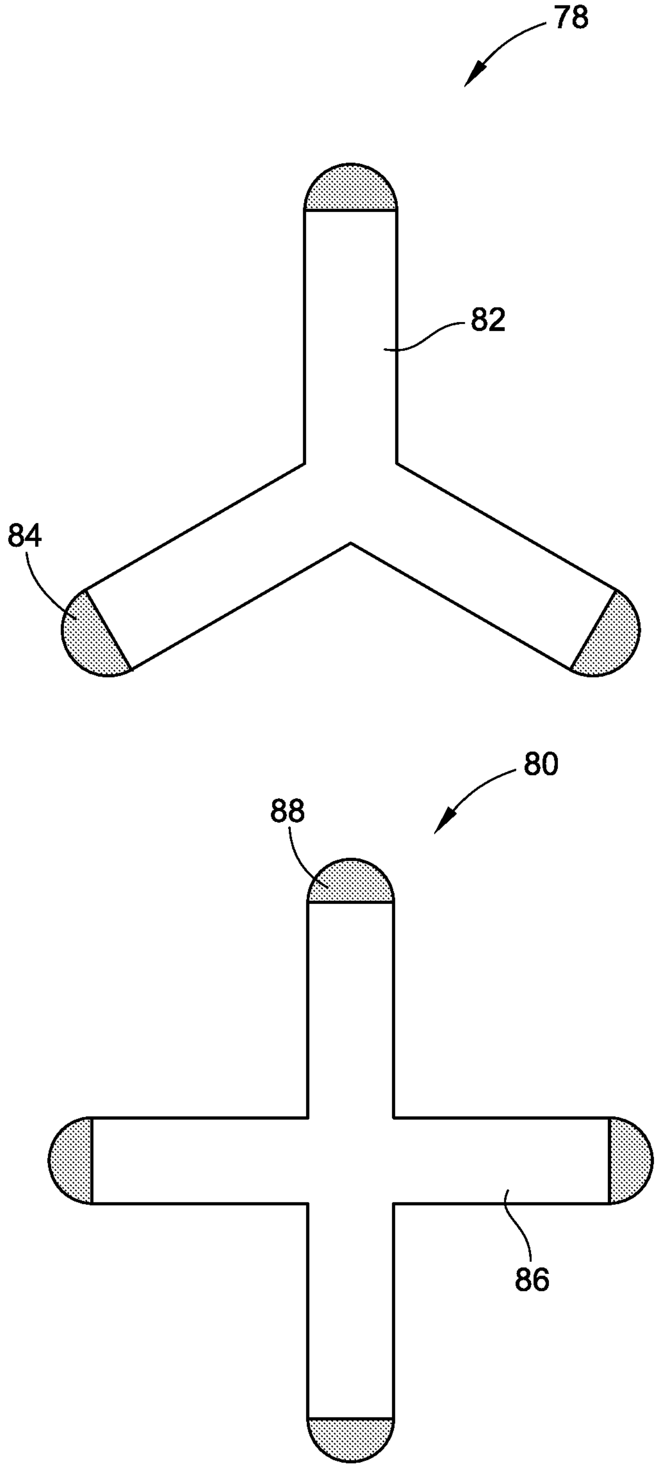

FIG. 10

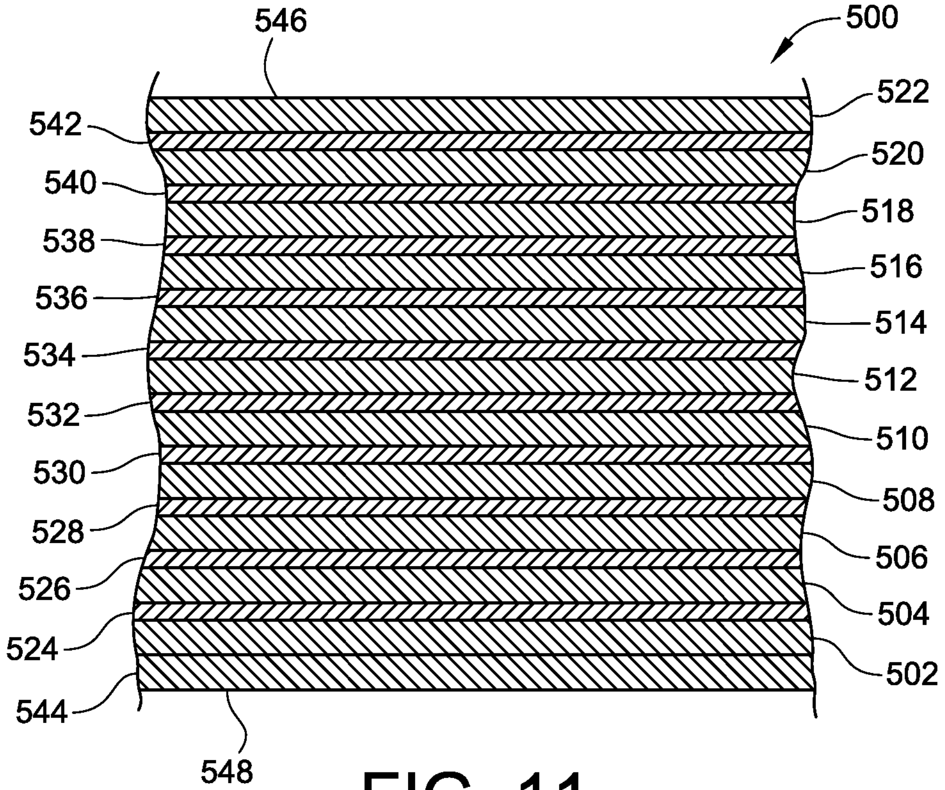
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FIG. 11

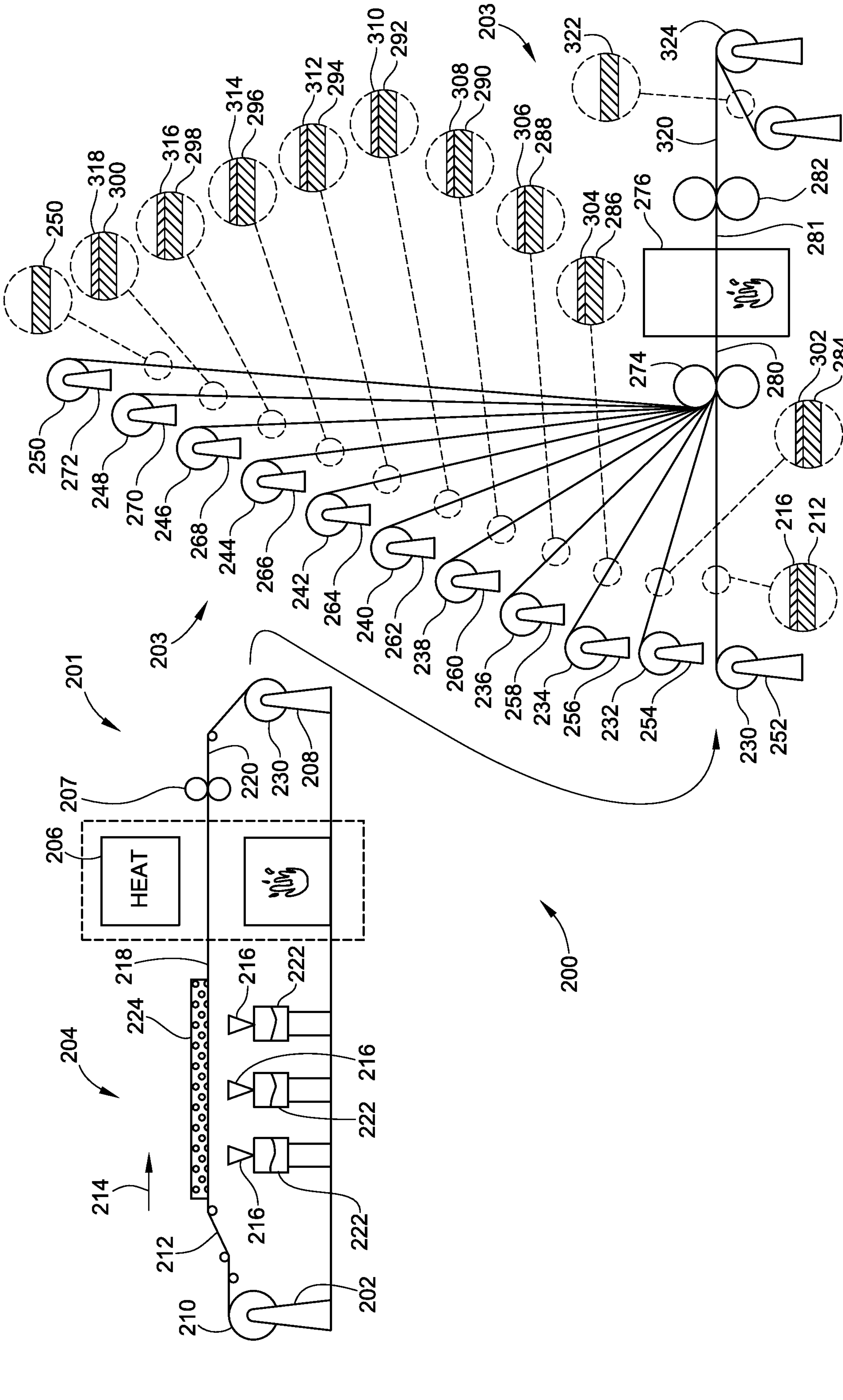

FIG. 12

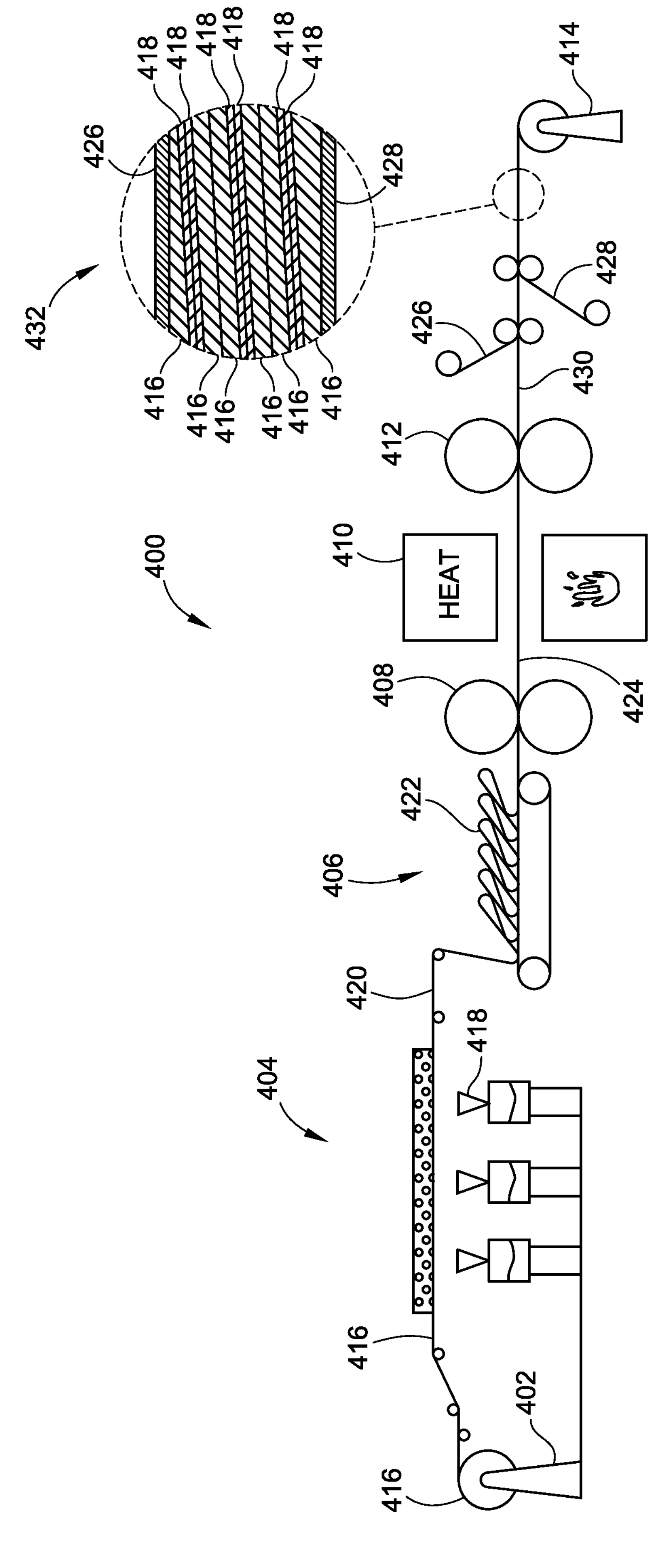
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FIG. 13

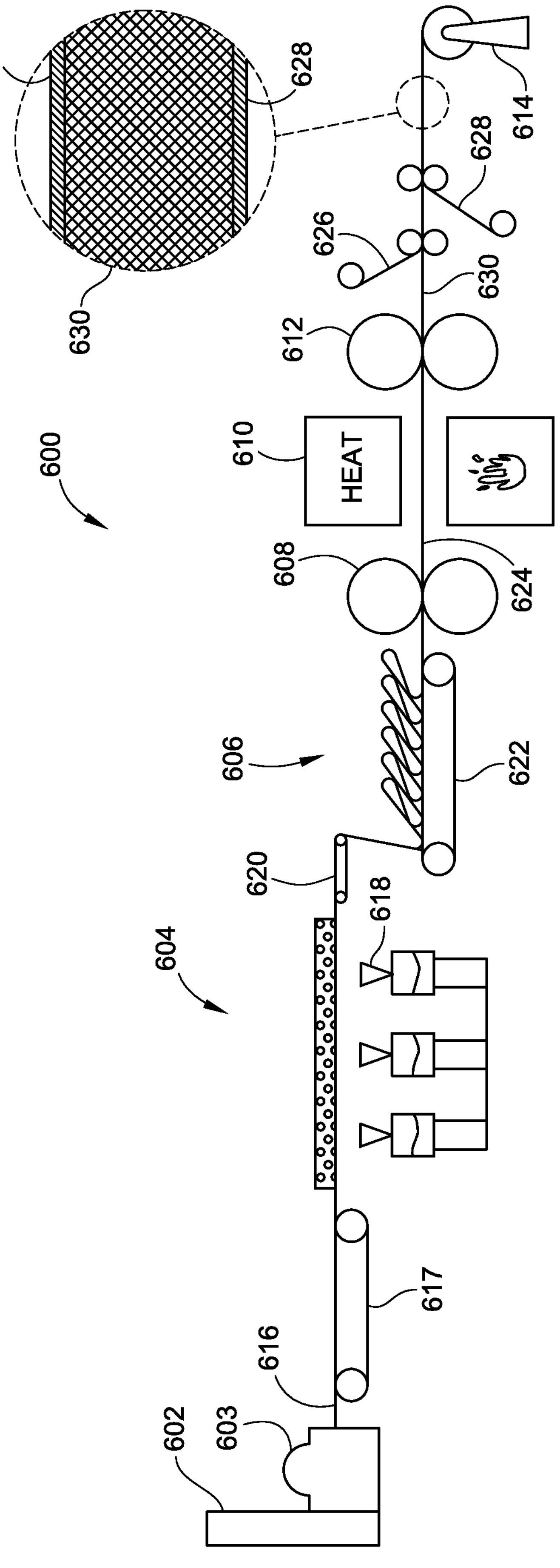
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FIG. 14

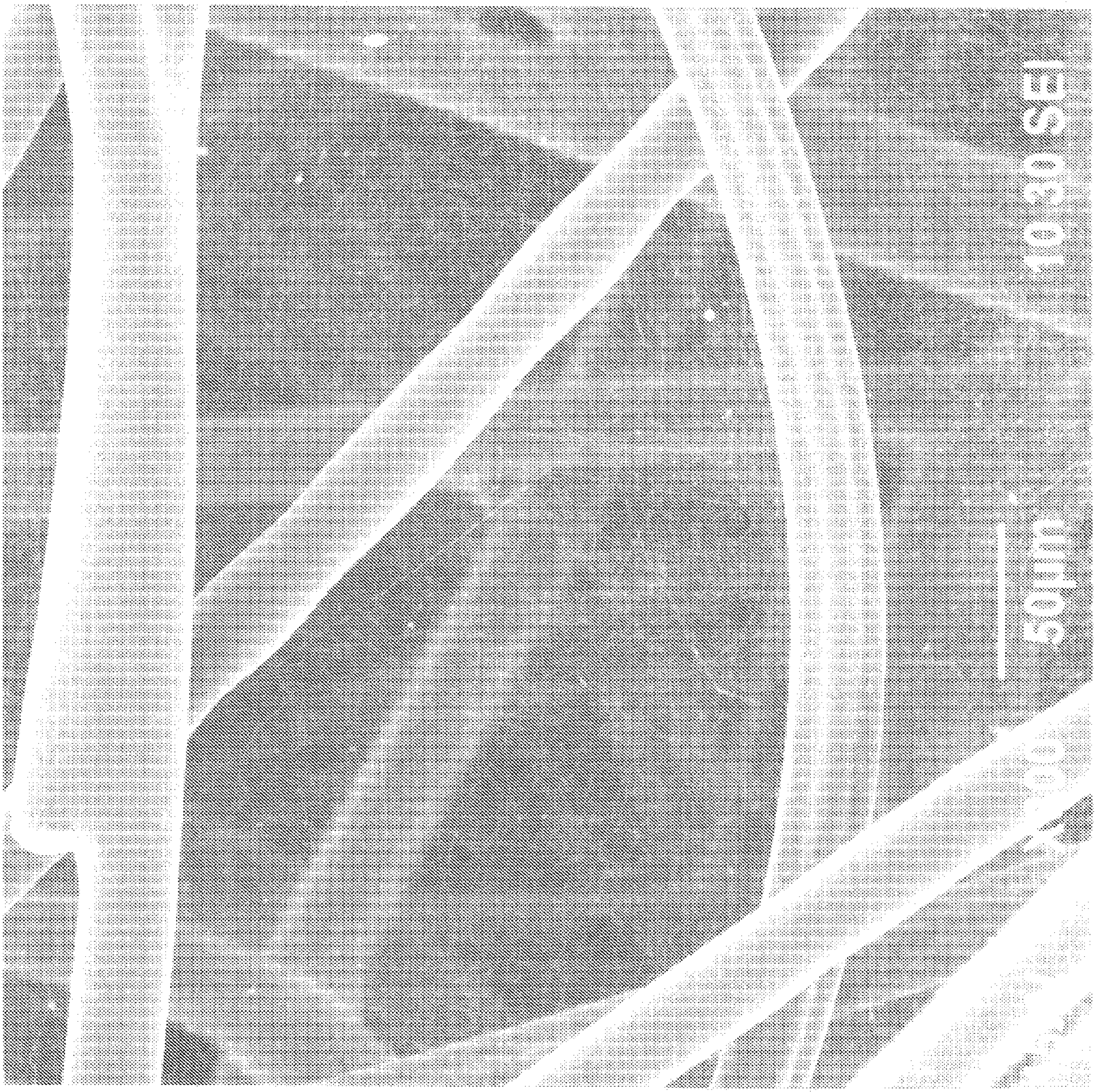

FIG. 15(A)

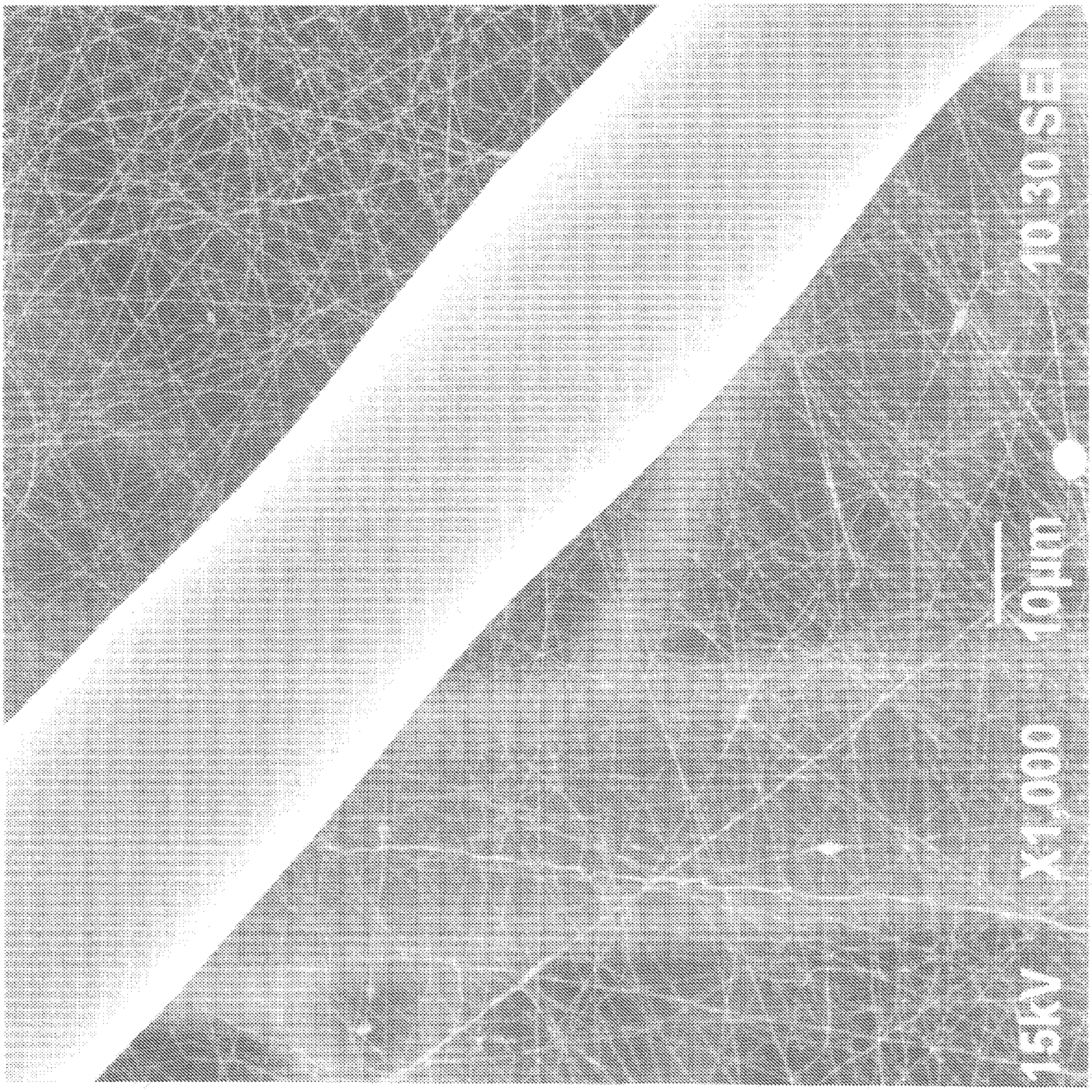

FIG. 15(B)

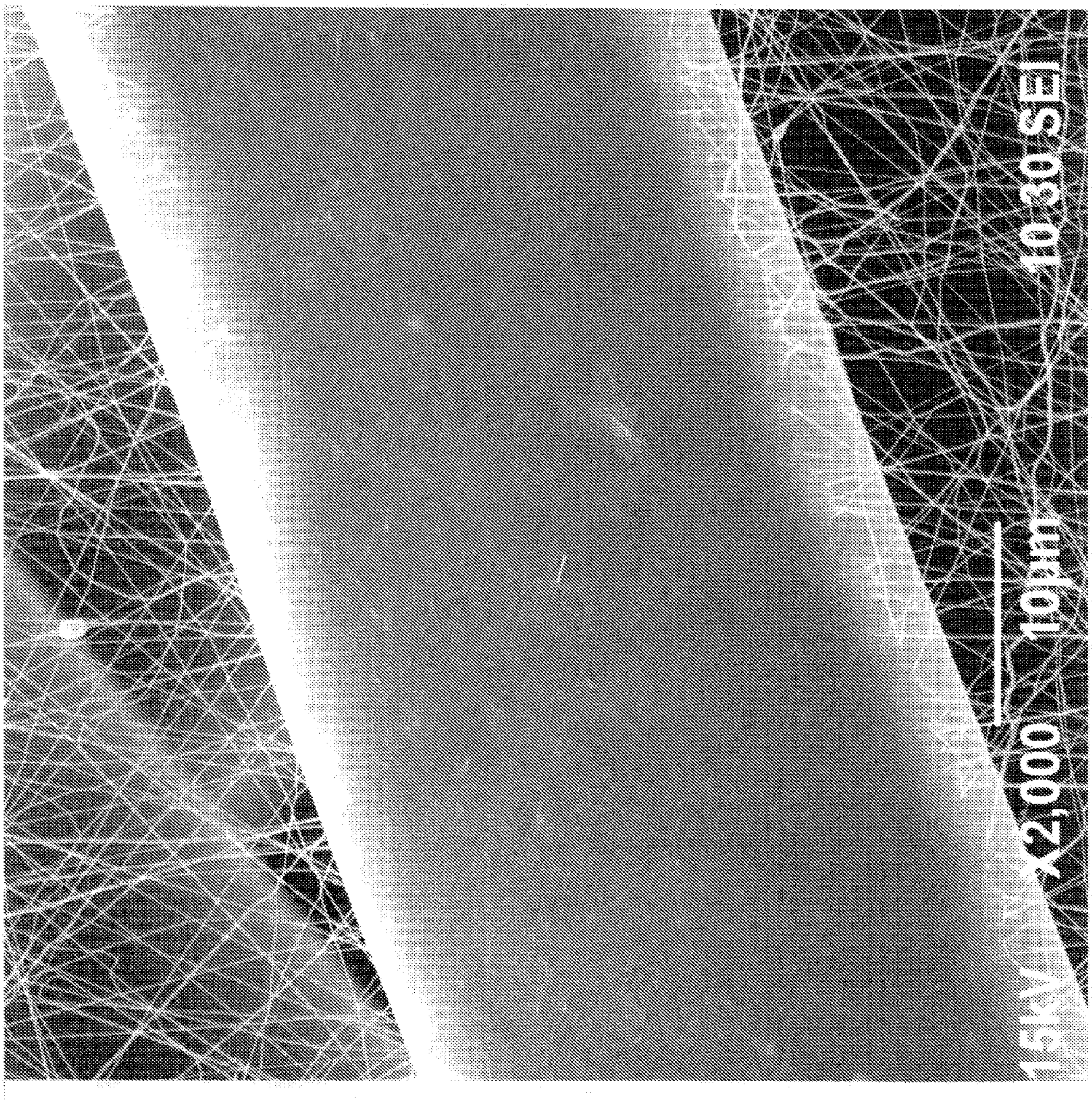

FIG. 15(C)

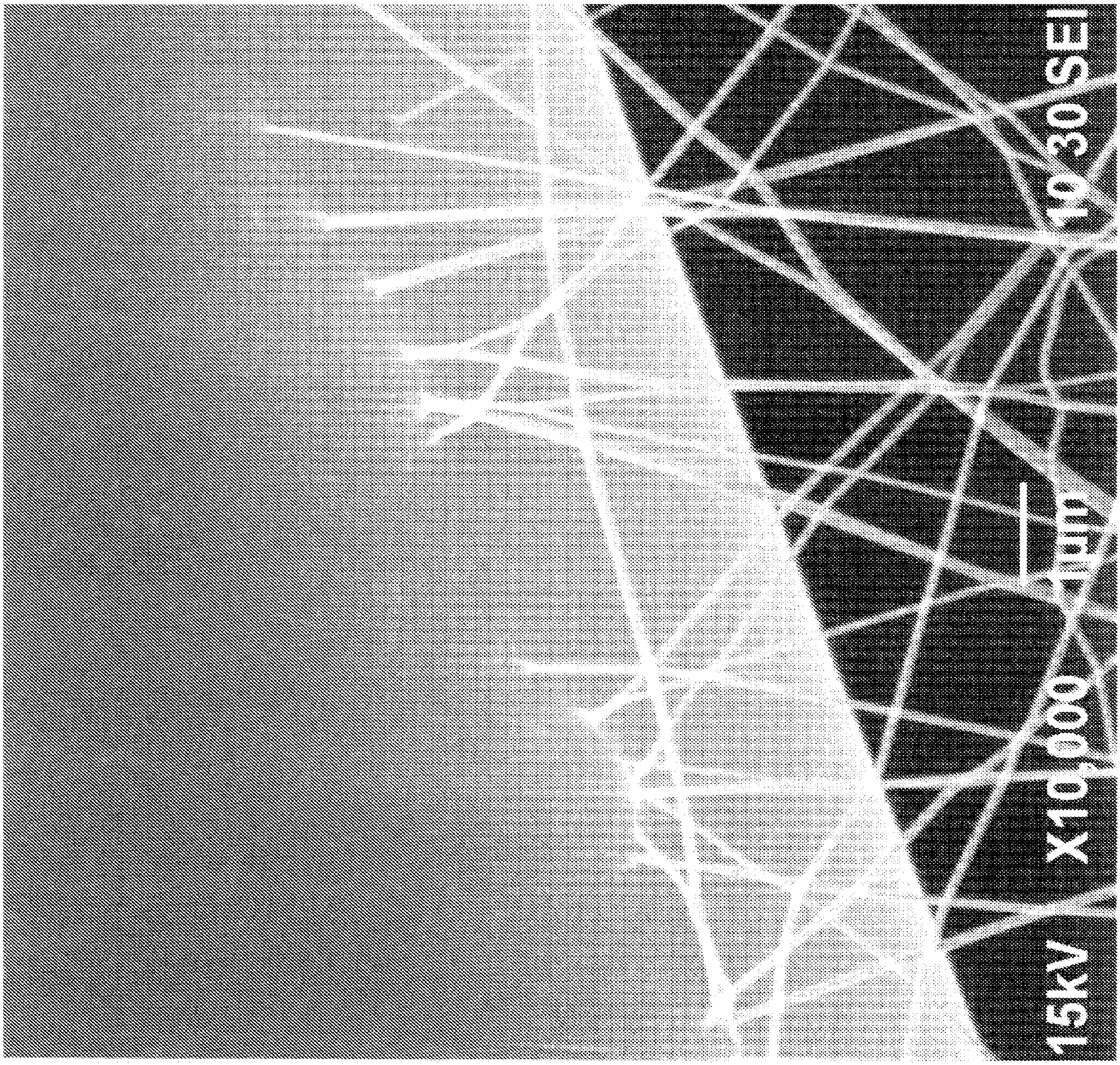

FIG. 15(D)

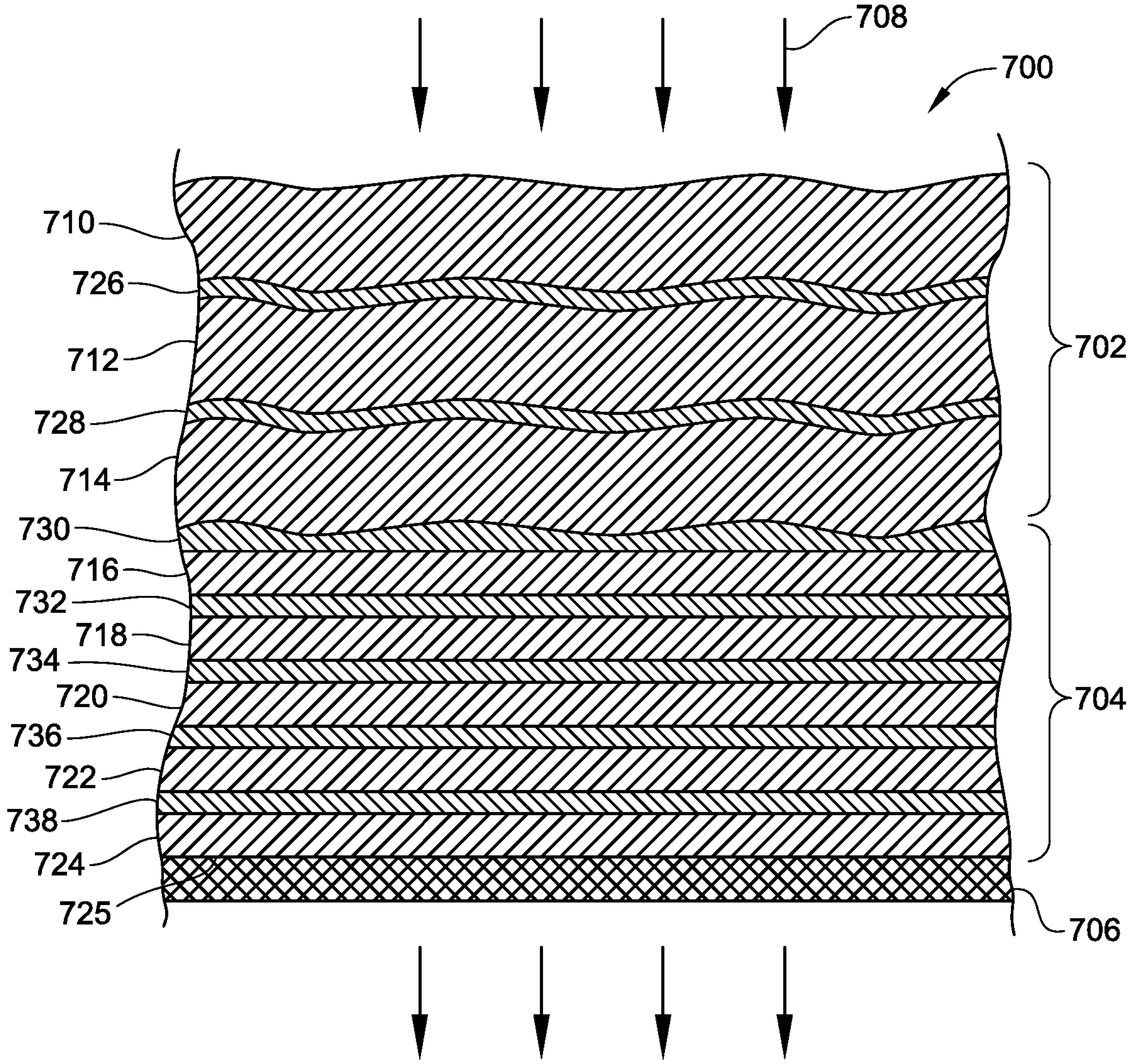
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FIG. 16