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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
13 February 2020 (13.02.2020)

WIPO | PCT

(10) International Publication Number
WO 2020/032995 A2

(51) International Patent Classification:
Not classified

(21) International Application Number:
PCT/US2019/012630

(22) International Filing Date:
08 January 2019 (08.01.2019)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/614,921 08 January 2018 (08.01.2018) US

(71) Applicant: **UNIVERSITY OF NOTRE DAME** [US/US]; 1400 E. Angela Blvd., South Bend, Indiana 46617 (US).

(72) Inventors: **HASEGAWA, Mitsugu**; 131 White Field, Notre Dame, Indiana 46556 (US). **SAKAUE, Hirotaka**; 106 Hessert Laboratory for Aerospace Research, Notre Dame, Indiana 46556 (US).

(74) Agent: **HAUSMAN, Garrett** et al.; 444 W. Lake Street, Suite 3200, Chicago, Illinois 60606 (US).

(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, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, 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, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, 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, KM, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

WO 2020/032995 A2

(54) Title: FIBERS FOR REDUCING DRAG

(57) Abstract: In one aspect of the present disclosure, a streamlined body for passing through a fluid is provided. The streamlined body includes an outer surface defining a leading edge and a trailing edge. The leading edge is oriented to pass through the fluid before the trailing edge during movement of the body through the fluid. The streamlined body further includes a plurality of fibers coupled to the outer surface. Each fiber of the plurality of fibers projects away from the outer surface.

FIBERS FOR REDUCING DRAG

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/614,921, filed with the United States Patent and Trademark Office on January 8, 2018, the contents of which are incorporated by reference herein.

STATEMENT REGARDING FEDERALLY-SPONSORED RESEARCH

[0002] This application was made with government support under grant FA-8650-15-C-2510 awarded by the Air Force Research Laboratory Information Directorate (AFRL/RI). The government has certain rights in the application.

BACKGROUND

[0003] This application relates generally to technologies for reducing drag. More specifically, this application relates to a plurality of fibers applied to a surface to reduce drag forces.

[0004] Drag is a type of friction or fluid resistance based on fluid motion. Drag force is generally proportional to relative velocity for a laminar flow of a fluid and generally proportional to the squared relative velocity for a turbulent flow of a fluid. Form drag is the result of fluid resistance to motion due to the shape of an object moving relative to the fluid, while skin friction drag is the result of the interaction of a surface with the fluid as the surface moves relative to the fluid. These drag forces reduce the velocity of the fluid relative to the object or body with which the fluid interacts. To maintain a desired velocity of either the body moving through the fluid or the fluid moving past the body in spite of developed drag forces, more energy is required than would otherwise be needed in the absence of drag.

[0005] Industries and municipalities utilize pipelines to transport fluids for numerous purposes. Example fluids to be transported include water, oil, natural gas, heated or cooled air, waste water, slurries of various materials, and the like. Pumps are utilized in most scenarios to force the fluid through the pipeline. These pumps must overcome drag forces acting on the fluid within the piping system in order to maintain a desired flow rate of the fluid through the pipeline.

[0006] A significant percentage of the total U.S. Air Force budget is spent on jet fuel. Much of this jet fuel is used with regard to legacy aircraft operationally less fuel efficient than more modern aircraft. Much of the fuel inefficiency of these legacy aircraft can be attributed to the drag forces experienced as they move through the air. Consequently, legacy aircraft engines must consume more fuel than comparable newer aircraft engines in order to overcome these drag forces. Fuel consumption due to vehicle drag forces affects not only aircraft, but watercraft, land vehicles, and the like.

[0007] Wind forces also interfere with outdoor structures including utility poles, power lines, and the like. Buffeting due to turbulent air flow around these structures can cause unwanted movement and stresses.

SUMMARY

[0008] Various aspects of the present disclosure are directed to a plurality of fibers applied to a surface subject to fluid interaction for reducing drag forces in a variety of applications.

[0009] In one aspect of the present disclosure, a pipe is provided. The pipe is utilized for transporting a fluid flow therethrough. The pipe includes an inner wall surface that defines an internal passageway of the pipe. The pipe further includes a plurality of fibers coupled to the inner wall surface. Each of the plurality of fibers projects away from the inner wall surface and into the internal passageway.

[0010] In another aspect of the present disclosure, a streamlined body is provided for passing through a fluid. The streamlined body includes an outer surface. The outer surface defines a leading edge and a trailing edge. The leading edge passes through the fluid before the trailing edge. The streamlined body further includes a plurality of fibers coupled to the outer surface. Each of the plurality of fibers projects away from the outer surface.

[0011] The foregoing summary is intended merely to provide a general overview of various aspects of the present disclosure, and is not intended to limit the scope of this application in any way.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] These and other more detailed and specific features of various aspects of the present disclosure are more fully described in the following description, reference being had to the accompanying drawings, in which:

[0013] Fig. 1A schematically illustrates a longitudinal cross-sectional view of a pipe subject to fluid flow therethrough.

[0014] Fig. 1B schematically illustrates a longitudinal cross-sectional view of a pipe with a bend, the pipe subject to fluid flow therethrough.

[0015] Fig. 2A schematically illustrates a perspective view of a coating having a plurality of fibers.

[0016] Fig. 2B schematically illustrates a cross-sectional view of the coating taken along line 2B-2B of Fig. 2A.

[0017] Fig. 3 illustrates example fiber configurations.

[0018] Fig. 4A illustrates an example fiber cross-section.

[0019] Fig. 4B illustrates another example fiber cross-section.

[0020] Fig. 4C illustrates another example fiber cross-section.

[0021] Fig. 4D illustrates another example fiber cross-section.

[0022] Fig. 5A schematically illustrates an example fiber arrangement and orientation on a surface subject to fluid interaction.

[0023] Fig. 5B schematically illustrates another example fiber arrangement and orientation on a surface subject to fluid interaction.

[0024] Fig. 5C schematically illustrates another example fiber arrangement and orientation on a surface subject to fluid interaction.

[0025] Fig. 6A illustrates a partial cross-sectional view of a body having a plurality of fibers positioned on a portion of the body in a fluid flow stream.

[0026] Fig. 6B illustrates a partial cross-sectional view of another body having a plurality of fibers positioned on a portion of the body in a fluid flow stream.

[0027] Fig. 7A illustrates a cross-sectional view of another body having a plurality of fibers coupled to the outer surface of the body.

[0028] Fig. 7B illustrates a cross-sectional view of another body having a plurality of fibers coupled to a portion of the outer surface of the body.

[0029] Fig. 7C illustrates a cross-sectional view of another body having a plurality of fibers coupled to a portion of the outer surface of the body.

[0030] Fig. 8A illustrates a cross-sectional view of a streamlined body having a plurality of fibers coupled to a portion of the outer surface of the body.

[0031] Fig. 8B illustrates a top plan view of the streamlined body of Fig. 8A.

[0032] Fig. 9A illustrates a side elevation view of another streamlined body having a plurality of fibers coupled to a portion of the outer surface of the body, the body moving through a fluid.

[0033] Fig. 9B illustrates a side elevation view of another streamlined body having a plurality of fibers coupled to a portion of the outer surface of the body.

[0034] Fig. 9C illustrates a side elevation view of another streamlined body having a plurality of fibers coupled to a portion of the outer surface of the body.

[0035] Fig. 9D illustrates a side elevation view of another streamlined body having a plurality of fibers coupled to a portion of the outer surface of the body.

[0036] Fig. 9E illustrates a side elevation view of another streamlined body having a plurality of fibers coupled to a portion of the outer surface of the body.

[0037] Fig. 9F illustrates a side elevation view of another streamlined body having a plurality of fibers coupled to a portion of the outer surface of the body.

DETAILED DESCRIPTION

[0038] It will be apparent to one skilled in the art that the specific details set forth in the following description are merely exemplary and explanatory, and are not intended to limit the scope of this application. The disclosure is capable of supporting other implementations and of being practiced or of being carried out in various ways.

[0039] A passive drag reduction technique requires no ongoing additional energy consumption to reduce drag. One passive drag reduction technique applicable to a pipe transporting a fluid flow is to apply a plurality of fibers to all or portions of the inner wall surface of the pipe's internal passageway.

[0040] Fig. 1A schematically illustrates a straight pipe **100** for transporting a fluid flow **102** therethrough. The fluid flow **102** may generally move along the length of the pipe **100**, which is defined as the dimension of the pipe extending along the longitudinal axis **103** of the pipe. The fluid flow **102** may be a flow of any appropriate fluid including, for instance, water, oil, natural gas, heated or cooled air, waste water, slurries of various materials, and the like. The pipe **100** includes an inner wall surface **104**, which defines an internal passageway **106** of the pipe. For purposes of illustrating the development of a flow boundary layer, the pipe **100** is subjected to the fluid flow **102** at a position sufficiently upstream to provide a developed flow profile. The fluid flow **102** may therefore include a laminar flow section **108**, a transitional flow section **110**, and a turbulent flow section **112** as the fluid flow moves along the inner wall surface **104** of the pipe **100** and in accordance with conventional boundary layer theory known to those of skill in the art.

[0041] A plurality of fibers **116** is applied to the inner wall surface **104**. Some embodiments of applying the plurality of fibers **116** on the inner wall surface **104** include applying a coating **114**, such as that illustrated schematically in Figs. 2A and 2B. In some embodiments, the coating **114** is in the form of a tape **118** with one or more adhesive layers **120** provided on the tape **118**. Other embodiments of producing the plurality of fibers **116** on the inner wall surface **104** include deposition of the fibers directly onto the inner wall surface.

[0042] With reference to Fig. 1B, a pipe **100** having a bend is contemplated herein. In such embodiments, the plurality of fibers **116** are positioned after the bend in the pipe **100**. The fluid flow **102** passes through the internal passageway **106** through the bend in the pipe **100** and continues downstream into a relatively straight section of the pipe. This change in direction can cause considerable turbulence in the fluid flow **102**. The internal passageway **106** of the pipe **100** downstream from the bend is consequently, depending on the characteristics of the fluid, subject to turbulent flow for a distance **112**. In this region, the plurality of fibers **116** are positioned to attenuate the turbulence of the fluid flow **102**.

[0043] Referring now to Fig. 3, example configurations of the fibers **116** are shown. The fibers **116** may be arranged in any appropriate shape and/or position relative to the inner wall surface **104** of the pipe and, additionally or alternatively, the coating **114**. Some non-limiting examples shown include a fiber **116** that is completely straight, wavy, curly, or curved. Other non-limiting examples include a fiber **116** that is partially shaped in, for instance, any of the above ways. Still other non-limiting examples include a fiber **116** that is a combination of two or more shapes such as, for instance, those discussed above.

[0044] Each of these and other configurations for the fibers **116** may include rigid or flexible fibers in part or whole. The rigidity of the fibers **116** may be adjusted by selecting a particular material of the fibers, adjusting a density of the material, adjusting a thickness of each fiber, and the like. Thicker fibers **116** and/or fibers made from materials such as nylon or polyester rather than cotton or rayon may be used to exhibit relatively increased rigidity. Fibers **116** should be more rigid for applications including relatively viscous fluids, such as water, oil, waste, slurries, and the like than fibers for applications including fluids such as air. In one exemplary embodiment, the fibers **116** are flexible enough to be directed by combing or other surface treatment of the fibers a part of additional fiber treatment steps after fiber deposition.

[0045] As illustrated in Figs. 4A-4D, each fiber may have any appropriate cross-sectional shape. Some non-limiting examples shown include fibers **116** with a circular cross-section, a cross-section made of multiple intersecting circles, a triangular cross-section, and a rectangular cross-section. Other non-illustrated cross-sections, such as hexagonal and the like, are also contemplated herein. One particular exemplary embodiment includes fibers **116** with a circular cross-section having a diameter of less than or equal to 50 μm. This diameter may correspond with flexible fibers **116**, while a relatively rigid fiber may include a diameter that is two or three times greater. The fibers **116** of a given coating **114** or of a given collection of fibers may all have the same uniform cross-section or may have cross-sections that vary in size and/or shape. The fibers **116** may be made of any appropriate material including, for instance, nylon, polyester, rayon, cotton, some combination thereof, and the like.

[0046] With reference to Figs. 5A-5C, the coating **114** includes the fibers **116** positioned or oriented in any appropriate manner relative to the fluid flow **102**. Some non-limiting examples shown include fibers **116** arranged in rows extending generally perpendicular to the direction of the fluid flow **102**, arranged in rows extending generally parallel to the direction of the fluid flow, and arranged in an offset or diagonal pattern. Other non-illustrated arrangements, such as curved or wavy fiber alignment patterns, are also contemplated herein. The entire coating **114** may have a uniformly spaced arrangement of fibers **116**, or the fibers may be arranged in a varied or even random pattern. Other non-illustrated shapes or positions of the fibers **116** may include an interwoven pattern of the fibers such as, for example, a tangled layer of fibers.

[0047] In some embodiments, the coating **114** is manufactured by covering a foil tape **118** with one or more of the adhesive layers **120**, such as an epoxy layer, provided on a side of the tape such that the plurality of fibers **116** easily couple to the tape. A voltage is applied to the foil tape **118** effective to provide an electrostatic field over the foil tape. The fibers **116**, such as nylon fibers, are attracted to and forced to move by the electrostatic field. Then, the fibers **116** are embedded into the adhesive layer **120** on the foil tape **118**. This method allows for fibers **116** that extend generally perpendicular to the surface of the tape **118**. The foil tape **118** may be adjusted in angle relative to the incoming fibers **116** to affect the deposition angle of the fibers on the tape. In some embodiments, the fibers **116** are deposited on the foil tape **118** in a swept-back orientation with the fibers being angled less than 90° and greater than 0° relative to the tape. Another adhesive layer **120** is provided on a side of the tape **118** opposite the side coupled to the fibers **116** such that the tape may be affixed to a desired surface (such as the inner wall surface **104** of the pipe **100**).

[0048] The coating **114** may be taped on a desired surface, such as the inner wall surface **104** of the pipe **100**, or it may be embedded into a layer, such as a sealant or paint layer, of the pipe. In an embedded embodiment, one of the adhesive layers **120** may be omitted. Alternatively, the fibers **116** may be directly applied to the pipe without a coating through direct deposition via one or more molds, a spray device, and the like.

[0049] In some direct fiber application embodiments, the plurality of fibers **116** may be in liquid form prior to deposition on the inner wall surface **104** (or onto the tape **118**). The molten ends of each section of material that will become a fiber **116** may dry onto the inner wall surface **104** (or onto the tape **118**), thereby coupling the fibers without an adhesive. The molds, for instance, may be shaped such that the fibers **116** produced are of any shape and orientation as those discussed above. Polyester is a non-limiting example of an appropriate material for the fibers **116** in some direct fiber application embodiments.

[0050] Returning now to Figs. 1A and 1B, in operation during a fluid flow event, the fibers **116** constrain and absorb developing eddies in the fluid flow **102** to inhibit the development of relatively large eddies. The constraint of developing eddies allows for a passive reduction in skin friction by turbulence control through delaying growth of the turbulent flow section **112**. The fibers **116** are either directly or indirectly coupled to the inner wall surface **104** of the pipe **100**. Each of the fibers **116** projects away from the inner wall surface **104** and into the internal passageway **106** of the pipe **100**. In the schematic illustrations shown, the fibers **116** are substantially parallel to each other as they extend into the internal passageway **106**.

[0051] The plurality of fibers **116** can be tailored for a specific application by adjusting at least one of the diameter, length, direction of extension, elasticity, cross-section, surface finish, composition, and the like of the fibers. Some example lengths for the fibers 116 include, but are not limited to, 0.5 mm, 1.0 mm, 1.5 mm, 2.5 mm, and 4.0 mm. The arrangement and density of the fibers **116** can also be adjusted as needed. In some embodiments, the density of the fibers **116** can be varied corresponding to the selected length of the fibers. As such, some embodiments include, for instance, 84 fibers per mm^2 with fibers that are 0.5 mm long, 60 fibers per mm^2 with fibers that are 1.0 mm long, 14 fibers per mm^2 with fibers that are 1.5 mm long, 6 fibers per mm^2 with fibers that are 2.5 mm long, 4 fibers per mm^2 with fibers that are 4.0 mm long, and the like.

[0052] The fibers **116** cover the entire inner wall surface **104** of the pipe **100** in some embodiments. In other embodiments, discrete sections of fibers **116** are separated by a discontinuity distance **D1** (Fig. 1A). In the illustrated embodiment, the discrete sections of fibers **116** are separated by the discontinuity distance **D1** in a direction extending along the length of the pipe **100**. Additionally or alternatively, the discrete sections of fibers **116** can be separated along a circumference of a pipe **100** having a circular cross-section (i.e., different arc lengths of sections of fibers and spacings or discontinuities between sections of fibers). In some embodiments, one or more sections of fibers **116** can be placed only in critical locations along the pipe **100** corresponding to unique characteristics of the fluid flow **102**. Some of these locations may include, for instance, the transitional flow section **110** of the pipe **100**, the turbulent flow section **112** of the pipe, and the like. Such selective application of the fibers **116** can save on costs and/or labor in manufacturing the pipe **100**.

[0053] As shown in Fig. 1A, some embodiments of the pipe **100** include a section of fibers **116** having a length **L1** that is shorter than the boundary layer thickness **T1** of the fluid flow. For instance, the fibers **116** include a section of short fibers **122** having a length **L1** of less than or equal to 0.5 mm. The section of short fibers **122** is shown positioned in the transitional flow section **110** of the fluid flow **102** and have a length **L1** that is shorter than the boundary layer thickness **T1** in the transitional flow section. These fibers **116** in the section of short fibers **122** are arranged such that they constrain the development of eddies in the transitional flow section **110** and, therefore, delay the development of the turbulent flow section **112**.

[0054] Also as shown in Fig. 1A, some embodiments of the pipe **100** include a section of fibers **116** having a length **L2** that is longer than the boundary layer thickness **T2** of the fluid flow. For instance, the fibers **116** include a section of long fibers **124** having a length **L2** of less than or equal to 4.0 mm. The fibers **116** in the section of long fibers **124** further have a length **L2** of greater than 0.5 mm. This section of long fibers **124** is positioned sufficiently downstream in the internal passageway **106** of the pipe **100** such that it is located in the turbulent section **112** of the fluid flow **102**. These fibers **116** in the section of long fibers **124** absorb eddies in the turbulent flow section **112** to control flow separation of the fluid flow **102**.

[0055] In the embodiment schematically illustrated in Fig. 1A, the section of short fibers **122** is positioned upstream of the section of long fibers **124**, and the sections are separated by the discontinuity distance **D1**. In other embodiments, the inner wall surface **104** at the position of the illustrated discontinuity distance **D1** may instead be occupied with additional sections of short fibers **122** or may be occupied with a section of fibers **116** that progressively increase in length from the length **L1** of the section of short fibers **122** to the length **L2** of the section of long fibers **124**.

[0056] In the embodiment schematically illustrated in Fig. 1B, only a section of long fibers **124** is provided because the fluid flow **102** is already in a turbulent section **112** due to the bend in the pipe **100** upstream of the fibers **116**.

[0057] Referring now to Figs. 6A and 6B, a streamlined body **200** for passing through a fluid **202** is schematically shown. The streamlined body **200** may be a hydrodynamic and/or aerodynamic body, and the fluid, as such, may be any appropriate fluid including water, air, and the like. The streamlined body **200** may be a portion or component of any appropriate aircraft (such as an airfoil or a portion thereof), watercraft (ship or undersea vessel), land vehicle (including commercial trucks), outdoor structure (such as a pole, building, or wind turbine), underwater structure, utility line, sensor (with or without mounting post), sportswear (such as helmets and clothing), sports vehicles (such as bobsleds and racing cars), and the like, all of which are represented schematically in Figs. 6A-9E.

[0058] The streamlined body **200** includes an outer surface **204**. The outer surface **204** defines a leading edge **206** and a trailing edge **208**. The leading edge **206** is positioned to pass through the fluid **202** before the trailing edge **208** passes through the fluid. Stated another way, the leading edge **206** leads, or is forward or upstream from, the trailing edge **208**.

[0059] A plurality of fibers **216**, with or without a coating as discussed above, are coupled to the outer surface **204** in any appropriate manner. For instance, the coating **214** may be taped on a desired portion of the outer surface **204**, embedded into a layer, such as a sealant or paint layer, of the outer surface, or deposited directly onto the outer surface in a manner similar to those discussed above. Each of the fibers **216**, once affixed, projects away from the outer surface **204**. Also as discussed above (with regard to the fibers **116**), the fibers **216** may be arranged in a variety of configurations. Further, the fibers **216** may be made of any appropriate material including, for instance, nylon, rayon, cotton, or polyester.

[0060] As shown in Fig. 6A, some embodiments of the streamlined body **200** include the fibers **216** covering a portion of the outer surface **204** nearer the leading edge **206** than the trailing edge **208**. In such embodiments, the fibers **216** may be a section of short fibers **222** with each fiber having a fiber length **L1** of less than or equal to 1.7 mm. Further embodiments may include the short fibers **222** having a fiber length **L1** of less than or equal to 0.5 mm. The fibers **216** are shown laid down due to the flow of the fluid **202** past the streamlined body **200**. Of course, the fibers **216** may instead be constructed to be laid down or swept back even without the influence of the flow of the fluid **202**. As discussed above, the fibers **216** may be flexible or elastic in some embodiments. The short fibers **222** are arranged such that they constrain the development of eddies in the transitional flow section **210** and, therefore, delay the development of the turbulent flow section **212**.

[0061] As shown in Fig. 6B, some embodiments of the streamlined body **200** include the fibers **216** covering a portion of the outer surface **204** nearer the trailing edge **208** than the leading edge **206**. In such embodiments, the fibers **216** may be a section of long fibers **224** with each fiber having a fiber length **L2** less than or equal to 10.0 mm. Further embodiments may include the long fibers **224** having a fiber length **L2** of less than or equal to 4.0 mm. The fibers **216** are shown swept back due to the flow of the fluid **202** past the streamlined body **200**, but may instead be manufactured in such an orientation without the influence of fluid flow. The long fibers **224** absorb eddies in the turbulent flow section **212** to minimize turbulence of the fluid **202** as it continues after the streamlined body **200**.

[0062] Turning now to Figs. 7A, 7B, and 7C, other potential arrangements of the fibers **216** on the streamlined body **200** are shown. With regard to Fig. 7A, some embodiments of the streamlined body **200** include the fibers **216** covering the entirety of the outer surface **204**. The fibers **216** of the streamlined body **200** in Fig. 7A may all be short fibers **222**, for instance. The outer surface **204** entirely covered with the coating **214** does not suffer from direction dependence with regard to the flow of the fluid **202** past the streamlined body **200**.

[0063] Fig. 7B illustrates an embodiment of the streamlined body **200** having the fibers **216** covering a portion of the outer surface **204** nearer the trailing edge **208** than the leading edge **206**. In this illustrated embodiment, the fibers **216** are set back by an angle **A1** from the direction of travel **D2** of the streamlined body **200**. The fibers **216** of the streamlined body **200** in Fig. 7B may all be long fibers **224**, for instance.

[0064] With regard to Fig. 7C, some embodiments of the streamlined body **200** include the fibers **216** covering separate portions of the outer surface **204** with two discrete sections of the fibers. The two sections of the fibers **216** may both be nearer the leading edge **206** than the trailing edge **208** and may be set back by an angle **A2** from the direction of travel **D2** of the streamlined body **200**. The two sections of the fibers **216** may be set back the same angle **A2** or may be set back at different angles. Each of the two sections of the fibers **216** may continue through a coverage angle **A3** that is less 90° about the streamlined body **200**. In this illustrated embodiment, the fibers **216** may all be short fibers **222**, for instance.

[0065] Turning now to Figs. 8A and 8B, the streamlined body **200** may be in the form of an airfoil. For purposes of discussion herein, the length of the airfoil streamlined body **200** may be considered the dimension of the airfoil extending from the leading edge **206** to the trailing edge **208**. In Figs. 8A and 8B, the airfoil streamlined body **200** includes two discrete sections of the fibers **216** in a manner similar to that described with regard to Fig. 7C above. As stated above, the fibers **216** may include all short fibers **222** in such an embodiment. Of course, many other configurations and arrangements of fibers **216** with regard to an airfoil streamlined body **200** are contemplated herein.

[0066] Figs. 9A-9F show examples of an airfoil streamlined body **200** that includes one or more sections of fibers **216** to reduce the skin friction coefficient in a transitional or turbulent fluid flow area. It should be understood that such a streamlined body **200**, although described with regard to air, may also be applicable in water or other fluids. The skin friction coefficient is reduced by minimizing the flow separation with the fibers **216** through attenuating eddies in the fluid flow. It is recognized herein that the angle of attack of the streamlined body **200** with regard to the fluid flow can have an effect on the efficacy of the fibers **216** in reducing skin friction coefficient. The greater the angle of attack, that is, the more the streamlined body **200** is positioned with the leading edge **206** higher than the trailing edge **208** in a direction perpendicular to the fluid flow, the more effective the fibers **216** may be. The airfoil streamlined body **200** in Fig. 9A is shown with the leading edge **206** extending above the trailing edge **208** at an angle of attack of between about 20° and about 30° relative to the horizontal flow of the fluid **202**. The airfoil streamlined body **200** is shown in Figs. 9B-9E in a generally horizontal position, which would have the angle of attack at about 0°. As the airflow moves from left to right on the Figures, the angle of attack is greater as the airfoil streamlined body **200** is rotated clockwise on the page as shown.

[0067] As shown in Fig. 9B, the airfoil streamlined body **200** may include a section of fibers **216** that covers a portion of the middle third of the length of the airfoil. The fibers **216** may be set back from the leading edge **206** by a fiberless first section **S1**. This first section **S1** may be approximately one third of the length of the airfoil streamlined body **200** in some embodiments. The fibers **216** may extend along the length of the airfoil streamlined body **200** to form a coverage section **S2**. The coverage section **S2** may be less than approximately one third of the length of the airfoil streamlined body **200** in some embodiments. The fibers **216** may be short fibers **222** or any other appropriate length.

[0068] With regard to Fig. 9C, the airfoil streamlined body **200** may be similar to that described above for Fig. 9B. The airfoil streamlined body **200** of Fig. 9C, however, may include the coverage section **S2** forming approximately one third of the length of the airfoil streamlined body **200**. The fibers **216** may be short fibers **222** or any other appropriate length.

[0069] In the embodiment shown in Fig. 9D, the fiberless first section **S1** extends approximately two thirds of the length of the airfoil streamlined body **200**. The coverage section **S2** forms the remaining approximately one third of the length of the airfoil streamlined body **200**. The fibers **216** may be long fibers **224** or any other appropriate length.

[0070] The embodiment shown in Fig. 9E includes a fiberless first section **S1** extending approximately one third of the length of the airfoil streamlined body **200**. The coverage section **S2** extends the remaining approximately two thirds of the length of the airfoil streamlined body **200**. The coverage section **S2** in this embodiment may include fibers **216** that gradually change from short fibers **222** to long fibers **224** as they progress away from the leading edge **206** toward the trailing edge **208** of the airfoil streamlined body **200**.

[0071] Fig. 9F shows yet another embodiment of an airfoil streamlined body **200**. The airfoil streamlined body **200** of this embodiment includes a fiberless first section **S1** extending approximately one third of the length of the airfoil. The airfoil streamlined body **200** in Fig. 9F includes two discrete sections of the fibers **216** in the form of a forward coverage section **S2** and a rearward coverage section **S4**. The two coverage sections **S2**, **S4** are separated by a fiberless second section **S3**. In the exemplary embodiment shown in Fig. 9F, the forward coverage section **S2** and the fiberless second section **S3** make up approximately one third of the length of the airfoil streamlined body **200**. The rearward coverage section **S4** extends the remaining one third of the length of the airfoil streamlined body **200**. In such an embodiment, the forward coverage section **S2** includes a section of short fibers **222** and the rearward coverage section **S4** includes a section of long fibers **224**.

[0072] Although the embodiments of Figs. 9B-9E were discussed with regard to the length of the airfoil streamlined body **200** divided into thirds, it should be understood that these embodiments are non-limiting. Other embodiments may include one or more fiberless sections **S1**, **S3** that are greater than or less than one third of the length of the airfoil streamlined body **200** and may include one or more coverage sections **S2**, **S4** that are greater than or less than one third of the length of the airfoil. Some exemplary embodiments include each coverage section **S2**, **S4** covering 10-20%, 15%, 25-25%, 30%, 55-65%, or 60% of the length of the airfoil streamlined body 200.

[0073] Thus, various embodiments including fibers applied to a surface to reduce drag have been described. While the above describes example embodiments of the present disclosure, these descriptions should not be viewed in a limiting sense. Rather, there are several variations and modifications which may be made without departing from the scope of the present disclosure.

CLAIMS

What is claimed is:

1. A streamlined body for passing through a fluid, the streamlined body comprising:

an outer surface defining a leading edge and a trailing edge, the leading edge oriented to pass through the fluid before the trailing edge during movement of the body through the fluid; and

a plurality of fibers coupled to the outer surface, each fiber of the plurality of fibers projecting away from the outer surface.

2. The streamlined body of claim 1, wherein the plurality of fibers is positioned on the entirety of the outer surface.

3. The streamlined body of claim 1, wherein the plurality of fibers is positioned on a portion of the outer surface nearer the leading edge than the trailing edge.

4. The streamlined body of claim 3, wherein each fiber of the plurality of fibers has a fiber length of less than or equal to 1.7 mm.

5. The streamlined body of claim 4, wherein each fiber of the plurality of fibers has a fiber length of less than or equal to 0.5 mm.

6. The streamlined body of claim 1, wherein the plurality of fibers is positioned on a portion of the outer surface nearer the trailing edge than the leading edge.

7. The streamlined body of claim 6, wherein each fiber of the plurality of fibers has a fiber length of less than or equal to 10.0 mm.

8. The streamlined body of claim 7, wherein each fiber of the plurality of fibers has a fiber length of less than or equal to 4.0 mm.

9. The streamlined body of claim 1, wherein the streamlined body is a portion of an aircraft, a portion of a land vehicle, a portion of a ship, a portion of an underwater vessel, or a portion of a wind turbine.

10. The streamlined body of claim 9, wherein the streamlined body is in the form of an airfoil.

11. The streamlined body of claim 1, wherein each fiber of the plurality of fibers is constructed of nylon.

12. The streamlined body of claim 1, wherein the plurality of fibers is positioned on the outer surface with at least two discrete sections of the plurality of fibers.

17. The streamlined body of claim 12, wherein one section of the at least two discrete sections of the plurality of fibers is nearer the leading edge than another of the at least two discrete sections, the one section nearer the leading edge having shorter fibers than the other section.

18. The streamlined body of claim 1, wherein each fiber of the plurality of fibers is constructed of cotton, rayon, or polyester.

19. The streamlined body of claim 1, wherein the streamlined body is substantially cylindrical in cross-section.

20. The streamlined body of claim 19, wherein the streamlined body is a wire, a pole, a portion of a garment to be worn by a user, or a portion of an antenna.

21. A pipe for transporting a fluid flow therethrough, the pipe comprising:

an inner wall surface defining an internal passageway of the pipe; and

a plurality of fibers coupled to the inner wall surface, at least some fibers of the plurality of fibers projecting away from the inner wall surface and into the internal passageway.

22. The pipe of claim 21, wherein the at least some fibers project from the inner wall surface substantially parallel to adjacent fibers of the plurality of fibers.

23. The pipe of claim 21, wherein the at least some fibers are of a length selected to exceed a boundary layer thickness of the fluid flow to be passed through the pipe.

24. The pipe of claim 21, wherein the at least some fibers are positioned sufficiently downstream in the internal passageway to be located in a turbulent section of the fluid flow to be passed through the pipe.

25. The pipe of claim 21, wherein the plurality of fibers is positioned on the entire inner wall surface of the pipe.

26. The pipe of claim 21, wherein the at least some fibers have a fiber diameter of less than or equal to 50 μm.

27. The pipe of claim 21, wherein the at least some fibers have a fiber length of less than or equal to 4.0 mm.

28. The pipe of claim 21, wherein the at least some fibers include a plurality of short fibers and a plurality of long fibers, the plurality of short fibers positioned upstream of the plurality of long fibers.

29. The pipe of claim 28, wherein the plurality of short fibers are separated from the plurality of long fibers by a discontinuity distance extending along a length of the pipe.

30. The pipe of claim 28, wherein each fiber of the plurality of short fibers has a fiber length of less than or equal to 0.5 mm.

31. The pipe of claim 30, wherein each fiber of the plurality of long fibers has a fiber length of greater than 0.5 mm and less than or equal to 4.0 mm.

32. The pipe of claim 21, wherein each fiber of the plurality of fibers is constructed of nylon.

33. The pipe of claim 21, wherein the pipe forms an air duct for an HVAC system.

34. The pipe of claim 21, wherein each fiber of the plurality of fibers is constructed of cotton, rayon, or polyester.

35. The pipe of claim 21, wherein the plurality of fibers is coupled to the inner wall downstream from a bend in the pipe.

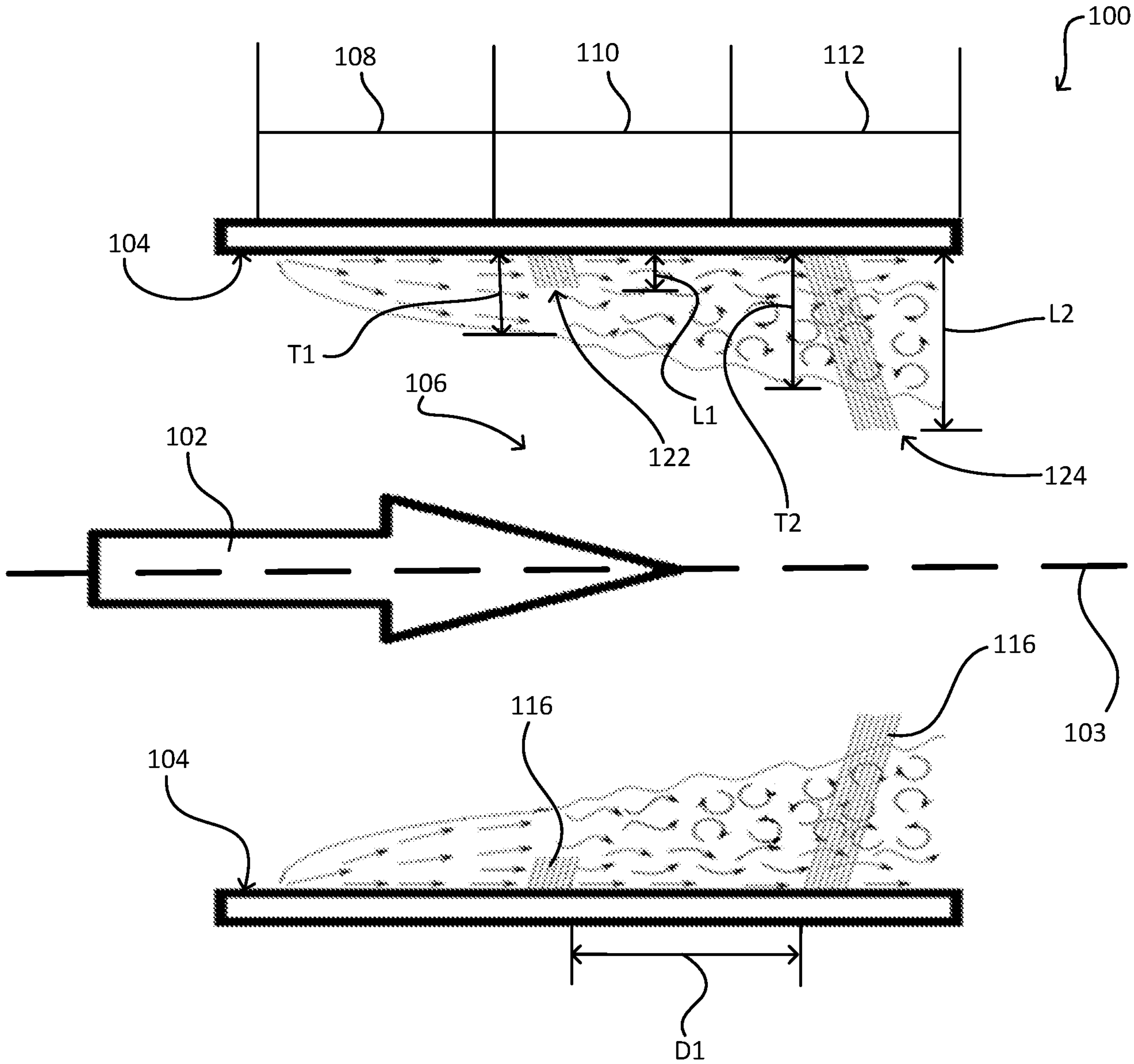

Fig. 1A

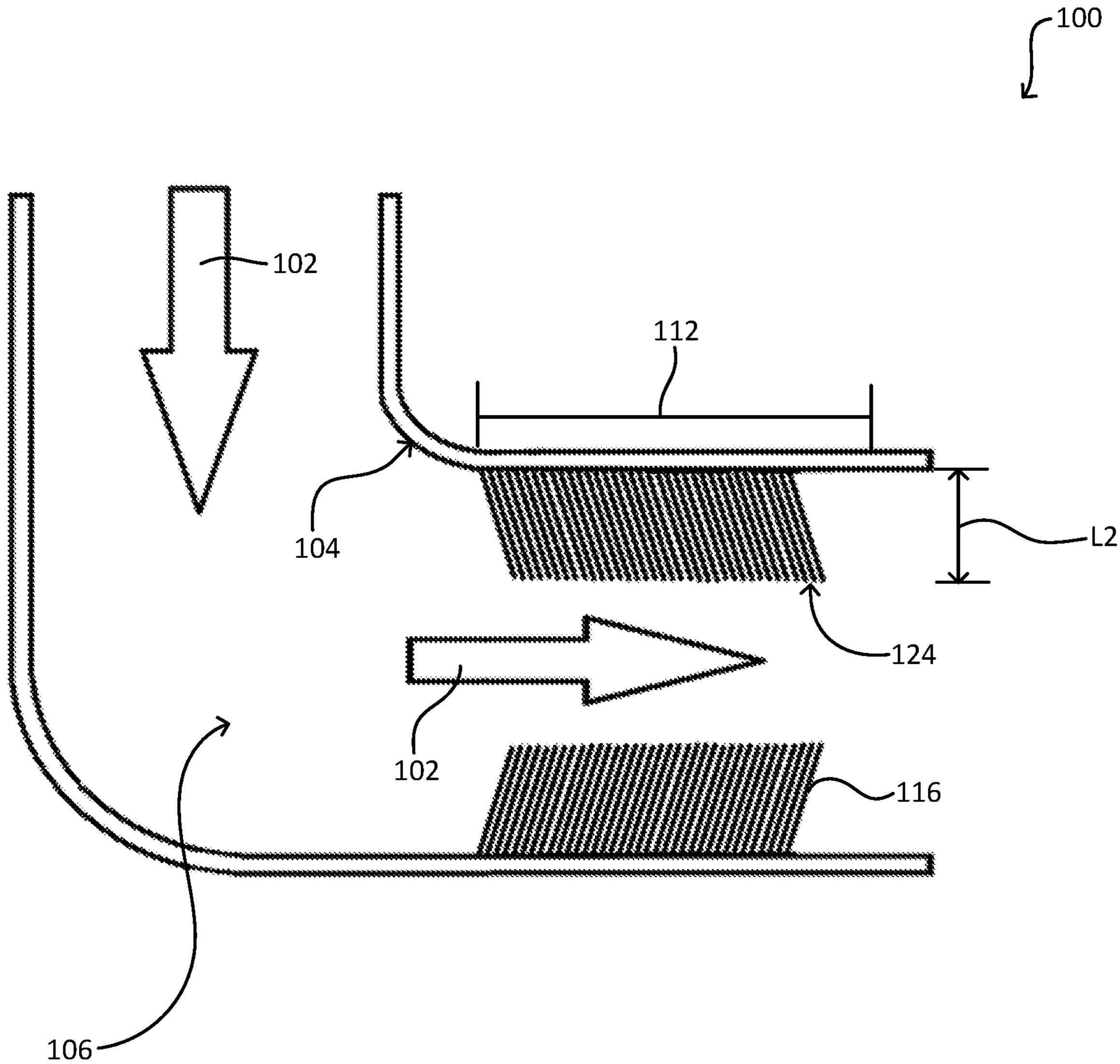

Fig. 1B

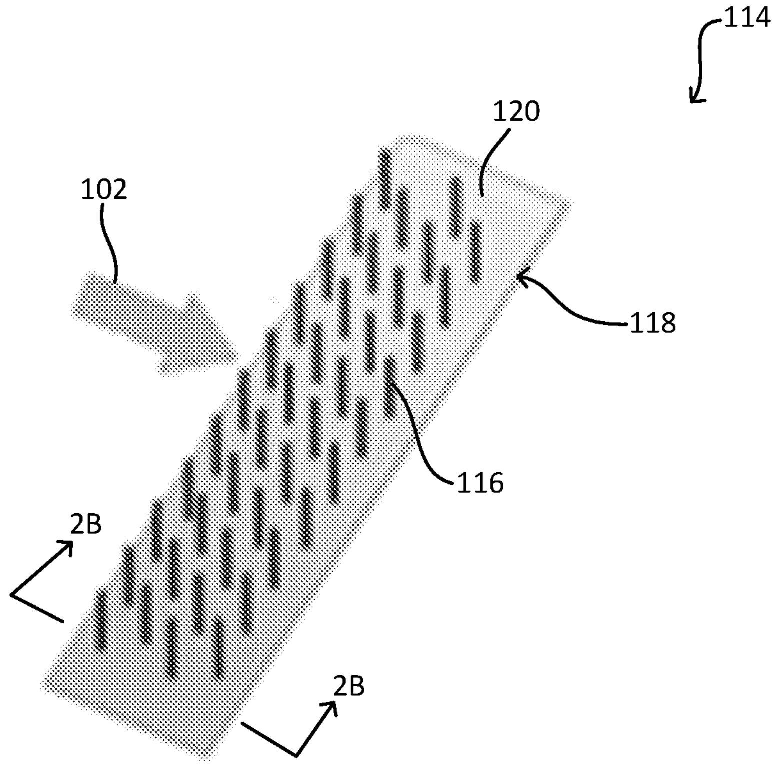

Fig. 2A

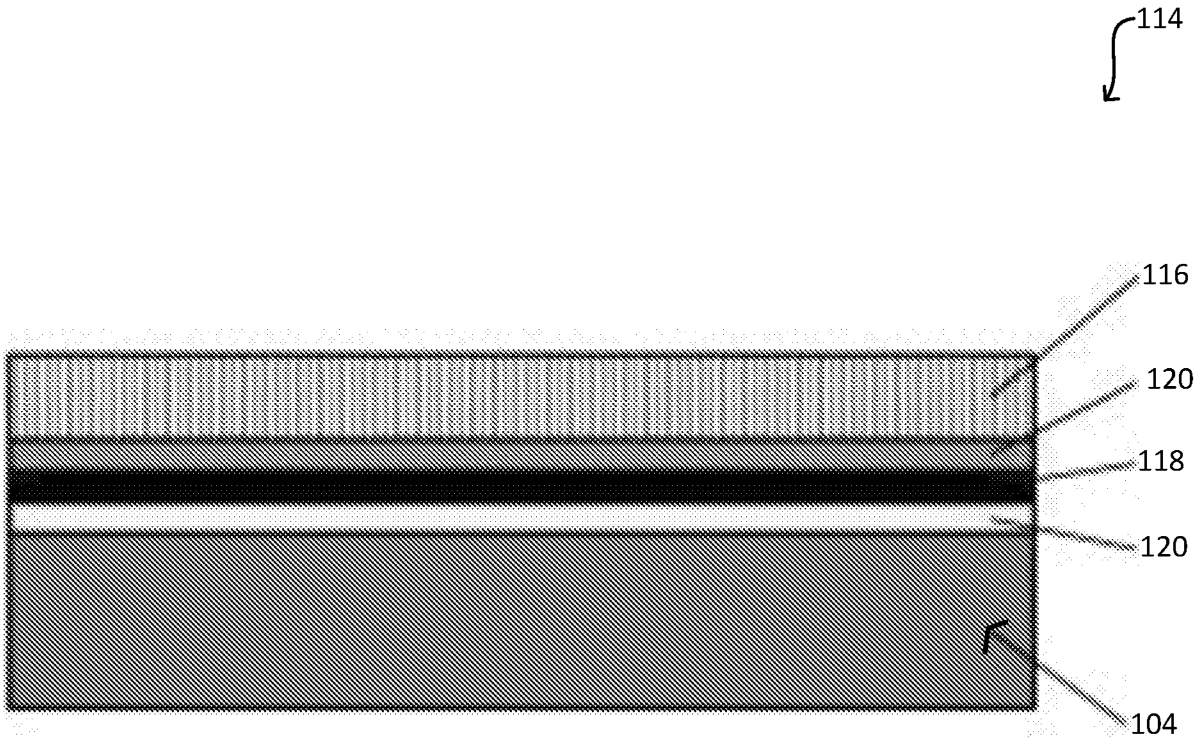

Fig. 2B

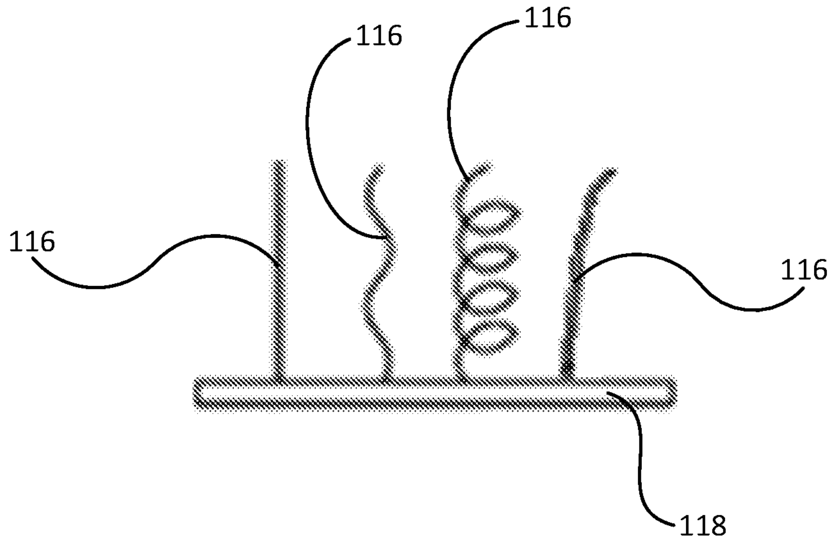

Fig. 3

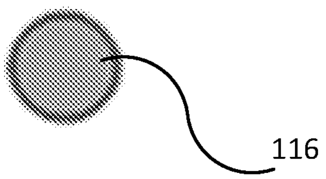

Fig. 4A

Fig. 4B

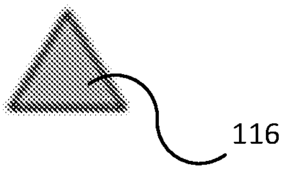

Fig. 4C

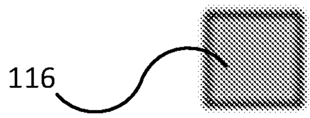

Fig. 4D

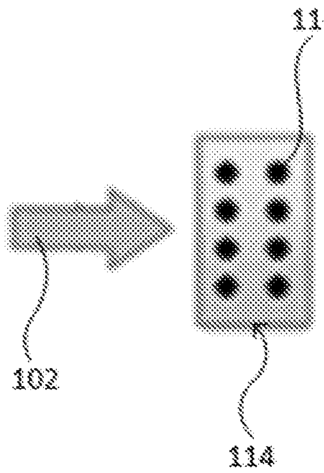

Fig. 5A

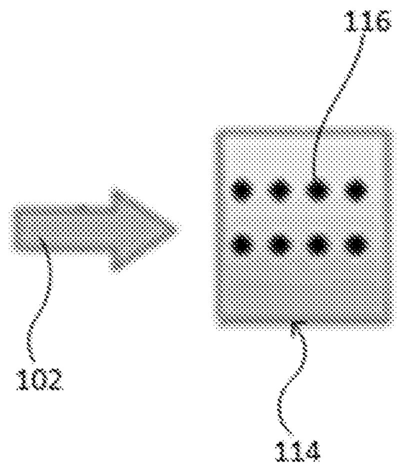

Fig. 5B

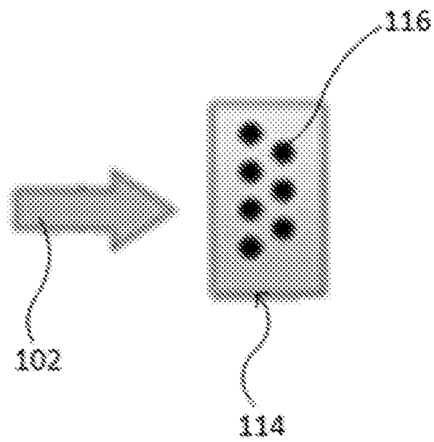

Fig. 5C

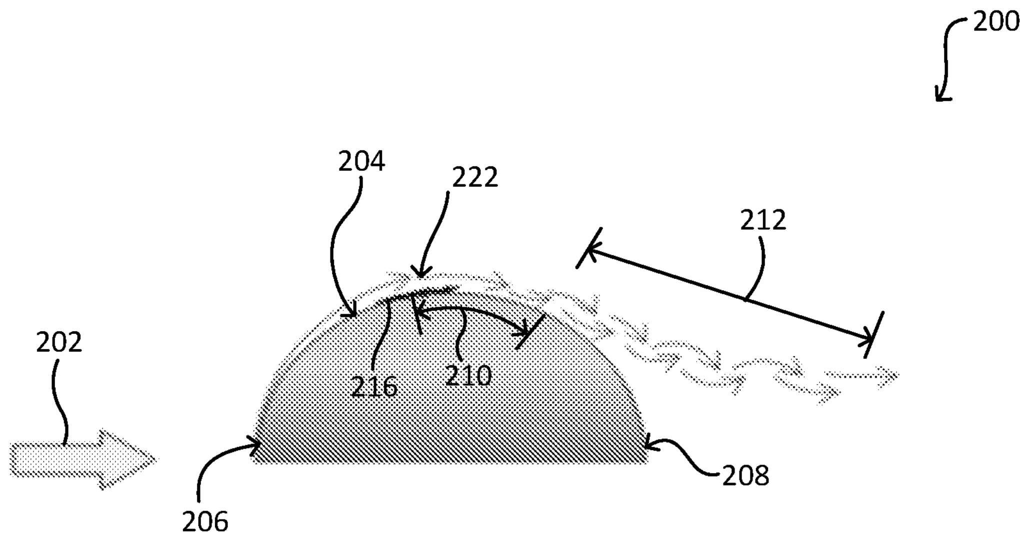
200
204
222
212
202
216
210
208
206

Fig. 6A

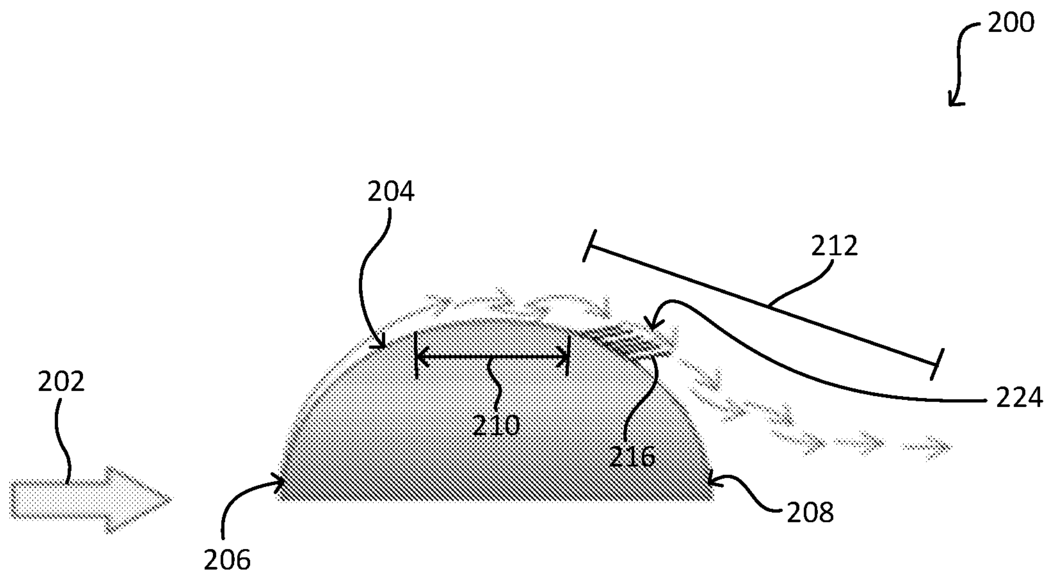
200
204
212
202
224
210
216
208
206

Fig. 6B

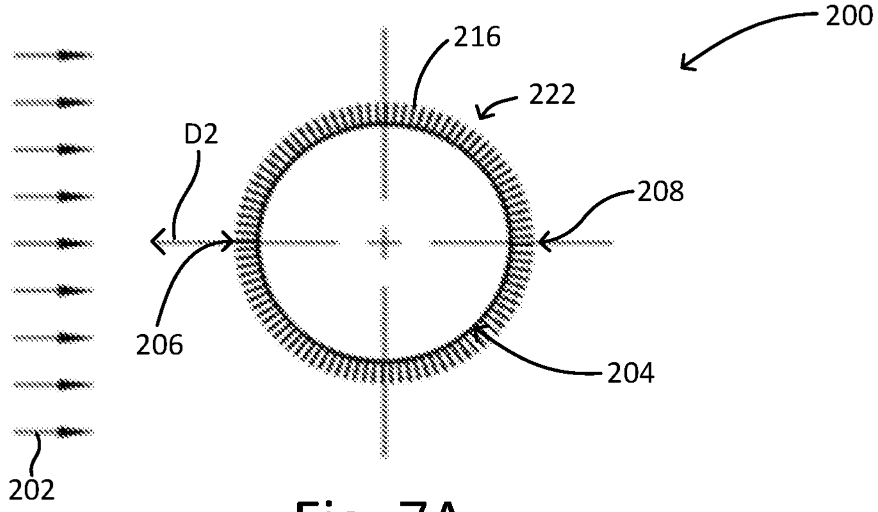

Fig. 7A

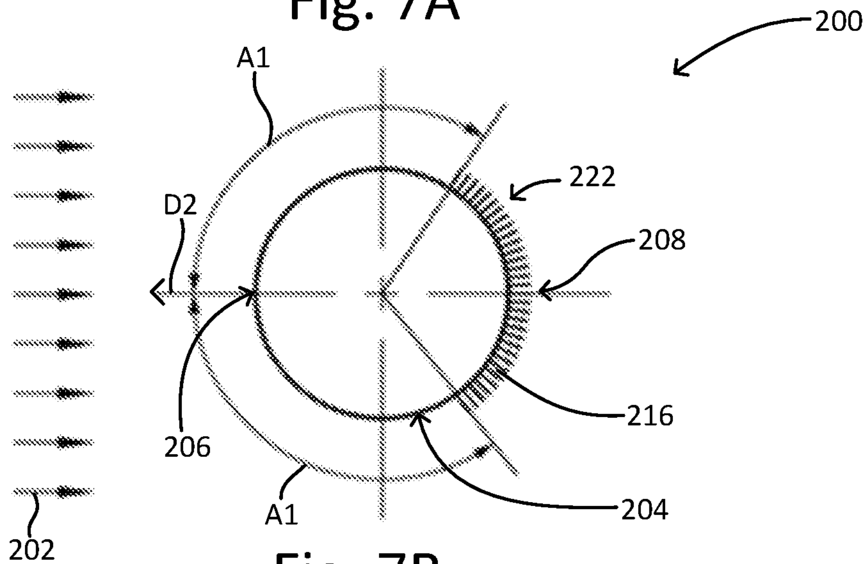

Fig. 7B

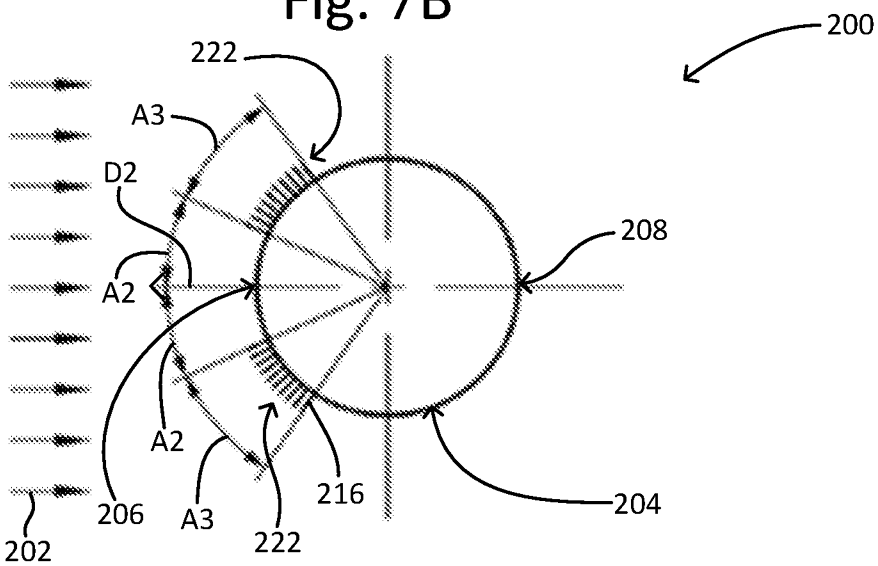

Fig. 7C

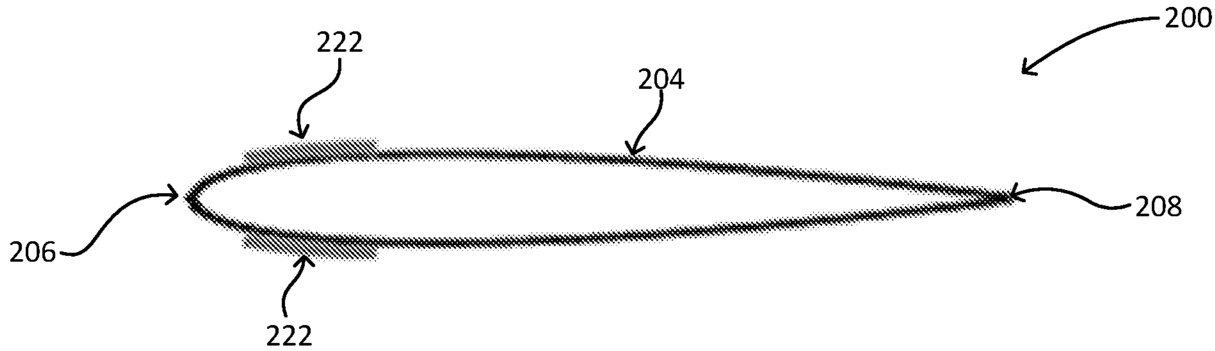

Fig. 8A

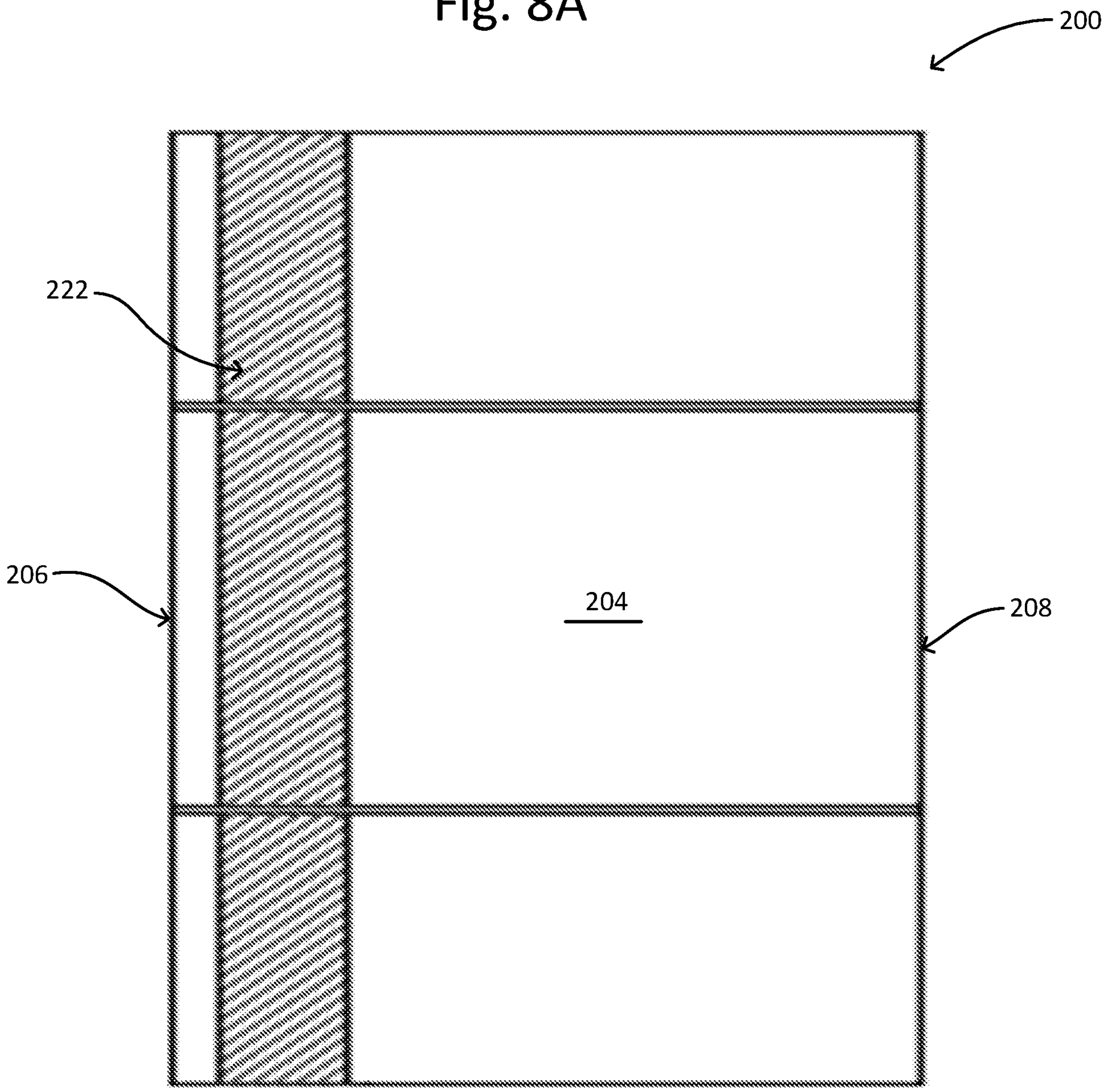

Fig. 8B

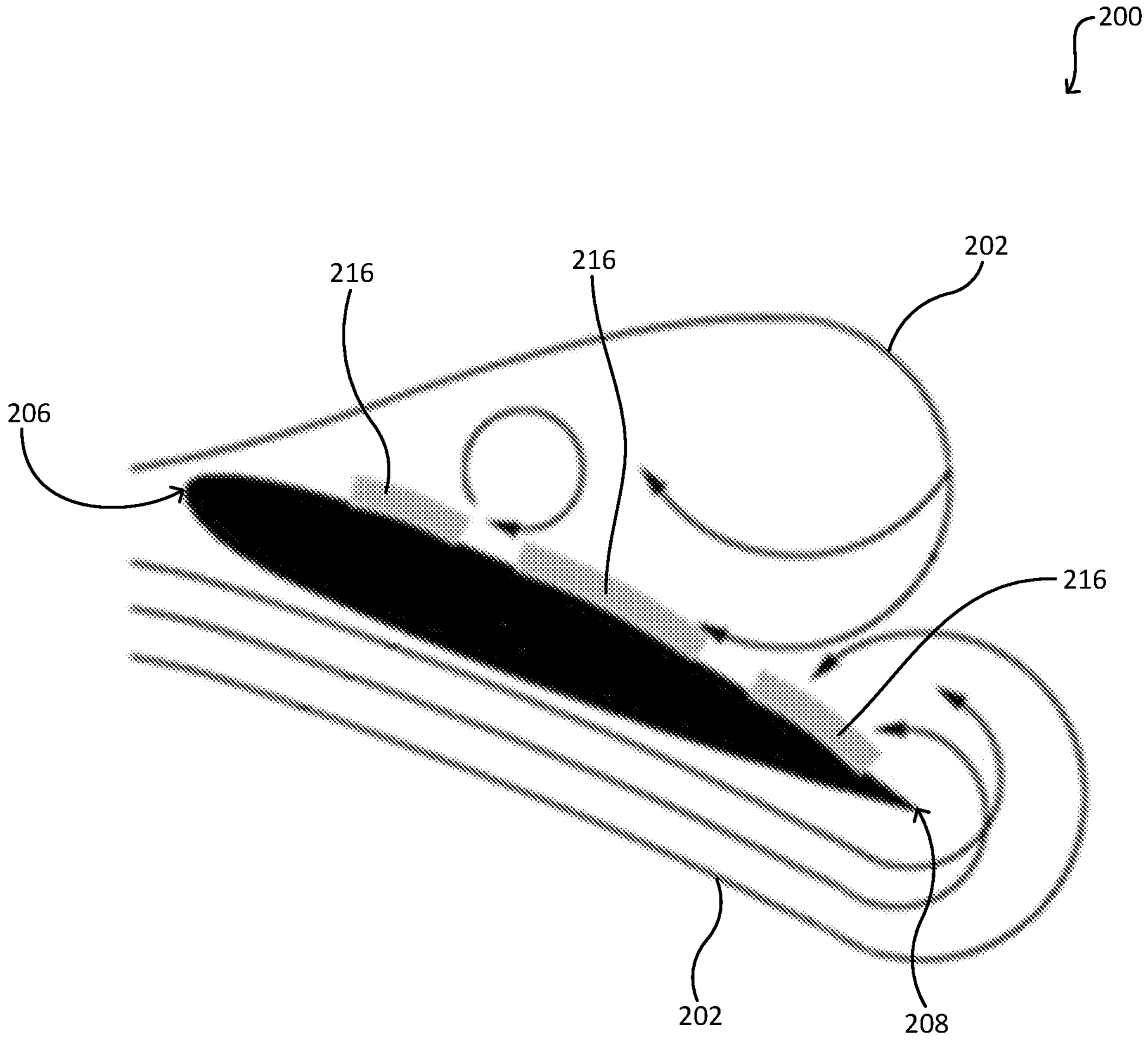

Fig. 9A

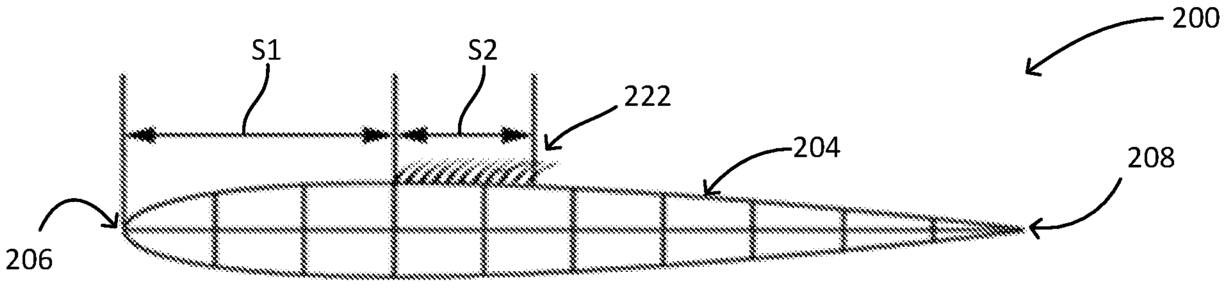

Fig. 9B

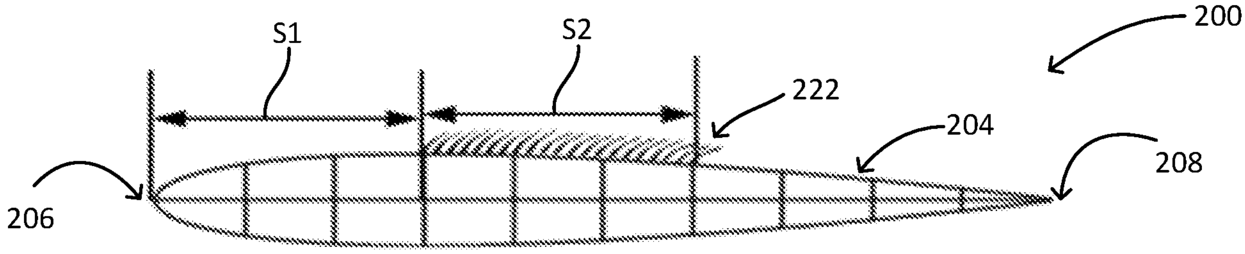

Fig. 9C

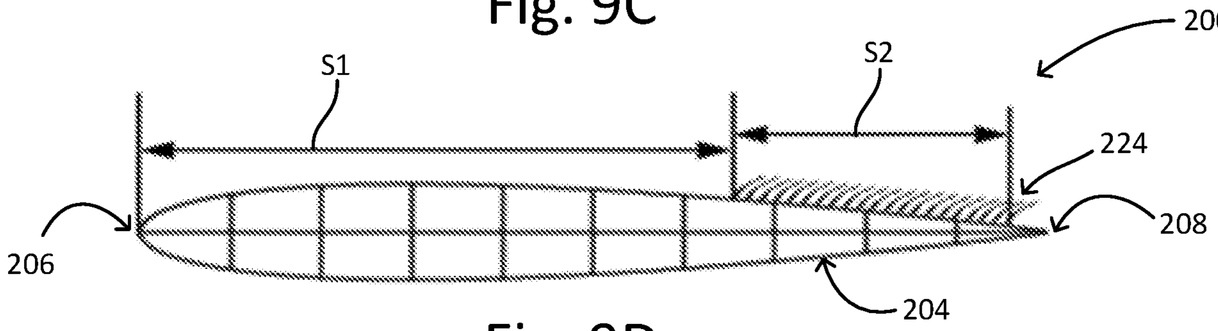

Fig. 9D

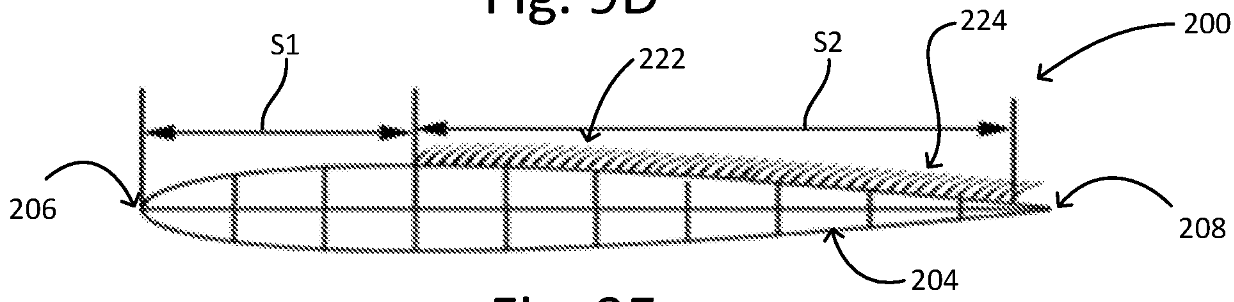

Fig. 9E

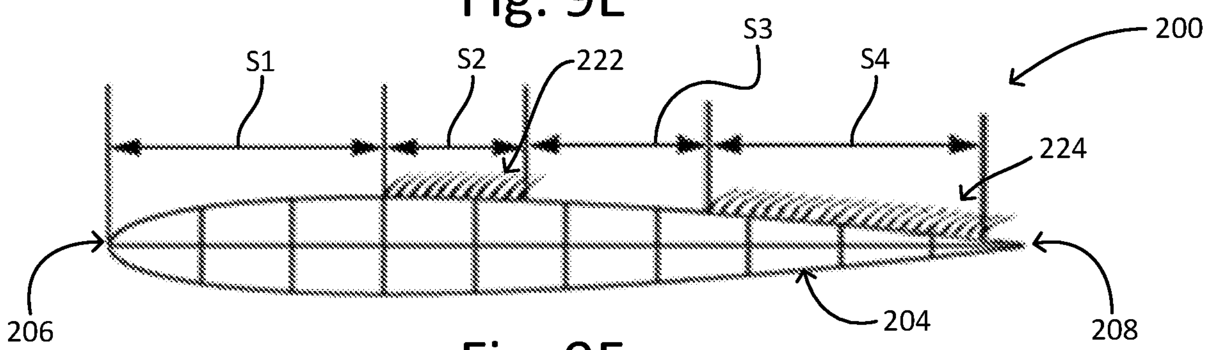

Fig. 9F