(12) STANDARD PATENT (11) Application No. AU 2011220737 B2
(19) AUSTRALIAN PATENT OFFICE

(54) Title
Expanded composite filter media including nanofiber matrix and method

(51) International Patent Classification(s)
B01D 69/10 (2006.01) ***B01D 69/02*** (2006.01)

(21) Application No: **2011220737** (22) Date of Filing: **2011.02.24**

(87) WIPO No: **WO11/106537**

(30) Priority Data

(31) Number	(32) Date	(33) Country
61/383,487	**2010.09.16**	**US**
61/308,488	**2010.02.26**	**US**
61/383,569	**2010.09.16**	**US**
61/330,462	**2010.05.03**	**US**

(43) Publication Date: **2011.09.01**
(44) Accepted Journal Date: **2013.06.27**

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(56) Related Art
US 2008/0314011
US 6649547

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
1 September 2011 (01.09.2011)

PCT

(10) International Publication Number
WO 2011/106537 A3

(51) International Patent Classification:
B01D 69/10 (2006.01) *B01D 69/02* (2006.01)

(21) International Application Number:
PCT/US2011/026093

(22) International Filing Date:
24 February 2011 (24.02.2011)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/308,488 26 February 2010 (26.02.2010) US
61/330,462 3 May 2010 (03.05.2010) US
61/383,569 16 September 2010 (16.09.2010) US
61/383,487 16 September 2010 (16.09.2010) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(88) Date of publication of the international search report:
12 January 2012

(54) Title: EXPANDED COMPOSITE FILTER MEDIA INCLUDING NANOFIBER MATRIX AND METHOD

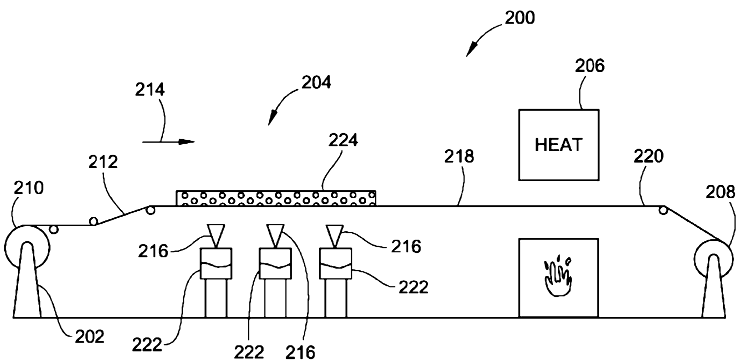

FIG. 14

(57) Abstract: A composite filter media includes an expanded substrate media carrying fine fibers, wherein the fine fibers are extended with the expanding substrate media, thereby improving dust holding capacity and slowing down pressure drop increase.

WO 2011/106537 A3

EXPANDED COMPOSITE FILTER MEDIA INCLUDING NANOFIBER MATRIX AND METHOD

FIELD OF THE INVENTION

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

BACKGROUND OF THE INVENTION

[0002] Fluid streams such as liquid flows and gaseous flows (e.g. air flows) often carry particulates that are often undesirable contaminants entrained in the fluid stream. Filters are commonly employed to remove some or all of the particulates from the fluid stream.

[0003] 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.

[0004] The invention provides improvement in filter media including fine fibers. 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

[0005] Fine fibers, such as and most preferably electrospun nanofibers according to certain embodiments, laid upon a substrate media can be reoriented after laying by modifying the substrate media, such as by modifying the thickness of that substrate media after the fine fibers are deposited. For example, an at least partially compacted substrate media (such as calendared media) can be expanded, in which larger fibers carry with them the smaller fibers thus also expanding the fine fiber layer. As a consequence, several advantages can flow from this, including greater volumetric coverage of nanofibers (more volumetric coverage for a same basis weight application – as the expansion can open up and expand the nanofibers into a 3D matrix); reduced pressure drop due to expansion; and/or slower pressure drop increase as it loads. Additionally, the undulating 3 dimensional characteristics of the nanofiber or other such fine fiber layer greatly increase dust holding capacity as it is believed to effectively create an undulating surface with a much greater volumetric holding area as opposed to merely flat, as in the case of prior systems – thus the effective volumetric area of the nanofiber layer can be increased.

[0006] In one embodiment, the substrate is a bi-component scrim including a high melt component and a low melt component. The fine fibers are electrospun polymer nanofibers. The high melt component and the electrospun polymer nanofibers have a higher melting temperature than the low melt component. The bi-component scrim has an unexpanded state and an expanded state, wherein the expanded bi-component scrim has a thickness greater than the unexpanded state. For example, the scrim in the unexpanded state may be preformed and calendared and thereby or otherwise at least partially compressed in which the fibers held in position in a biased state by being bonded and thereby held to one another (large fiber to fiber bonds holding these large fibers in place). In one embodiment, the unexpanded bi-component scrim carrying the fine fibers is expanded by heating, wherein the low melt component melts or softens and bonds with the fine fibers. During this heating, the larger fibers of the substrate are also freed from at least partially compressed state and allowed to slide about and move back toward a more natural state – such as at least partially toward uncompressed and expanded state (e.g. toward the uncompressed that occurred prior to the formation of the scrim in the first place). During heating, the larger fibers of the bi-component scrim are relaxed and reoriented, carrying the much smaller fine fibers therewith, wherein the fine fibers extend with expanding bi-component scrim. The resulting composite filter media has an undulating surface and an expanded thickness causing the fine fibers to not merely have a planar characteristic as is the case with conventional nanofiber laying techniques, but a 3 dimensional matrix. The expanded filter media has improved dust holding capacity, a slower pressure drop increase as dust loads, and/or lower initial pressure drop.

[0007] In one aspect, the invention provides a method of making a filter media. The method includes steps of depositing fine fibers on a surface of a substrate having a first thickness, the fine fibers having an average diameter of less than 1 micron, and expanding the substrate to a second thickness greater than the first thickness carrying the fine fibers therewith.

[0008] In another aspect, the invention provides a filter media comprising a substrate of first fibers having an average fiber diameter of greater than 1 micron carrying fine fibers having an average fiber diameter of less than 1 micron. The substrate has an undulating surface, wherein the fine fibers are integrated into 3-dimensional matrix with the first fibers of the undulating surface.

[0009] 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

[0010] 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:

[0011] FIG. 1 is a schematic cross-sectional view of an expanded composite filter media having an undulating surface comprising fine fibers carried by a substrate media according to an embodiment of the present invention;

[0012] FIG. 2 is a schematic cross-sectional view of the composite filter media of FIG. 1 in its unexpanded state having a generally flat surface;

[0013] FIG. 3 is a schematic illustration of a concentric sheath/core type bi-component fiber of a substrate media according to an embodiment of the present invention;

[0014] FIG. 4 is a schematic illustration of an eccentric sheath/core type bi-component fiber of a substrate media according to an embodiment of the present invention;

[0015] FIG. 5 is a schematic illustration of a side-by-side type bi-component fiber of a substrate media according to an embodiment of the present invention;

[0016] FIG. 6 is a schematic illustration of a pie wedge type bi-component fiber of a substrate media according to an embodiment of the present invention;

[0017] FIG. 7 is a schematic illustration of a hollow pie wedge type bi-component fiber of a substrate media according to an embodiment of the present invention;

[0018] FIG. 8 is a schematic illustration of an islands/sea type bi-component fiber of a substrate media according to an embodiment of the present invention;

[0019] FIG. 9 is a schematic illustration of a trilobal type bi-component fiber of a substrate media according to an embodiment of the present invention;

[0020] FIG. 10 is a schematic illustration of tipped typed bi-component fiber of a substrate media according to an embodiment of the present invention;

[0021] FIG. 11 is a schematic cross-sectional view of a composite filter media in an unexpanded state according to an embodiment of the present invention;

[0022] FIG. 12 is a schematic cross-sectional view of the composite filter media of FIG. 11 in its expanded stated;

[0023] FIG. 13 is a schematic cross-sectional view of an expanded composite filter media according to a different embodiment of the present invention;

[0024] FIG. 14 is a schematic illustration of a system for making an expanded composite filter media according to an embodiment of the present invention;

[0025] FIG. 15(A) is a Scanning Electron Microscopic image of bi-component fibers and the fine fibers proximate the surface of the substrate media of the expanded composite filter media of FIG. 1 taken at a magnification level x300;

[0026] FIG. 15(B) is a Scanning Electron Microscopic image of bi-component fibers and the fine fibers proximate the surface of the substrate media of the expanded composite filter media of FIG. 1 taken at a magnification level x1,000;

[0027] FIG. 15(C) is a Scanning Electron Microscopic image of bi-component fibers and the fine fibers proximate the surface of the substrate media of the expanded composite filter media of FIG. 1 taken at a magnification level x2,000;

[0028] FIG. 15(D) is a Scanning Electron Microscopic image of bi-component fibers and the fine fibers proximate the surface of the substrate media of the expanded composite filter media of FIG. 1 taken at a magnification level x10,000;

[0029] FIG. 16 is a schematic illustration of a system for making an expanded composite filter media according to another embodiment of the present invention;

[0030] FIG. 17 is a graph showing MFP Efficiency test results of an expanded composite filter media according to an embodiment of the present invention and two other conventional filter medias;

[0031] FIG. 18 is a graph showing MFP Dust Holding test results over a 200 minutes test period of the expanded composite filter media of FIG. 17 and two other conventional filter medias;

[0032] FIG. 19 is a graph showing MFP Dust Holding test results over a 650 minutes test period of the expanded composite filter media of FIG. 17 and two other conventional filter medias;

[0033] FIG. 20 is an optical microscopic image of an unexpanded substrate media in the form of a scrim before heat expansion, taken at a magnification level x120, according to an embodiment of the present invention;

[0034] FIG. 21 is an optical microscopic image of an expanded composite media including two fine fiber coated substrate medias laminated together with the fine fiber layers facing each other, such as the expanded composite media of FIG. 12, taken at a magnification level x120, according to an embodiment of the present invention;

[0035] FIG. 22 is a perspective view of a pleated filter element according to an embodiment of the present invention, wherein the pleated filter media is formed by pleating an expanded composite filer media;

[0036] FIG. 23 is a perspective view of a fluted filter element according to an embodiment of the present invention, wherein the fluted filter media is formed of an expanded composite filter media;

[0037] FIG. 24 is a Scanning Electron Microscopic image taken at a magnification level x2,500 of a composite filter media including two medias coated with fine fibers and laminated together such that the fine fibers are facing each other, according to an embodiment of the present invention; and

[0038] FIG. 25 is a perspective view of a panel filter according to an embodiment of the present invention, wherein the pleated filter media is formed of an expanded composite filter media;

[0039] FIG. 26 is a schematic illustration of a system for making an expanded composite filter media including two layers of fine fiber coated medias laminated together with the fine fibers facing each other, according to an embodiment of the present invention; and

[0040] FIG. 27 is a schematic illustration of a system for making an expanded composite filter media including two layers of fine fiber coated media and another layer of media laminated together with each layer of fine fibers sandwiched between medias, according to an embodiment of the present invention.

[0041] 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

[0042] FIG. 1 is a schematic cross-sectional view of a composite filter media 10 according to an embodiment of the present invention. As shown, the composite filter media 10 comprises a substrate media 12 and fine fibers 14 carried along a surface 16 of the substrate media 12. The composite media 10 has an undulating surface 18, which is illustrated only very schematically in FIG. 1, which is formed by expansion of the substrate media 12.

[0043] To form the expanded composite filter media 10 of FIG. 1, compressed and at least partially compacted media is used as shown in FIG. 2. FIG. 2 is a schematic cross-sectional view of a composite filter media 10 of FIG. 1 in an unexpanded state prior to the expansion, which can also be seen as the fine fibers 14 that have been deposited prior to the expansion.. As shown, the composite filter media 10 has a generally flat surface 20 prior to expansion, wherein the fine fibers 14 form a generally flat layer. The substrate media 12 in the unexpanded state has a thickness t'. When the composite filter media 10 is subjected to the expansion, the thickness of the substrate media 12 expands to t as shown in FIG. 1 and the surface relaxes to form the undulated surface 18 of FIG. 1. In some embodiments, the thickness t can be a least 1.5 times the original thickness, and more preferably nearly doubles or triples or increases even more.

[0044] In one embodiment, the expansion of the filter media 10 is accomplished through a heat treatment, although other relaxants such as a solvent spray (partially soluble to the substrate only), or other processing may be used for relaxing. For example, the scrim in the unexpanded state may be preformed and calendared or otherwise at least partially compressed in which the fibers are held in position in a biased state by being bonded and thereby held to one another (large fiber to large fiber bonds holding these large fibers in place). In one embodiment, the unexpanded bi-component scrim carrying the fine fibers is expanded by heating, wherein the low melt component melts or softens and bonds with the fine fibers. During this heating, the larger fibers of the substrate are also freed from at least partially compressed state and allowed to slide about and move back toward a more natural state – such as at least partially toward uncompressed and expanded state (e.g. toward the uncompressed state that occurred prior to the formation of the scrim in the first place). During the heat treatment, according to certain preferred embodiments, fibers of the substrate media 12 relax and reorient to increase an average distance between the fibers. As such, the substrate media 12 expands, wherein the thickness of the substrate media 12 increases and the surface of the substrate media 12 becomes undulated as opposed to flat in character. Further, as the fibers proximate the surface of the substrate media 12 relax and reorient, the fine fibers 14, which are carried by these fibers move and reorient with the fibers. Thus, fine fibers 14 are extended, pushed and pulled with the larger fibers.

[0045] Now that the composite filter media having an expanded thickness and an undulated surface is generally described, according to an embodiment of the present invention, some of its advantages will be discussed before providing further details and other embodiments of the composite filter media.

[0046] There are several factors that affect characteristics of a filter media. Filter or filtration capacity is the amount of particles that a filter captures during its service life. Generally, a higher filter capacity will provide a longer filter life, which can reduce a frequency of filter change or service. Filter capacity is often related to pressure drop or restriction, when the restriction to the desired fluid flow becomes too high (hence increased pressure drop), a filter needs to be changed to facilitate the desired amount of fluid flow. Pressure drop is related to resistance to a fluid flow created by the filter media. Pressure drop is the pressure differential from the dirty side to the clean side of the media. Generally, the higher the resistance, the greater the energy required and/or higher the pressure drop at a given flow rate. Thus, all other considerations being equal, the filter with a lower pressure drop is preferred. Filter efficiency is the percentage of particles that are removed from a fluid stream by the filter media, and is usually given for a particular particle size or sizes. Of course, it is often desirable to remove more particles from the fluid stream, but at the same time not be overly restrictive to fluid flow. The filter life is a duration before a filter needs to be changed or serviced due to the pressure drop becoming too large or blow-throughs.

[0047] The composite filter media, according to embodiments of the present invention, has an expanded thickness and undulating surface providing a greater filter media volume when compared to the unexpanded filter medias which have not been subjected to an expansion process. As it relates to the nanofiber layer 14 specifically, this is considered a surface loading type layer and by having the area expanded from planar to undulating in nature the effective volumetric area is increased. Thus, based on the expansion, more particles can be captured throughout the increased filter media volume. Further and as discussed above, the fibers of the substrate media and the fine fibers carried thereon are reoriented during the expansion process. Such reorientation of fibers can create improved filter media pore structures to capture particles more efficiently with a less fluid flow resistance. It may also allow a higher coverage level of nanofibers without causing increased resistance because of the nanofiber reorientation. Thus, an expanded composite filter media can improve filter efficiency while maintaining a same level of pressure drop, or lower pressure drop while maintaining a same filter efficiency, when compared to the composite filter media in its unexpanded state. Therefore, the composite filter media having an expanded thickness and an undulating surface can improve the filtration quality by providing an increased dust holding capacity, a reduced pressure drop and/or restriction, and/or a longer filter life.

[0048] Returning to FIGS. 1 and 2, more detailed construction of the composite filter media 10 will now be discussed. The substrate media 12 can be formed of any suitable porous material. Preferably, the substrate media 12 is formed of a multi-component filter media.

[0049] As used herein, the term "multi-component filter media", "multi-component 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.

[0050] In one preferred embodiment, the substrate media 12 is formed of bi-component fibers including two different materials having different melting points. A composite filter media comprising fine fibers and a substrate media 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.

[0051] In this embodiment, one component of the bi-component fibers of substrate 12 has a lower melting point than the other component. The low melt component can be any suitable polymers 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. Preferably, the fibers are compressed to form the substrate media 12 in the form of a web of media or scrim having a certain thickness.

[0052] In one embodiment, the substrate media 12 is a scrim formed of bi-component fibers including 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.

[0053] 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 melt 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.

[0054] The fibers of the substrate media 12 are formed to have a larger average fiber diameter than that of the fine fibers 14. Preferably, the fibers of the substrate media 12 has an average fiber diameter of greater than about 1 micron, and more preferably, greater than 5 micron. In one embodiment, an average diameter of the fibers of the substrate media 12 are between about 1 micron and about 40 micron. In the unexpanded state, the coarser fibers are compressed, for example via a set of calendering rollers, to form the substrate media 12 having a thickness between about 0.05 and 1.0 mm, preferably between about 0.1 and 0.5 mm. Such bi-component fiber substrate media 12 can provide a structural support necessary for the fine fibers 14. Various thicknesses bi-component scrims suitable for the substrate media 12 are commercially available through HDK Industries, Inc. of Rogersville, TN, or other filter media suppliers. Thus, the substrate may be preformed off the shelf bi-component media.

[0055] Other types of bi-component fibers may be used to form the substrate media 12 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.

[0056] 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.

[0057] 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.

[0058] 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.

[0059] 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.

[0060] 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.

[0061] 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.

[0062] The fine fibers 14 can be deposited on the substrate media 12 as they are formed. Alternatively, the fine fibers 14 may be separately prepared as a web of a media, then laminated with the substrate media 12. Although, the fine fibers 14 may comprise fibers having various fiber diameters, preferably, the fine fibers 14 are nanofibers having very fine fiber diameter. Such fine fibers 14 can be formed by electrospinning or other suitable processes. In one embodiment, the fine fibers 14 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 without significantly increasing overall solidity of the filter, thus can increase filter efficiency without increasing pressure drop.

[0063] The fine fibers 14 may be formed by various suitable polymeric materials. In one embodiment, the fine fibers 14 can be formed of nylon-6 (polyamide-6, also referred to as "PA-6" herein) via electrospinning, wherein the electrospun fine fibers 14 are deposited directly on the substrate media 12, although any polymer may be used. To avoid destruction of the fine fibers during heat expansion, the fine fibers 14 are formed of a material having a higher melt temperature than the low-melt polymer of the bi-component.

In this embodiment, the substrate media 12 is 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 between a set of calendering rollers to form a web of scrim. The bonding between the substrate media 12 and the fine fibers 14 may involve solvent bonding, pressure bonding, and/or thermal bonding. In one embodiment, the low melt may be used to bond the fine fibers to the coarser fibers of the substrate, as shown in FIGS. 15A-15D. In this manner, when the coarser substrate fibers are mobilized through the relaxing process and slide around, they carry the more delicate fine fibers therewith which are bonded thereto.

[0064] The composite filter media 10 before expansion has a thickness t' and a substantially flat surface 20 as shown in FIG. 2. This unexpanded composited filter media 10 is heat treated, for example at 250°F for 5 minutes, wherein the compressed fibers of the substrate media 12 are relaxed and reoriented, thereby expanding the substrate media 12. As a result, the thickness of the substrate media 12 expands to t, and the substantially flat surface 20 of FIG. 2 relaxes to form an undulating surface 18 as shown in FIG. 1 – it will be appreciated that the undulated surface will be irregular as opposed to the ordinarily planar nature of a substrate/scrim such as those commercially available. Indeed, filter media rolls typically come in prewound rolls of media that is usually characterized for many medias as generally flat in character. As the coarser substrate fibers proximate, the surface of the substrate media 12 are relaxed and reoriented, the fine fibers 16 carried by these fibers also move with the fibers and are extended and integrated into 3-dimensional matrix with fibers of the undulating surface. Further, the low melt polyester of the bi-component fibers melts or becomes soft during the heat treatment, which allows the adjacent fine fibers to embed in the low melt polyester and enhance bonding between the bi-component fibers and the fine fibers 14.

[0065] In one embodiment, the substrate media 12 is 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 fine fibers 14 have an average fiber diameter between about 0.01 and 0.5 microns and fine fiber coverage between about 0.012 g/m^2 and 0.025 g/m^2. In this embodiment, the expanded composite filter media 10 has a Frazier air permeability between about 100 and 200 CFM; a MFP efficiency equivalent to MERV 11 –

16; and a MFP dust holding weight of about 400 - 600 mg/100 cm^2 with a final pressure drop of about 1.5 inch W.G.

[0066] FIGS. 11 and 12 illustrate a composite filter media 90 according to a different embodiment of the present invention. The composite filter media 90 comprises a media 92 and fine fibers 93 in addition to the substrate media 12 and the fine fibers 14 of the composite filter media 10 of FIG. 2. As shown, the fine fibers 14 and 93 of the composite filter media 90 are sandwiched between the substrate media 12 and the media 92. The media 92 and the substrate media 12 may be formed of a same scrim or filter media or different scrims or filter medias. The composite filter media 90 can be constructed, for example, by laminating two layers of composite filter media 10 of FIG. 2, such that the fine fibers face each other, and expanding the substrate media layers, wherein fine fibers are reoriented with the adjacent substrate media.

[0067] In one embodiment, the substrate media 12 is a scrim formed of low melt polyester/high melt polyester bi-component fibers as described in the previous embodiment. The fine fibers 14 are electrospun nylon-6 nanofibers deposited on the substrate media 12. Similarly, the media 92 is deposited with the electrospun nylon-6 nanofibers forming the fine fibers 93. The substrate media 12 deposited with the fine fibers 14 and the media 92 deposited with the fine fibers 93 are laminated together such that the fine fibers 14 and the fine fibers 93 are facing each other to form the composite filter media 90 of FIG. 11. In this embodiment, the media 92 is formed of the same scrim used for the substrate media 12. The fine fibers 14 and the fine fibers 93 may have a same fine fiber coverage level or different fine fiber coverage levels. For example, the fine fibers 14 has a fine fiber coverage level between about 0.005 g/m^2 and 0.030 g/m^2, preferably between about 0.012 g/m^2 and 0.025 g/m^2. Similarly, the fine fibers 93 has a fine fiber coverage level between about 0.005 g/m^2 and 0.030 g/m^2, preferably between about 0.012 g/m^2 and 0.025 g/m^2. Therefore, when laminated, the two layers of the fine fibers 14, 93 can have a fine fiber coverage level between about 0.010 g/m^2 and 0.060 g/m^2, preferably between about 0.024 g/m^2 and 0.050 g/m^2. The composite filter media 90 may optionally be compressed using a set of rollers to facilitate bonding among layers 12, 14, 93, 92. As shown in FIG. 11, the unexpanded composite filter media 90 has a substantially flat surface 94 and a thickness t''. The unexpanded composite filter media 90 is then heat treated as it was with the previous embodiments. The heat treatment can be performed at or near the melting temperature of the low melt component of the bi-component fibers. In this embodiment, the unexpanded composite filter media 90 is heated to or near the melting temperature of the low melt polyester.

[0068] During the heat treatment, the bi-component fibers of the substrate media 12 and the media 92 are relaxed and reoriented to expand the thickness of the composite filter media 90 to t''' and form an undulating surface 96, as shown in FIG. 12. As the bi-component fibers of the substrate media 12 relax and reorient, the fine fibers 14 also move with the adjacent bi-component fibers of the substrate media 12. Similarly as the bi-component fibers of the media 92 relax and reorient, the fine fibers 93 also move with the adjacent bi-component fibers of media 92.

[0069] Such composite filter media 90 having an expanded thickness and an undulating surface can have superior dust holding capability and reduced pressure drop when compared to the unexpanded composite filter media or other conventional filter medias. Further, the increased filter media volume due to the filter media expansion via the relaxation make the expanded composite filter media 90 (FIG. 12) well suited for a depth filter media having improved dust holding capacity and lower pressure drop, wherein more particles can be trapped throughout the increased volume of the composite filter media 90, and the fine fiber layer can in large part set a maximum particle capture efficiency without being unduly restrictive.

[0070] While FIGS. 11 and 12 are schematic, FIGS. 20-21 show actual optical microscopic images of a substrate media and an expanded composite filter media taken at x120 magnification. FIG. 20 is an optical microscopic image of a substrate media, such as the medias 12 and 92 of FIG. 11, before the fine fiber deposition and expansion. FIG. 21 is an optical microscopic image of an expanded composite filter media, wherein two samples of the media of FIG. 20 are deposited with fine fibers and laminated such that the fine fibers on the two sample medias are facing each other, such as the expanded composite filter media 90 shown in FIG. 12. While the composite filter media of FIG. 21 includes fine fibers, at this magnification of the image, only the coarse fibers of the media layers can be seen. The fine fibers are much smaller and carried by the coarser fibers, which can be seen with reference to FIG. 24, which is a Scanning Electron Microscopic image of a composite filter media taken at a magnification level x2,500. In FIG. 24, the fine fibers coated on one media layer are in focus in the image, while the fine fibers coated on the other media layer are out of focus in the image. The two layers of fine fiber coated medias are laminated with the fine fibers facing each other, and heat expanded to form an expanded composite filter media.

[0071] Depth filter medias load particulates substantially throughout the volume or depth, and thus, the depth medias can be loaded with a higher weight and volume of particulates as compare with surface loading systems over the lifespan of the filter. Usually, however, depth media arrangements suffer from efficiency drawbacks. To facilitate such high holding capacity, a low solidity of media is often chosen for use. This results in large pore sizes that have the potential to allow some particulates to pass more readily. The expanded composite filter media according to embodiments of the present invention can provide superior dust holding capability and filtration efficiency while maintaining a same low level of pressure drop via expanded media and fine fibers.

[0072] In other embodiments, an expanded composite filter media can include multiple layers of fine fibers and multiple filter layers. FIG. 13 shows a composite filter media 100 comprising two layers of fine fibers 16, 102, sandwiched between three filter layers 12, 92, 104, according to an embodiment of the present invention. The filter layers 12, 92, 104 may be formed of a same filter media or scrim, such as the low melt polyester/high melt polyester bi-component fiber scrim of the previous embodiments. Alternatively, the filter layers 12, 92, 104 may be formed of different filter medias or scrims depending on desired filter media characteristics. When the different filter medias or scrims are used to form the filter layers 12, 92, 104, fibers of the filter layers 12, 92, 104 may relax and reorient differently during the expansion. As such, the filter layers 12, 92, 104 may expand differently. For example, a thickness of the filter layers 12 and 92 may double, while a thickness of the filter layer 104 may not increase or increase very slightly.

[0073] Further, the fine fiber layers 16, 102 may include a same amount of fine fibers or different amount of fine fibers. The materials of the filter layers 12, 92, 104 and the amount of fine fibers of the fine fiber layers 16, 102 can be selected to create a gradient depth media. For example, filter layers 12, 92, 104 can be formed of the bi-component fiber scrim similar to the bi-component scrim used for the substrate media 12 and the filter layer 92 of the previous embodiments. However, the bi-component fiber scrim of the filter layer 104 can have less solid density, and thereby less filtration efficiency, than the scrim selected for the filter layer 92. Further, the scrim selected for the substrate media 12 can have more solid density than the scrim used for the filter layer 92. Further, the fine fiber layer 16 can be formed to include more fine fibers than the fine fiber layer 102. For example, the fine fiber layer 102 can be formed to include electrospun fine fibers of PA-6 at about 0.015 g/m^2, while the fine fiber layer 16 is formed to include electrospun fine fibers of PA-6 at about 0.025 g/m^2. Preferably, each of the fine fiber layer(s) in the various embodiments has a nanofiber coverage level between about 0.005 g/m^2 and 0.030 g/m^2, and more preferably between about 0.012 g/m^2 and 0.025 g/m^2. It should be noted that due to the reorientation of fibers after the deposition/coverage into an undulating 3D matrix, much more fine fibers can be deposited (greater fine fiber coverage or basis weight) without unduly causing restriction or pressure drop issues, and in fact the reverse is true due to the greater effective volumetric area as a result of the expansion. Such gradient composite filter media 100 can allow more dust particles to be loaded throughout the thickness of the composite filter media 100.

[0074] In an embodiment, the composite filter media 100 in its unexpanded state includes the filter layers 12, 92, 104 formed of a bi-component fiber scrim having a thickness of about 0.005" and the fine fiber layers 16, 102 comprising electrospun PA-6 nanofibers at a coverage level of about 0.019 g/m^2. The unexpanded composite filter media 100 has a total thickness of about 0.015". After the heat expansion, the thickness of the each of the filter layers 12, 92, 104 can increase about 2 to 3 times or even higher, thereby providing the expanded composite filter media 100 having the total thickness of 0.030" or 0.045" or higher.

[0075] Other configurations of the expanded composite filter media may be beneficial to different filtration applications to optimize dust holding and pressure drop characteristics. In other embodiments, an expanded composite filter media may include more than three filter layers and more than two fine fiber layers configured in various orders.

[0076] Additionally, after the expansion of the media resulting in the reorientation of fine fibers, the expanded composite filter media may then be configured into a filter element with a gathered configuration such as a fluted filter or a pleated filter or other such typical filter element arrangement. Such gathered filter arrangements may be in the form of a cylindrical or oval element with end caps, frames and the like and often times with an annular sealing gasket as indicated in some of the patents incorporated by reference herein. This media may also be incorporated into such filter elements. Further, the expanded composite filter media can be pleated and used in a panel filter.

[0077] FIG. 22 shows a pleated filter element 300 including a pleated filter media 302 wound about a cylindrical core 304, and end caps 306, 308 attached to each end, according to an embodiment of the present invention. The pleated filter media 302 can be formed by pleating an expanded composite filter media having an undulating surface, such as the expanded filter medias of FIGS. 1, 12 and 13. Such pleated filter element is disclosed in U.S. Patent No. 4,184,966, the teachings and disclosures of which are hereby incorporated by reference in its entirety to the extent not inconsistent with the present invention.

[0078] FIG. 23 shows a fluted filter element 320 according to a different embodiment of the present invention. The fluted filter element includes a frame 324, a filter media seal 326, an annular seal 328, and a fluted filter media 330. The fluted filter media 330 includes a face sheet and a convoluted sheet secured together and wound about a center frame 332 to define a plurality of flutes 334 including first flutes closed proximate one face and second flutes closed proximate the other face. In this embodiment the face sheet and/or the convoluted sheet can be formed of an expanded composite filter media having an undulating surface, such as the expanded composite filter medias of FIGS. 1, 12 and 13. Such fluted filter element is disclosed in U.S. Patent Application Publication No. 2009-0320424, Filter Frame Attachment and Fluted Filter Having Same, assigned to the present assignee, the teachings and disclosures of which are hereby incorporated by reference in its entirety to the extent not inconsistent with the present disclosure.

[0079] FIG. 25 shows a panel filter 350 according to an embodiment of the present invention. The filter media 352 comprises an expanded composite filter media such as the expanded composite filter media 90 shown in FIG. 12. The expanded composite filter media is pleated to form the filter media 352, which is enclosed in a frame 354 to form the panel filter 350.

[0080] Now that different embodiments of the expanded composite filter media, according to the present invention are described, methods of forming the expanded composite filter media will be explained.

[0081] FIG. 14 schematically illustrates a representative process of making an expanded composite filter media, which may produce any of the embodiments discussed above, according to a processing embodiment of the present invention. The system 200 include an unwinding station 202, an electrospinning station 204, a heat treatment station 206 and a rewinding station 208.

[0082] In the system 200, a roll of scrim 210 is unwound from the unwinding station 202. In one embodiment, the roll of scrim 210 is formed of high melt polyester core/low melt polyester sheath bi-component staple fibers, which were already compressed via a set of calendering rollers to form the roll of scrim 210 having a desired thickness and solidity. The web of scrim 212 travels in a machine direction 214 toward the electrospinning station 204. In the electrospinning station 204, fine fibers 216 are formed and deposited on the web of scrim 212 to form a composite filer media 218. The composite filer media 218 then enters the heat treatment station 206, wherein the composite filter media 218 is heated to or near a melting temperature of the low melt polyester. During the heat treatment, the composite filter media 218 relaxes and expands to form an expanded composite filter media 220, which is rewound on the rewinding station 208. The bonding between the web of scrim 212 and the fine fibers 216 is also enhanced during the heat treatment. Each component of the system 200 is discussed in detail below.

[0083] The scrim may be formed in an upstream process of the system 200 (and either part of a continuous 1 line process or interrupted 2 line process) or may be purchased in a roll form from a suitable 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. Alternatively, the media may be other single component media that may be compressed and held in place via a solvent bond, heat bond or the like. 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 considered a substrate). The web of fibers is then compressed using a set of calendering rollers to form the roll of scrim 210 (also which can be considered 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.

[0084] 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.

[0085] 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.

[0086] 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.

[0087] In yet another embodiment, the multi-component filter media is web-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.

[0088] Referring back to FIG. 14, the web of scrim 212 enters the electrospinning station 204, wherein the fine fibers 216 are formed and deposited on the web of 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).

[0089] 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 a small diameter filaments. An average diameter of fibers may be controlled by the design of eletrospinning cells 222 and formulation of polymeric solutions.

[0090] 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 polyamide, which is also commonly known as nylon-6. Reference can be had to the aforementioned patents for further details on electrospinning of fine fibers.

[0091] In the system 200, 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. 14, 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 web of the scrim 212 in the machine direction 214. As configured, the web of 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 web of scrim 212. In embodiments, wherein the web of 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.

[0092] In one 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 the surface of the web of scrim 212. As the fine fibers 216 are deposited on the surface of the web of scrim 212, some fine fibers 216 entangle with fibers of the scrim proximate the surface facing the electrospinning cells 222. When some fine fibers 216 entangle with some fibers proximate the surface of the scrim, some solvent remaining in the fine fibers 216 from the electrospinning process can effectuate a solvent bonding between the fine fibers 216 and the fibers of the web of scrim 212. To effectuate the solvent bonding, the fibers of the web of scrim 212 need to be soluble or at least react with the solvent in the fine fibers. A cross-sectional view of the composite filter media 218 formed in the electrospinning station 202 may look like the unexpanded composite filter media 10 of FIG. 2.

[0093] Upon exiting the electrospinning station 206, the composite filter media 218 proceeds to an expansion process. In this embodiment, the expansion of the composite filter media 218 is accomplished in the heat treatment station 206. The heat treatment station 206 can be any suitable conventional oven such as a convection oven, or a heating device utilizing other suitable types of heating mechanism such as an infrared oven. Wherein the scrim 212 comprises high melt/low melt bi-component fibers, the composite filter media 218 is heated to or near a melting temperature of the low melt polymer component of the bi-component fibers. As the bi-component fibers of the scrim 212 are heated to or near the melting temperature of the low melt polymer component, the bi-component fibers relax and reposition. Some bi-component fibers, such as the eccentric sheath/core type bi-component fibers of FIG. 4, may curl and twist in various directions when subjected to the heat treatment. Further, the bi-component fibers which were compressed together during the forming of the scrim, for example via a set of calendering rollers, are decompressed as the heat releases the compressive force and allows the bi-component fibers to reposition to increase an average distance between the fibers. As such, the web of scrim 212 expands in its thickness and becomes wavy to form an undulating surface.

[0094] Further, as the bi-component fibers proximate the surface carrying the fine fibers 216 move and reorient, the fine fibers 216 also move with the bi-component fibers. As discussed above, the fine fibers 216 are deposited on the surface of the web of scrim 212, wherein some fine fibers 216 come in contact with the bi-component fibers proximate the surface of the web of scrim 212 and may be bonded via solvent bonding. The bonding between bi-component fibers and the fine fibers 216 is enhanced during the heat treatment as the outer low melt polymer component of the bi-component fibers softens or melts and embeds the fine fibers 216. 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 filter 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 web of 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.

[0095] FIGS. 15(A)-15(D) are Scanning Electron Microscopic (SEM) images of the bi-component fibers of scrim 212 and the fine fibers 216 proximate the surface of the web of 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 fine fibers 216 which are embedded on the surface of the bi-component fibers move with the bi-component fibers as the bi-component fibers are relaxed and reoriented during the heat treatment. The bi-component fibers may curl, twist and move in different directions as the bi-component fibers are heated. Some bi-component fibers carrying the fine fibers 216 may move outwardly expanding the surface while some bi-component carrying the fine fibers 216 may stay at the original surface level or even move inwardly in the opposite direction. As such, the substantially flat surface of the composite filter media 218 becomes undulated as the fibers orient during the heat treatment. Further, the fined fibers 216 which were deposited at the surface level of the scrim 212 are extended as they move with the bi-component fibers, thereby increasing the depth of the fine fibers 216 integration into the web of scrim 212 as the composite filter media 218 expands during the heat treatment. The reorientation of the bi-component fibers and the fine fibers 216 can also improve overall pore structure of the expanded composite filter media 218. Therefore, the decrease in percent solid due to the expansion (same amount of fibers with increased volume) and the improved pore structure of the expanded composite filter media 218 provide improved filter capacity and a slower pressure drop increase. The expanded composite filter media 220 may resemble the expanded composite filter media of FIG. 1 having the undulating surface and the expanded thickness.

[0097] In some embodiments, the expanded composite filter media 220 may be processed through a set of rollers downstream of the heat treatment station. A small amount of pressure may be applied to the expanded composite filter media 220 to facilitate adhesion between the fine fibers 216 and the substrate scrim 212 and/or to slightly reduce the thickness the composite filter media 220 to a desired thickness. However, the expanded composite filter media 220 substantially retains the undulating surface and the expanded thickness from the heat treatment through the set of rollers.

[0098] FIG. 16 schematically illustrates a system 230 for making an expanded composite filter media according to a different embodiment of the present invention. The system 230 includes an equipment 232 for forming a substrate media 236, an equipment 234 for forming a filter layer 238, an electrospinning station 240, a set of rollers 242, a heat treatment station 244 and an rewinding station 252.

[0100] The substrate media 236 and the filter layer 238 may be formed of various suitable materials and methods. Further, the substrate media 236 and the filter layer 238 may be formed of a same filter media or scrim, or different filter medias or scrims. In one embodiment, the substrate media 236 and the filter layer 238 are formed of a same bi-component fiber scrim. In this embodiment, bi-component staple fibers comprising a high melt polyester core and a low melt polyester sheath are formed in to a web of scrim having a desired thickness and width in the equipment 232 and the equipment 234.

[0101] The substrate media 236 comprising the bi-component fiber scrim enters the electrospinning station 240, wherein PA-6 nanofibers 254 are formed and deposited on the surface of the substrate media 236 in the manner described for the electrospinning station 204 of FIG. 14. The substrate media 236 carrying the fine fibers 254 is then laminated with the filter layer 238 via the set of rollers 242. As shown, the filter layer 238 is laminated on the fine fiber deposited side of the composite filter media 246. The set of rollers 242 may apply a desired amount of pressure to enhance bonding between the fine fibers 254 and the substrate media 236 and bonding between the fine fibers 254 and the filter layer 238. The composite filter media 248 exiting the set of rollers 242 may look like the unexpanded composite filter media 90 of FIG. 11.

[0102] The composite filter media 248 then enters the heat treatment station 244. In the heat treatment station 244, the composite filter media 248 is heated to or near the melting point of the low melt polyester component of the bi-component fibers. The bi-component fibers of the substrate media 236 and the filter 238 relax and reorient as described above with regard to the embodiment of FIG. 14. As discussed above, the fine fibers 254 are also reoriented with the bi-component fibers. The expanded composite filter media 250 exiting the heat treatment station 244 may look like the expanded composite filter media of FIG. 12. The expanded composite filter media 250 has an expanded thickness and an undulating surface. Finally, the expanded composite filter media 250 is wound into a roll in the rewinding station 252. In some embodiments, the expanded composite filter media 250 may be processed through a set of rollers downstream of the heat treatment station. A small amount of pressure may be applied to the expanded composite filter media 250 to facilitate adhesion between different layers and/or to slightly reduce the thickness the composite filter media 250 to a desired thickness. However, the expanded composite filter media 250 substantially retains the undulating surface and the expanded thickness from the heat treatment through the set of rollers.

[0103] FIG. 26 schematically shows a system 400 for making an expanded composite filter media according to a different embodiment of the present invention. The system 400 includes two unwind stations 402, 404, an oven 406, and a rewind station 408. A roll of fine fiber coated media 410 including a substrate media 414 and fine fibers 418 is unwound from the unwind station 402 with the fine fibers 418 facing fine fibers 420 of a fine fiber coated media 412. The roll of fine fiber coated media 412 including a substrate media 416 and fine fibers 420 is unwound from the unwind station 404 with the fine fibers 420 facing the fine fibers 418. The fine fibers 418, 420 are deposited on the substrate media 414, 416 via an electrospinning method such as the electrospinning method described in the system 200 of FIG. 14. In this embodiment, the fine fibers 418, 420 are electrospun nylon-6 nanofibers described in the previous embodiments. The substrate medias 414, 416 comprise the bi-component fiber scrim including high melt polyester/low melt polyester fibers, which is described in the previous embodiments.

[0104] Two layers of the fine fiber coated medias 410, 412 are laminated together between a set of rollers 422, wherein a pressure is applied to facilitate adhesion between layers 414, 418, 420, 416. In some embodiments, the set of rollers 422 may be heated to enhance adhesion between layer 414, 418, 420, 416. The laminated composite filter media 424, before entering the oven 406, looks similar the unexpanded composite filter media 90 shown in FIG. 11. The composite filter media 424 enters the oven 406. In the oven, the composite filter media 424 is heated to or near a melting point of the low melt polyester, wherein the substrate medias 414, 416 expand as described in the previous embodiments. As the substrate media 414 expands, the fine fibers 418 carried by the coarse bi-component fibers of the substrate media 414 also move and reorient into a 3-dimensional matrix. Similarly, as the substrate 416 expands, the fine fibers 420 carried by the coarse bi-component fibers of the substrate media 416 move and reorient into a 3-dimensional matrix. Further, as the composite filter media 424 is heated, a thermal bonding can be effectuated to enhance adhesion between layers 414, 418, 420, 416. After heat expansion in the oven 406, the expanded composite filter media 426 looks similar to the expanded composite filter media 90 of FIG. 12, wherein the fine fiber layers 418, 420 are laminated facing each other. The expanded composite filter media 426 is wound into a roll on the rewind station 408.

[0105] FIG. 27. schematically illustrates a system 430 for making an expanded composite filter media according to yet another embodiment of the present invention. The system 430 includes three unwind stations 432, 434, 436, an oven 438, and a rewind station 440. A roll of fine fiber coated media 442 including a substrate media 448 and fine fibers 452 is unwound from the unwind station 432 with the fine fibers 452 facing a substrate media 450 of a roll of fine fiber coated media 444. The roll of fine fibers coated media 444 including a substrate layer 450 and fine fibers 454 is unwound from the unwind station 434 with the substrate layer 450 facing the fine fibers 452. The fine fiber coated media 442 and the fine fiber coated media 444 are laminated between a set of rollers 456, wherein a pressure is applied to facilitate adhesion between layers 448, 452, 450, 454. The set of rollers 456 may be heated to enhance adhesion between layers 448, 452, 450, 454 via a thermal bonding. A roll of media 446 is unwound from the unwind station 436 and laminated on top of the fine fibers 454 via a set of rollers 458. A further pressure may be applied by the set of rollers 458 to facilitate lamination between layers. The set of rollers 458 may also be heated to enhance adhesion between layers 448, 452, 450, 454, 446.

[0106] The fine fibers 452, 454 are deposited on the substrate media 448, 450 via an electrospinning method such as the electrospinning method described in the system 200 of FIG. 14. In this embodiment, the fine fibers 452, 454 are electrospun nylon-6 nanofibers described in the previous embodiments. The substrate medias 448, 450, and the media 446 comprise the bi-component fiber scrim including high melt polyester/low melt polyester fibers, which is described in the previous embodiments. The laminated composite filter media 460 including three layers of media 446, 448 450, and two layers of fine fibers 452, 454 enters the oven 438, wherein the composite filter media 460 expands via heat as described in the previous embodiments. As the composite filter media 460 is heated in the oven 438, a thermal bonding can be effectuated to improve adhesion between layers 448, 452, 450, 454, 446. The expanded composite filter media 464 upon exiting the oven 438 looks similar to the expanded composite filter media 100 shown in FIG. 13. The expanded composite filter media 462 is wound into a roll in the rewind station 440.

[0107] EXAMPLES AND TEST RESULTS

[0108] Test samples for the expanded composite filter media 100 of FIG. 13 according to an embodiment of the present invention were prepared in a laboratory. A bi-component fiber scrim comprising a high melt polyester core and a low melt polyester sheath having a basis weight of 1.25 OSY was used for the substrate media 12, the filter layer 92 and the filter layer 104.

[0109] The fine fibers were formed via an electrospinning process from a polymeric solution comprising PA-6. The PA-6 nanofibers were formed and deposited on the bi-component fiber scrim at a coverage level of about 0.019g/m^2. Two layers of such bi-component fiber scrim carrying the fine fibers and an uncoated bi-component fiber scrim were laminated together, such that the fine fibers are sandwiched between the bi-component fiber scrim layers as shown in FIG. 13. Then the composite filter media test samples were heated in an oven at about 250°F for about 5 min.

[0110] The samples were tested for efficiency and dust holding capacity, and the test results of the samples were compared with that of other comparable filter medias available in the market. The test protocols for MFP Dust Holding test were: ISO Fine test dust at a concentration of 140mg/m^3, sample size of 100^{2}cm, face velocity 10cm/s. The test protocols for MFP Efficiency test were: ISO Fine test dust at a concentration of 70mg/m^3, sample size of 100^{2}cm, face velocity 20cm/s. FIGS. 17-19 show the efficiency and dust holding test results of the composite test samples compared to two comparable filter medias available through Lydall Inc. (Lydall MERV 14 Grade SC8100 and Lydall MERV 11 Grade SC8110.)

[0111] As shown in FIG. 17, the composite media test sample (CLC Media) performed superior in the efficiency test than Lydall SC8110 and performed very close to Lydall SC8100. However, the composite media test samples (CLC Media Sample 1 and CLC Media Sample 2) performed much better in the dust holding test exhibiting lower pressure drop over the test periods as shown in FIGS. 18 and 19.

[0112] 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.

[0113] 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.

[0114] 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 making a filter media, comprising:

depositing fine fibers on a surface of a substrate having a first thickness, the fine fibers having an average diameter of less than 1 micron; and

expanding the substrate to a second thickness greater than the first thickness carrying the fine fibers therewith.

2. The method of claim 1, further comprising forming the substrate, wherein multi-component fibers having a low melt polymer component and a high melt polymer component are compressed to form the substrate having the first thickness.

3. The method of claim 2, wherein depositing fine fibers comprises electrospinning the fine fibers and depositing the fine fibers directly on the surface of the substrate, wherein some of the fine fibers are attached to some of the multi-component fibers proximate the surface of the substrate.

4. The method of claim 3, electrospinning the fine fibers involves depositing the fine fibers on the surface of the substrate to obtain a fine fiber coverage between about 0.012 g/m^2 and 0.025 g/m^2.

5. The method of claim 3, wherein expanding comprises heating the filter media, wherein the multi-component fibers of the substrate relax and reorient, thereby expanding the substrate to the second thickness and forming an undulating surface; wherein the fine fibers are extended as the fine fibers move with the multi-component fibers carrying the fine fibers, wherein the fine fibers are integrated into 3-dimensional matrix with multi-component fibers of the undulating surface.

6. The method of claim 5, wherein heating comprises heating the filter media to about a melting temperature of the low melt polymer component, wherein the low melt polymer component melts or softens, wherein some of the fine fibers are embedded in the melted or softened low melt polymer component.

7. The method of claim 1, wherein the second thickness is at least 1.5 times the first thickness after expansion.

8. The method of claim 1, wherein the second thickness is at least double the first thickness after expansion.

9. The method of claim 1, further comprising laminating a filter layer such that the fine fibers are sandwiched between the substrate media and the filter layer, wherein the filter media comprising the substrate media, fine fibers and the filter layer is heated, wherein the substrate and filter layer expand and the fine fibers are extended.

10. The method of claim 1, further comprising laminating multiple layers of the substrate carrying the fine fibers and a filter layer, such that each layer of the fine fibers is sandwiched between the substrates or between the substrate and the filter layer; wherein the laminated layers are heated, wherein the substrates and the filter layer expand, and fine fibers are extended and integrated within undulating surfaces of the substrates.

11. A filter media comprising:

a substrate of first fibers having an average fiber diameter of greater than 1 micron carrying fine fibers having an average fiber diameter of less than 1 micron, the substrate having an undulating surface such that the fine fibers are integrated into 3-dimensional matrix with the first fibers of the undulating surface.

12. The filter media of claim 11, wherein the substrate is an expanded scrim comprising multi-component fibers, the expanded scrim having a first unexpanded state, the scrim in the first unexpanded state having a generally flat surface and a thickness less than that of the expanded scrim, the undulating surface being formed during an expansion from the first expansion state to the expanded scrim.

13. The filter media of claim 12, wherein the multi-component fibers include a first component and a second component, wherein the first component has a higher melting temperature than the second component; wherein the fine fibers are attached to the multi-component fibers of the undulating surface via the second component.

14. The filter media of claim 13, wherein the first component is formed of a high melt polyester and the second component is formed of a low melt polyester; wherein the fine fibers are electrospun polyamide nanofibers.

15. The filter media of claim 12, wherein the scrim carries the fine fibers on or proximate a surface level in the first unexpanded state, wherein the first fibers are reoriented in the expanded scrim, the first fibers carrying and extending the fine fibers therewith; wherein fine fibers are integrated beyond the surface level to a greater depth in the expanded scrim than in the unexpanded state.

16. The filter media of claim 15, wherein the filter media including the expanded scrim has a higher dust holding capacity and a slower pressure drop increase than the filter media including the scrim in the first unexpanded state.

17. The filter media of claim 11, further including a scrim, wherein the fine fibers are laminated between the substrate and the scrim.

18. The filter media of claim 11, wherein the filter media comprises multiple layers of the substrate carrying the fine fibers; and further comprising a scrim; wherein the each layer of the fine fibers are sandwiched between layers of the substrate or the substrate and the scrim.

19. The filter media of claim 18, wherein each layer of the substrate is formed of a multi-component scrim comprising a multi-component fibers, the multi-component fibers including a high melt component and a low melt component; wherein the fine fibers are formed of electrospun polymer nanofibers; wherein the electrospun polymer nanofibers and the high melt component has a higher melting temperature than the low melt component; wherein the multi-component scrim is expanded from an unexpanded state via heating; wherein the low melt component melts or softens during heating and bonds with the fine fibers; wherein the fine fibers are extended as the multi-component scrim expands.

20. The filter media of claim 10, wherein the substrate is formed of a multi-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; wherein the fine fibers have an average fiber diameter between about 0.01 and 0.5 microns; and each layer of the fine fibers has a fine fiber coverage between about 0.012 g/m^2 and 0.025 g/m^2; wherein the filter media has a Frazier air permeability between about 100 and 200 CFM, and a MFP dust holding weight of about 400 - 600 mg/100 cm^2 with a final pressure drop of about 1.5 inch W.G.

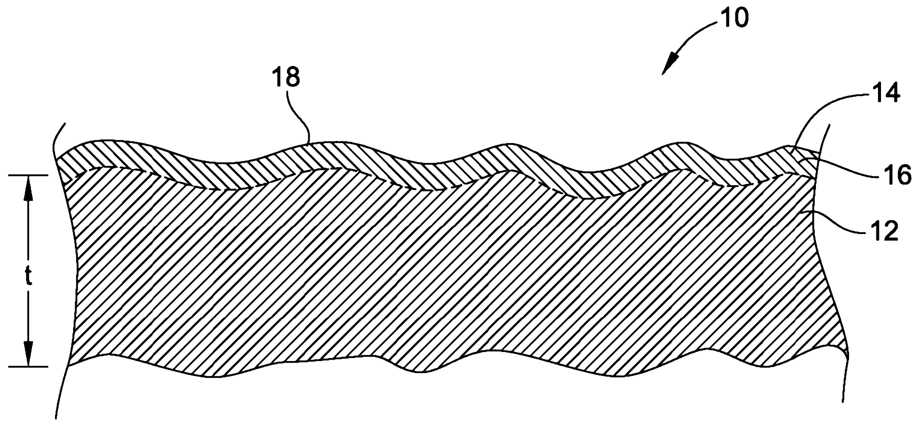

FIG. 1

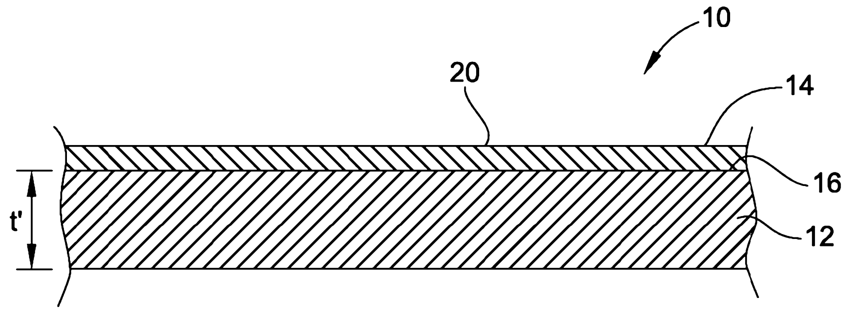

FIG. 2

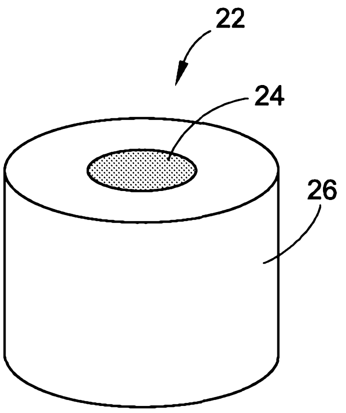

FIG. 3

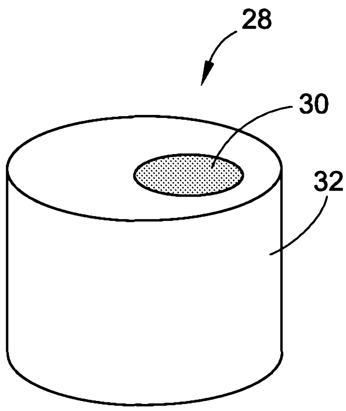

FIG. 4

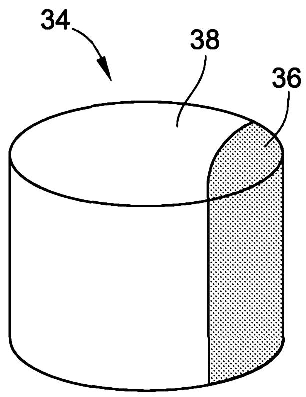

FIG. 5

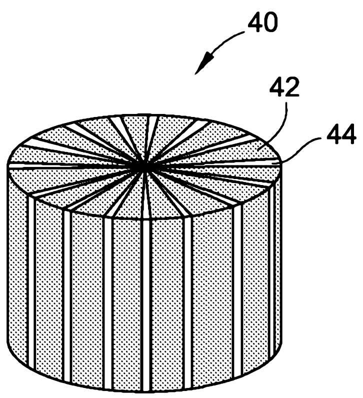

FIG. 6

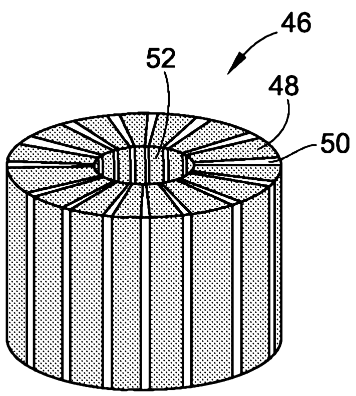

FIG. 7

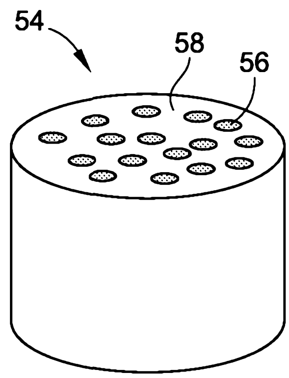

FIG. 8

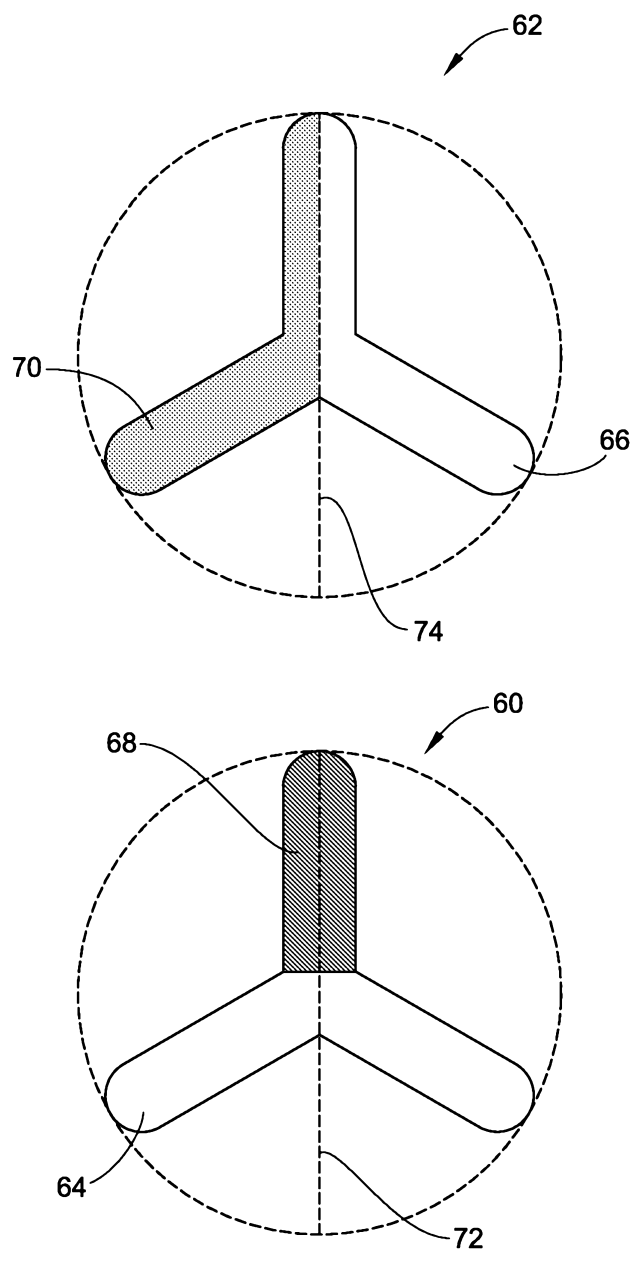

FIG. 9

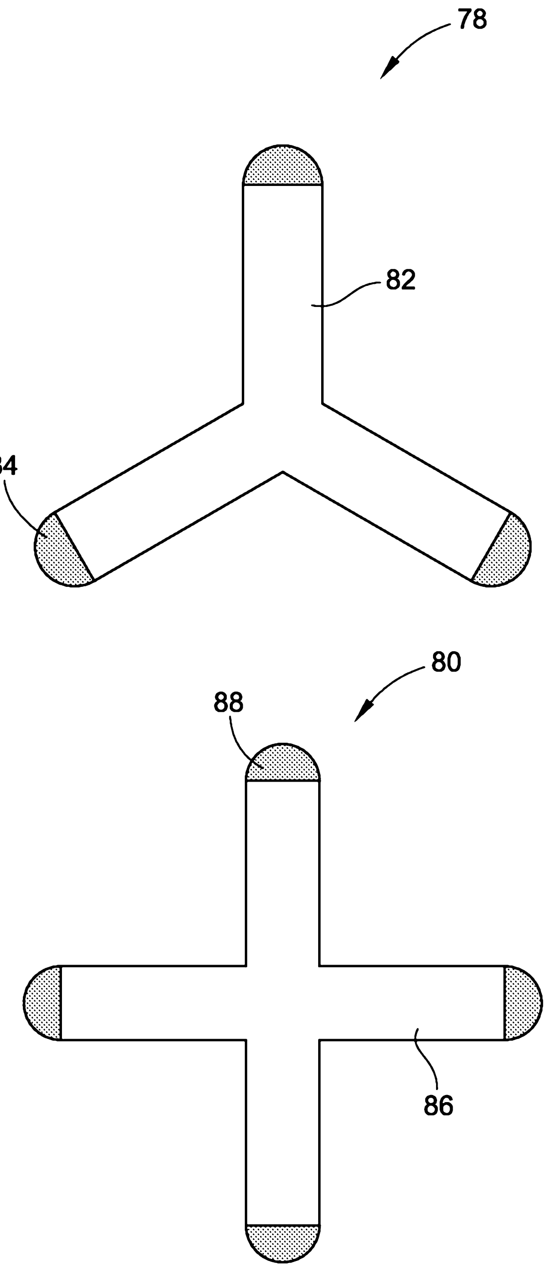

FIG. 10

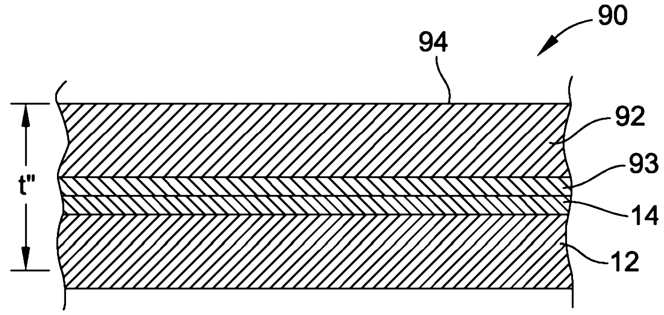

FIG. 11

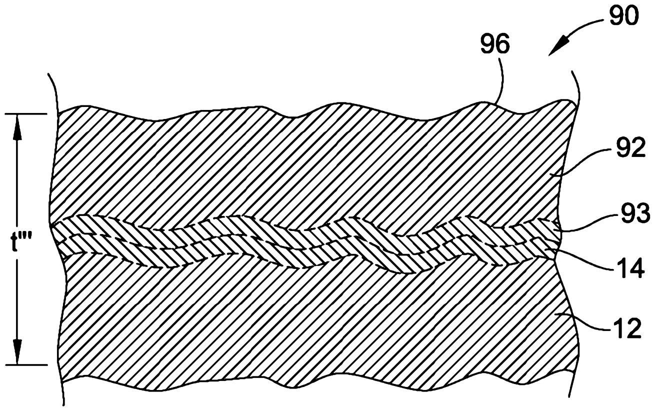

FIG. 12

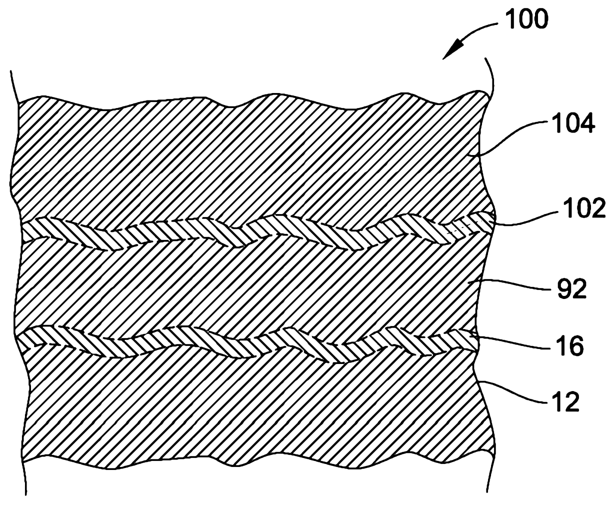

FIG. 13

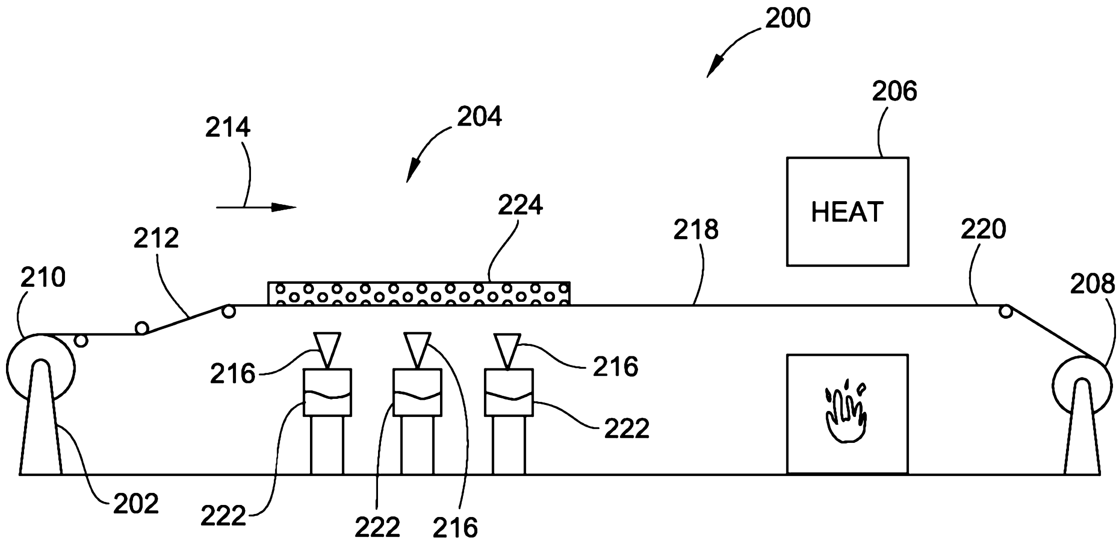
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FIG. 14

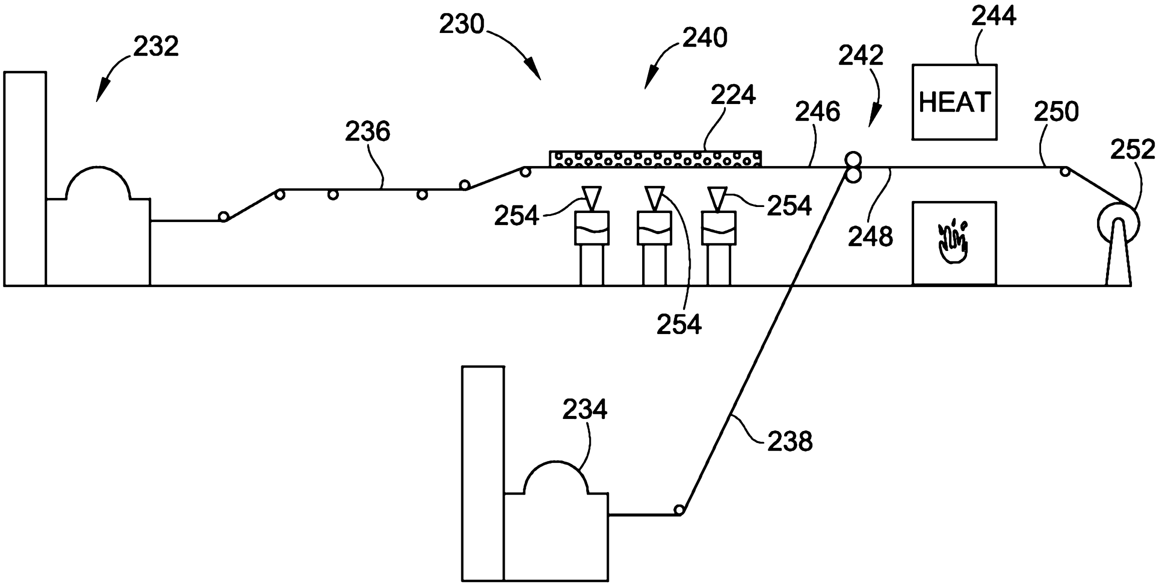
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FIG. 16

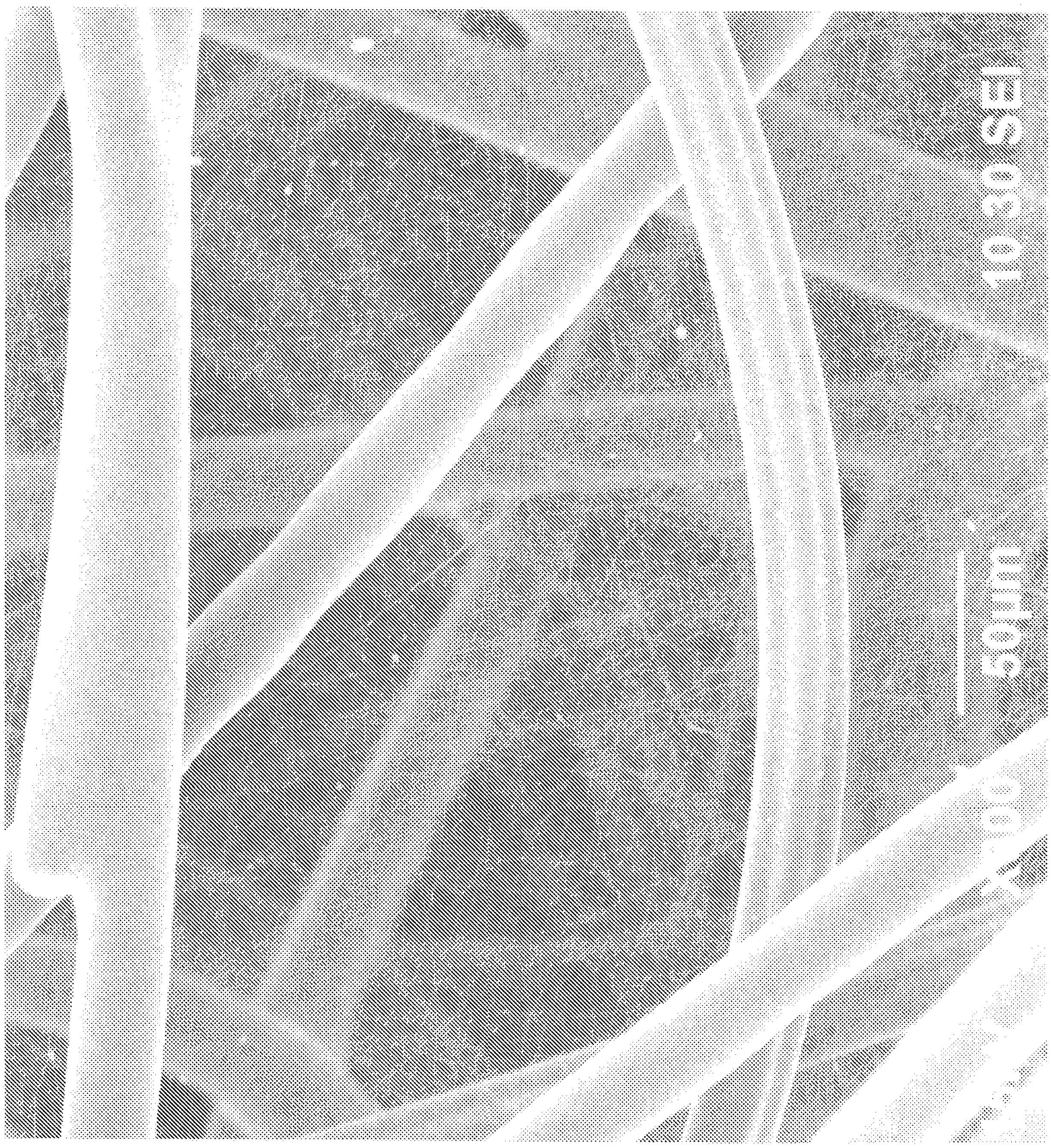


FIG. 15(A)

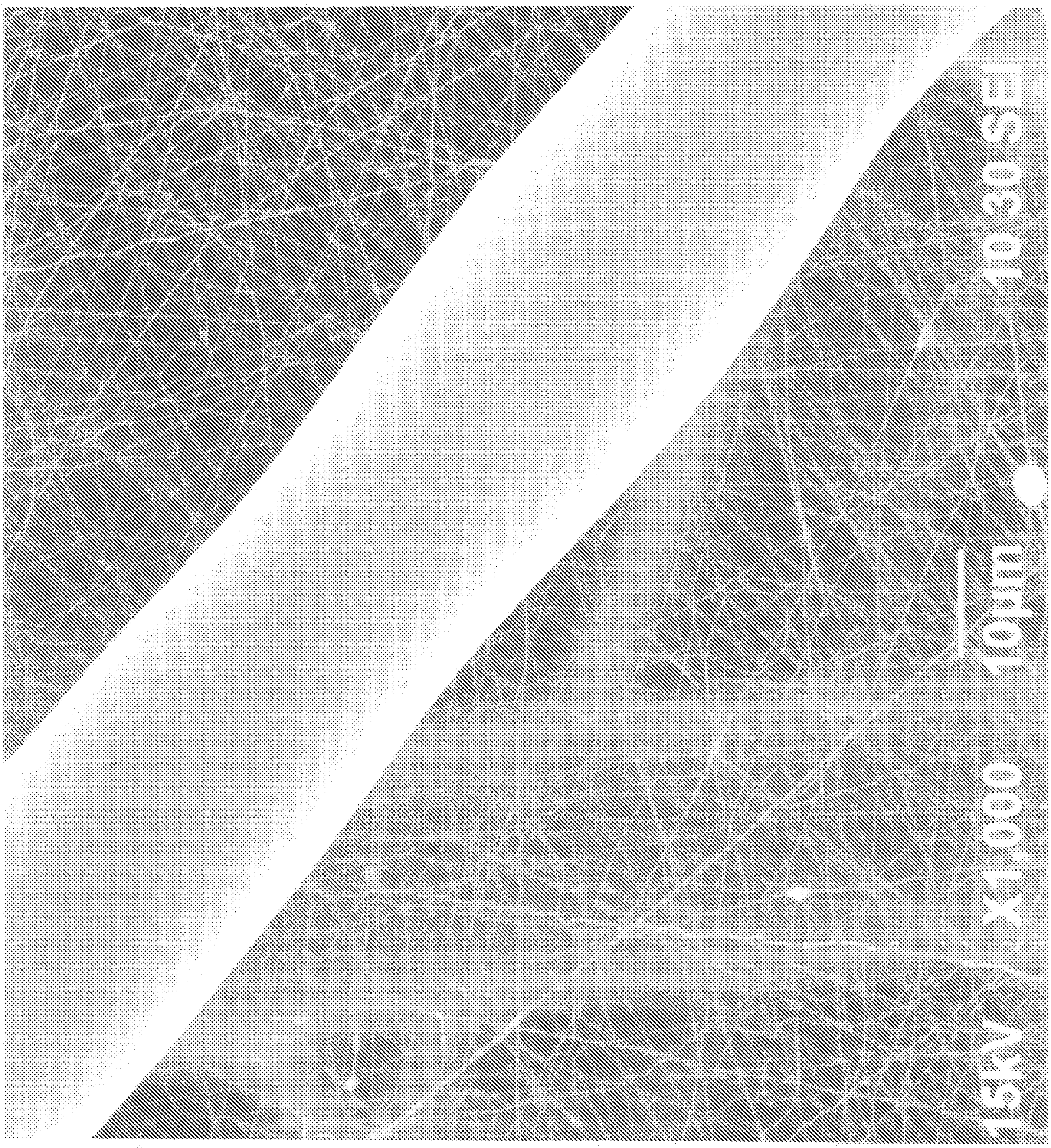


FIG. 15(B)

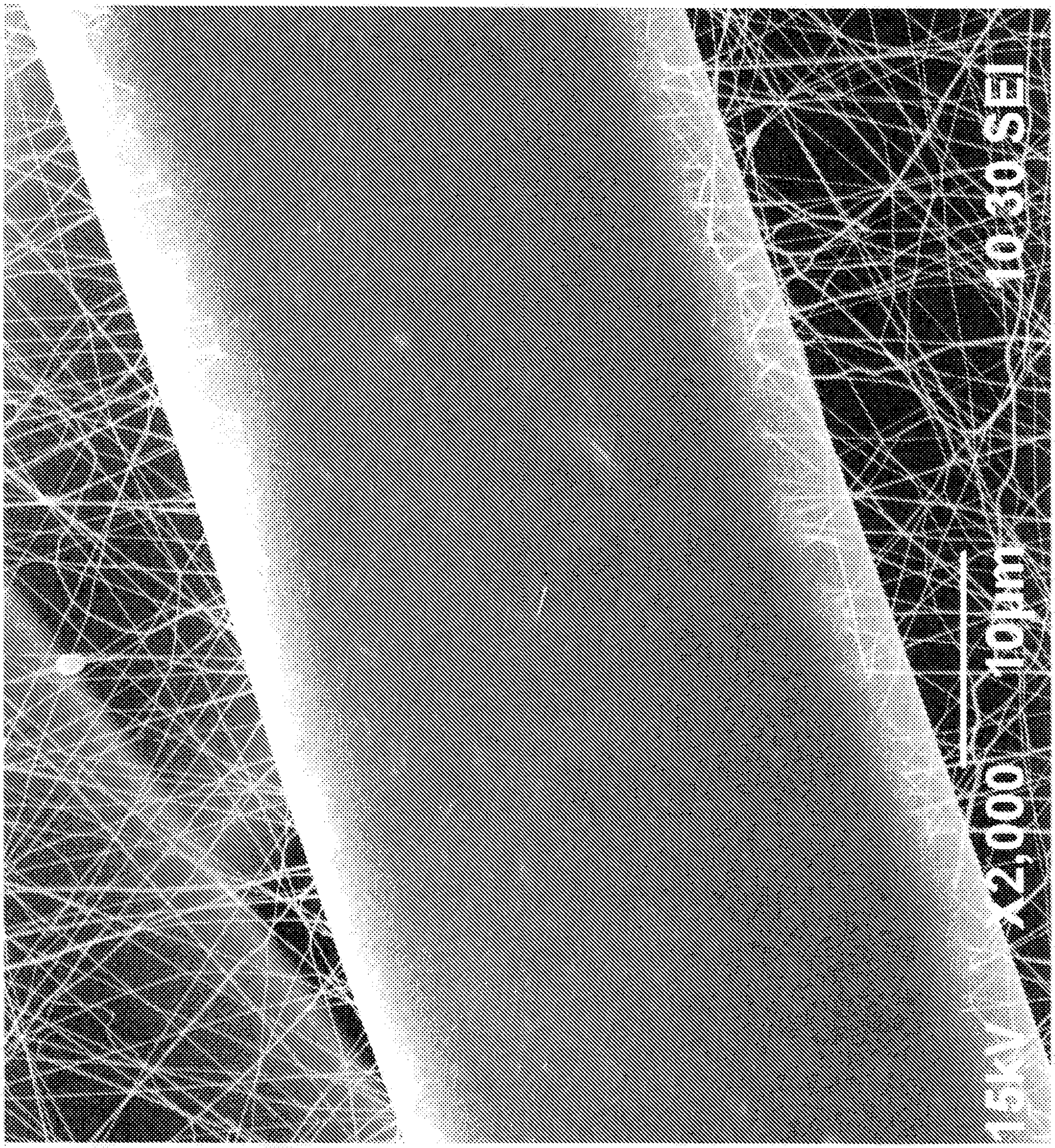


FIG. 15(C)

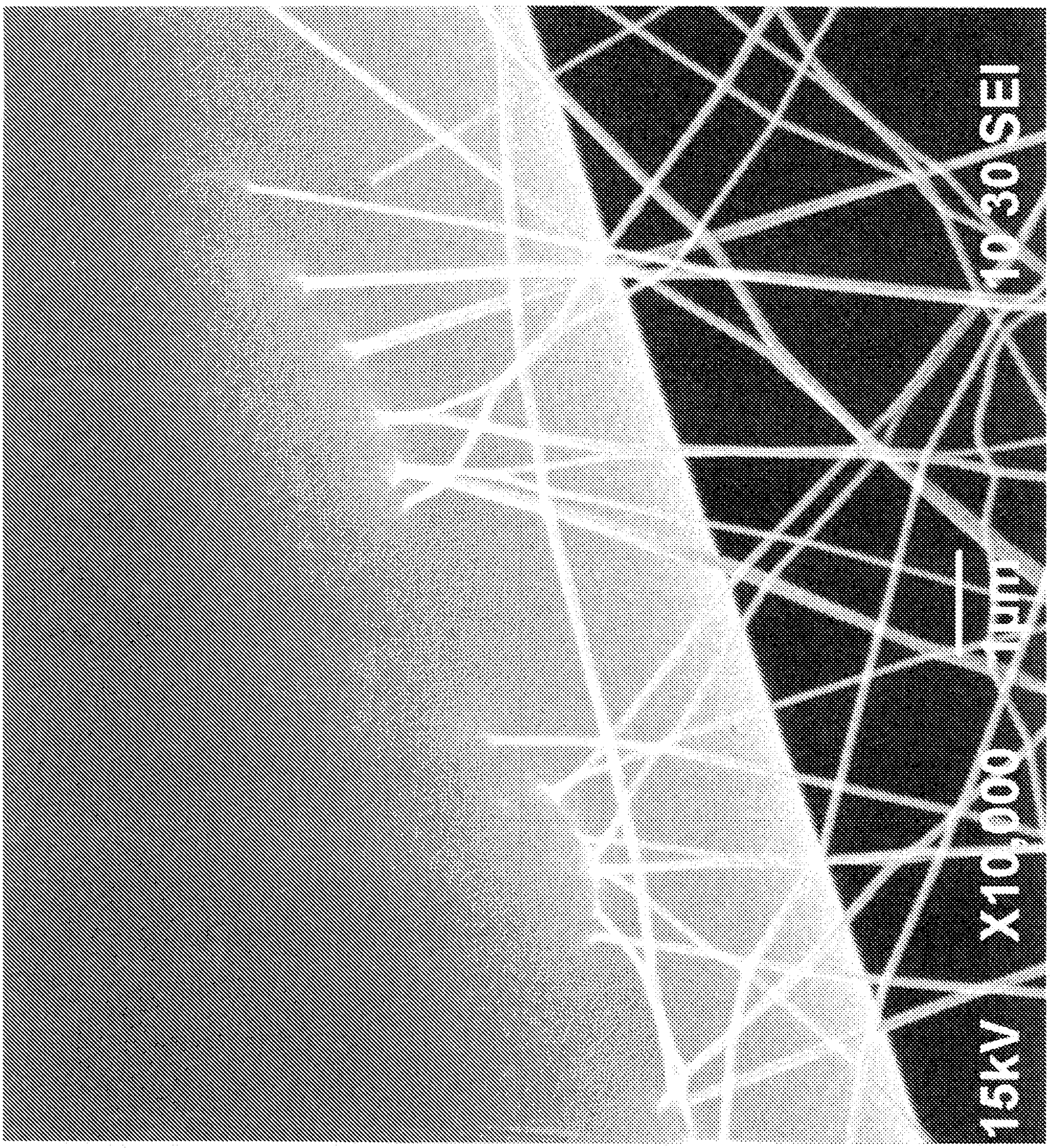


FIG. 15(D)

	CLC MEDIA ■	Lydall SC8100 ▲	Lydall SC8110 ●
Frazier (CFM)	160	55	150
MERV	15	15	11
E1	86.4	91.5	61.9
E2	95.3	97.7	77.9
E3	99.2	99.9	95.4
DPI ("WG)	0.2	0.5	0.2

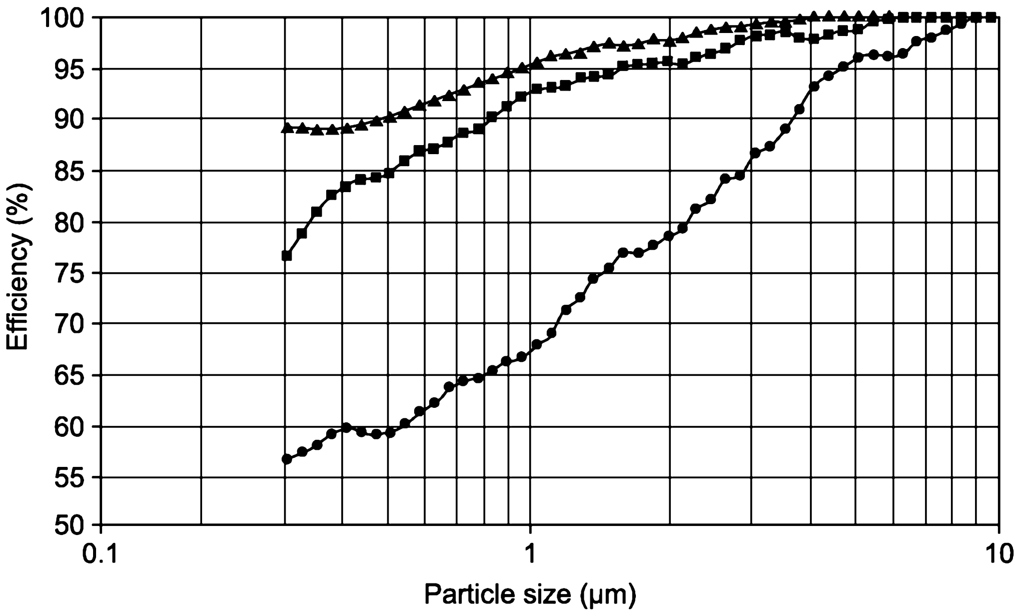


FIG. 17

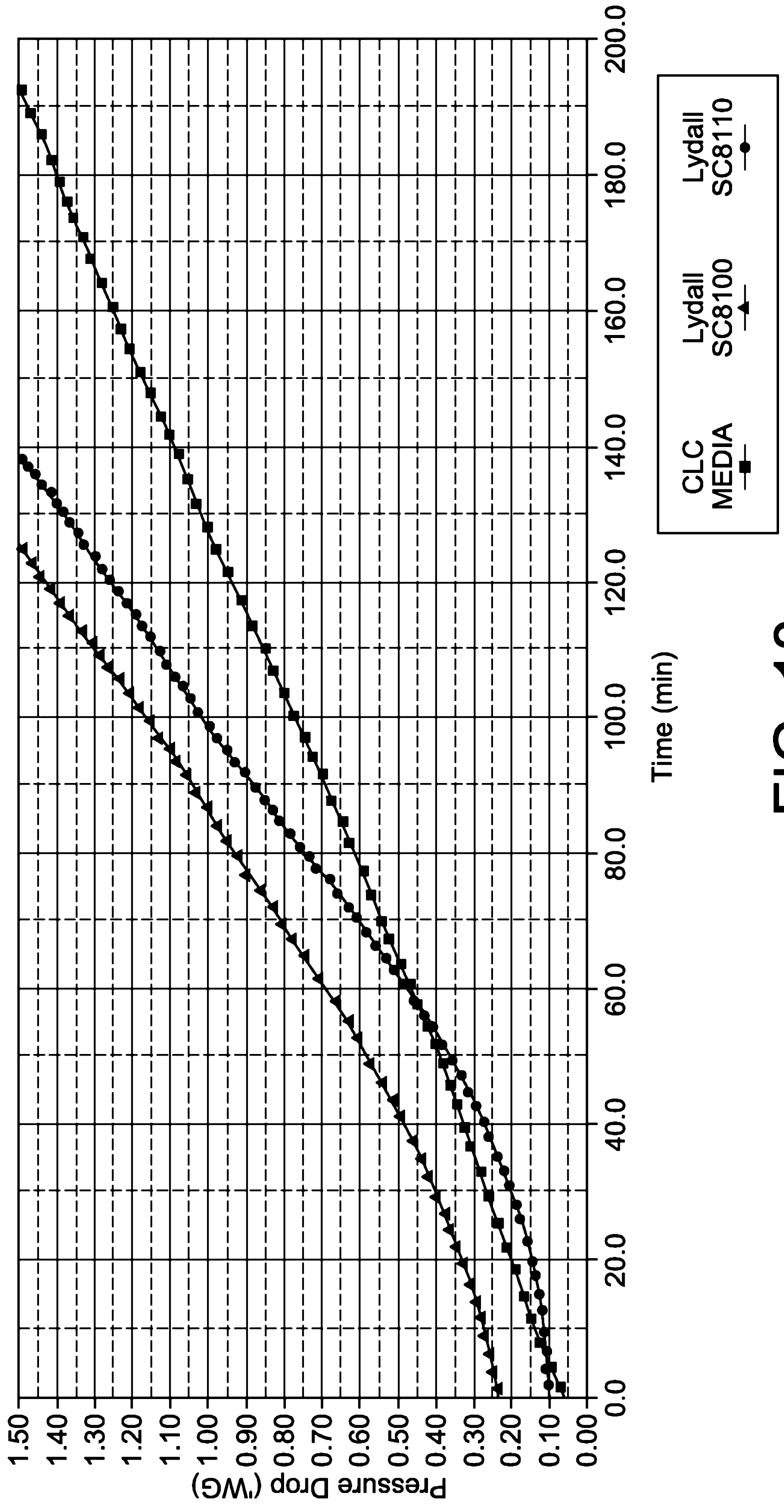
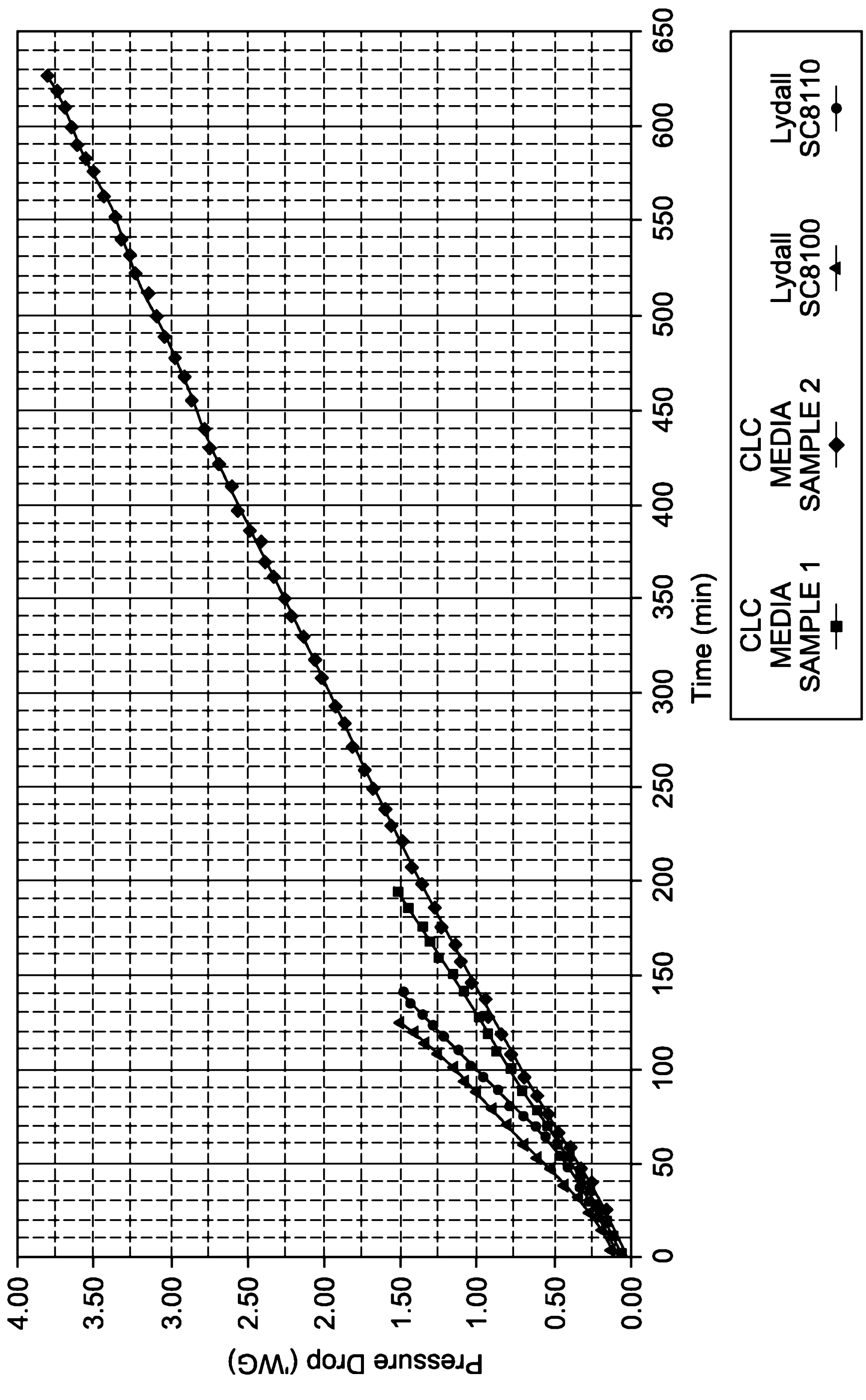

Pressure Drop ("WG)
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Time (min)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
CLC MEDIA
Lydall SC8100
Lydall SC8110

FIG. 18


Pressure Drop ("WG)
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0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Time (min)
0
50
100
150
200
250
300
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400
450
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CLC MEDIA SAMPLE 1
CLC MEDIA SAMPLE 2
Lydall SC8100
Lydall SC8110

FIG. 19

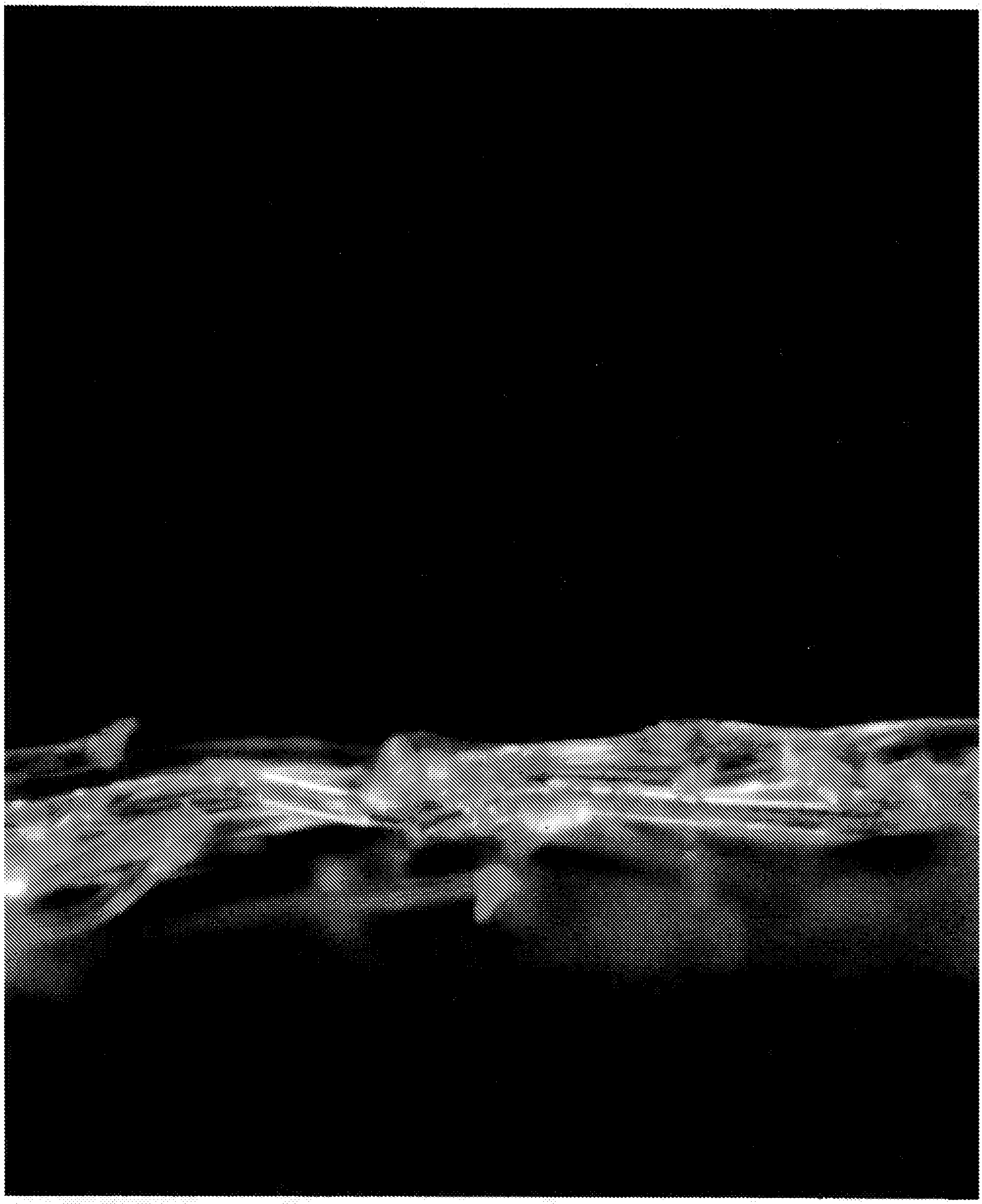

FIG. 20

FIG. 21

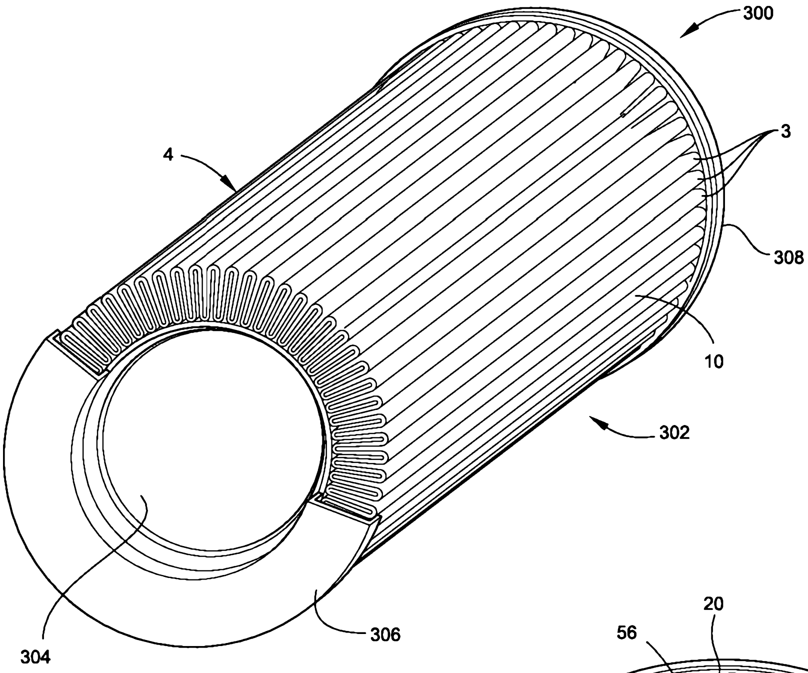
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FIG. 22

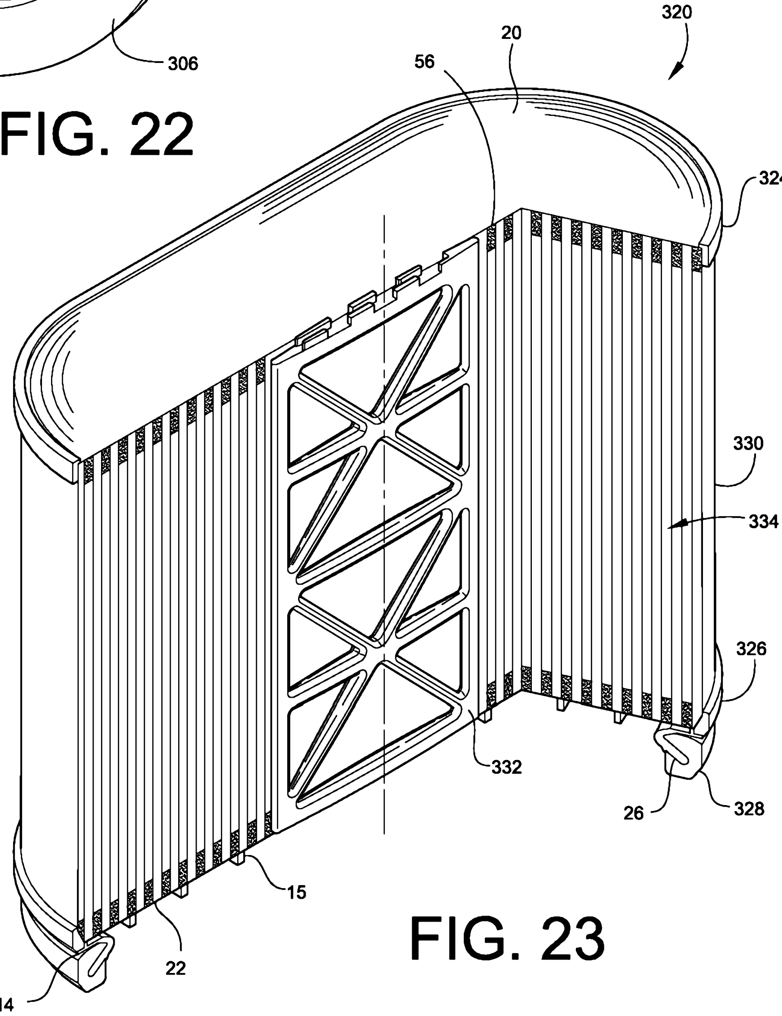
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FIG. 23

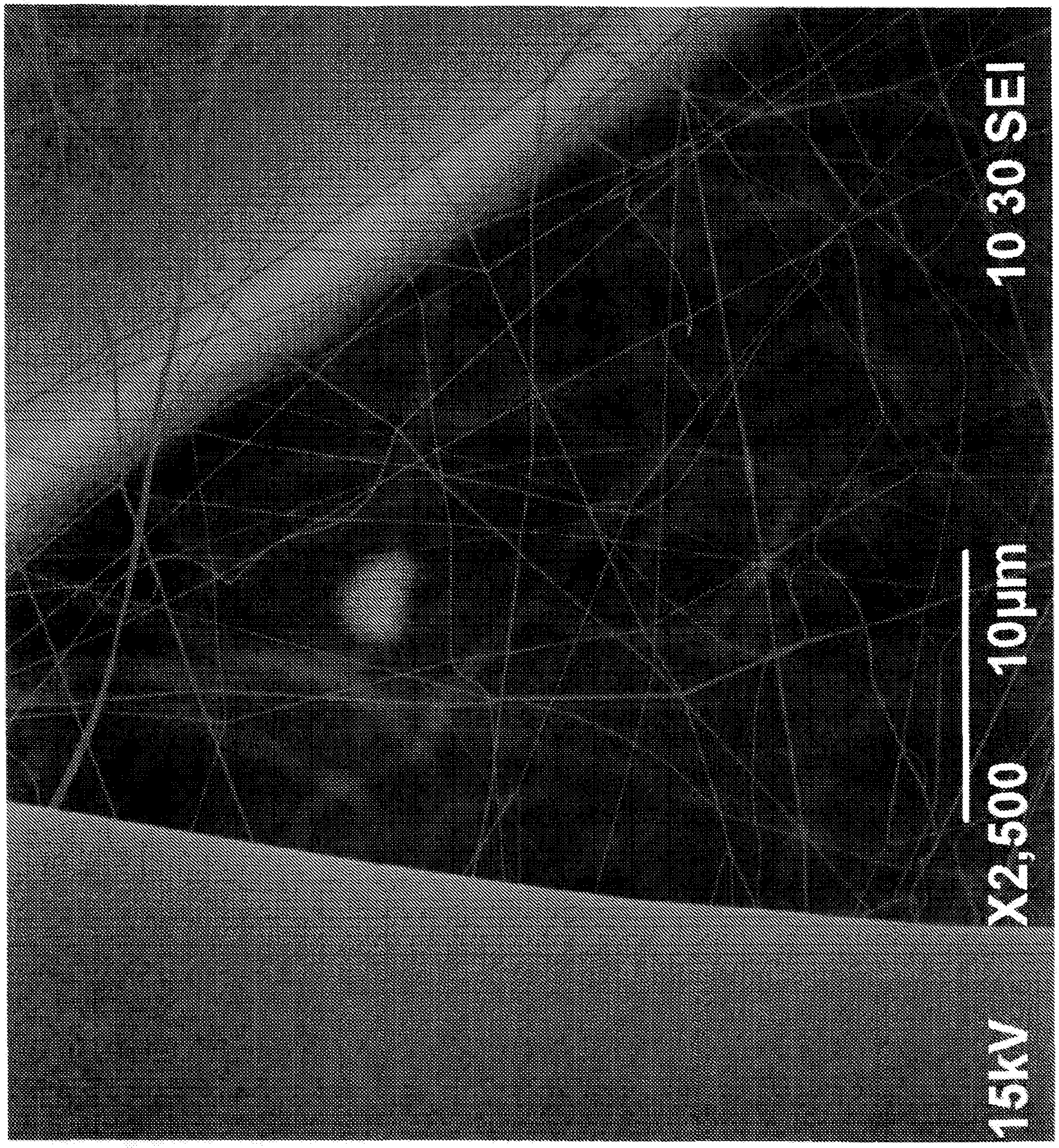

FIG. 24

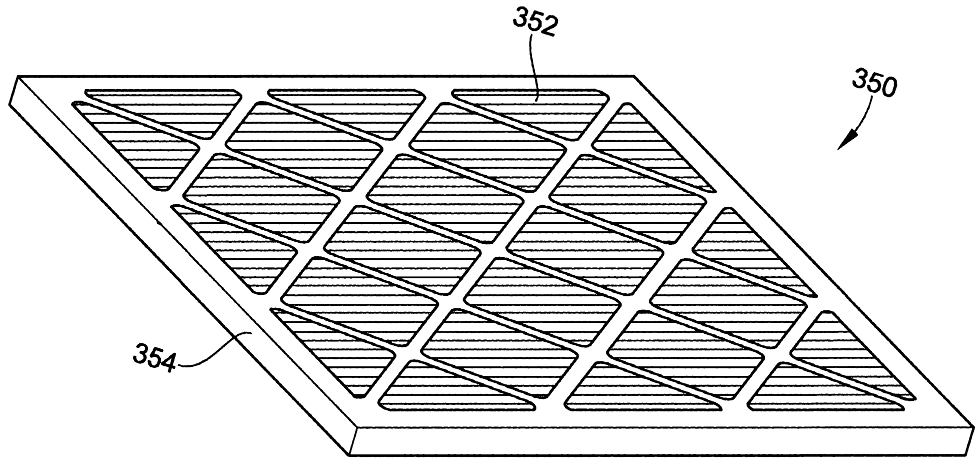

FIG. 25

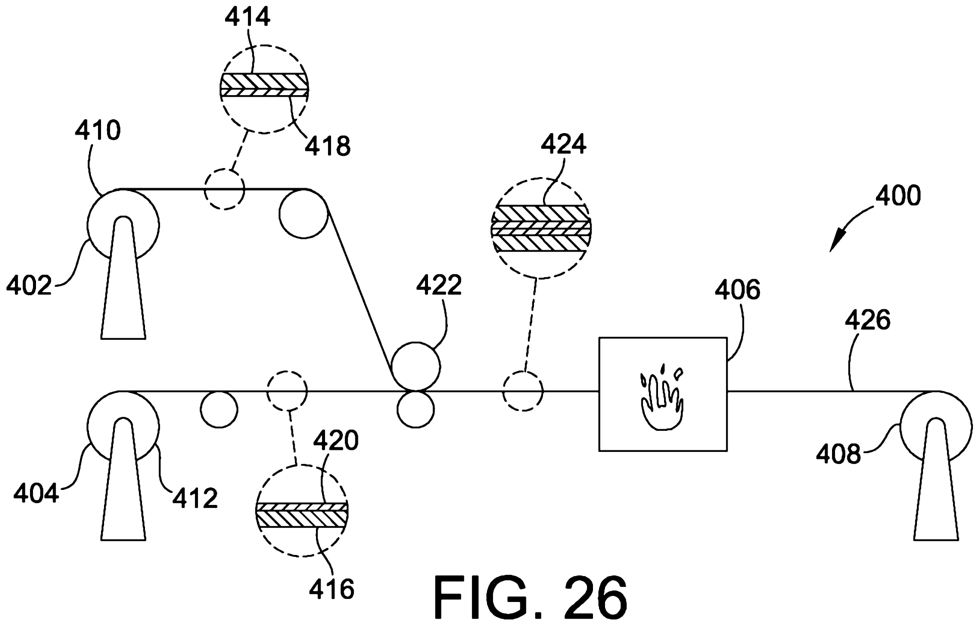

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FIG. 26

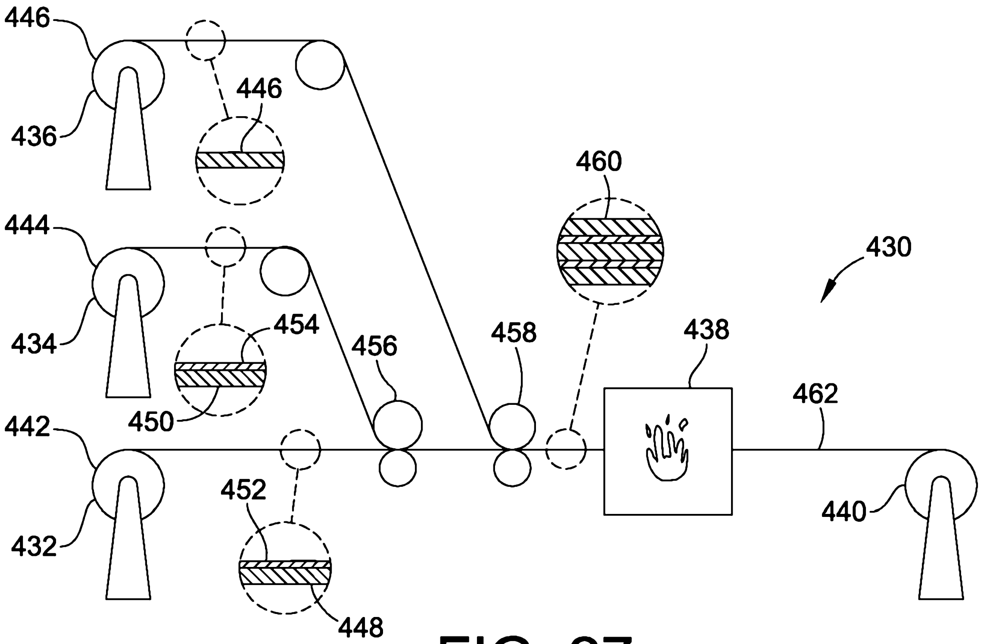

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FIG. 27