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(54) Title: NON-CONTACTING ROTATING MEMBER SEAL FOR A TURBOMACHINE

(57) Abstract: A non-contacting rotary member seal for a turbomachine is provided. The non-contacting rotary member seal may include an annular seal body having an inner annular surface extending axially from a first axial end to a second axial end. The inner annular surface may define a plurality of apertures extending into the annular seal body from the inner annular surface, where an aperture of the plurality of apertures has a first end portion at the inner annular surface and the aperture terminates at a second end portion axially offset, circumferentially offset, or both from the first end portion.

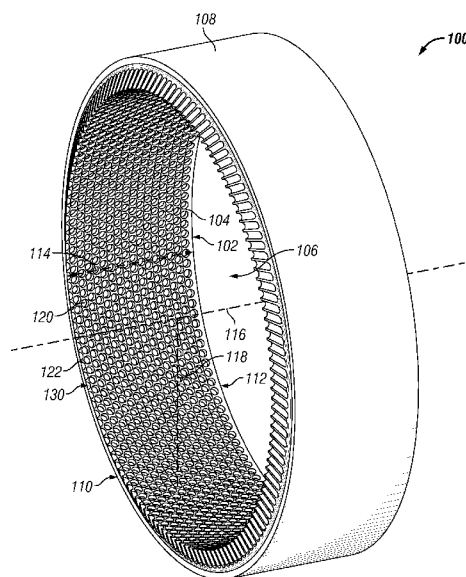


FIG. 2

NON-CONTACTING ROTATING MEMBER SEAL FOR A TURBOMACHINE

[0001] This application claims priority to U.S. Provisional Patent Application having Serial No. 62/112,700, which was filed February 6, 2015. The aforementioned patent application is hereby incorporated by reference in its entirety into the present application to the extent consistent with the present application.

[0002] Non-contacting rotating member seals have been implemented in turbomachines (e.g., turbines, compressors, etc.) to prevent leakage of process fluid between different regions within the turbomachine, or between an internal region of the turbomachine and the external environment. One example of a conventional non-contacting rotating member seal is a labyrinth seal, which generally includes an inner annular seal surface having an axial extent including one or more stationary teeth circumferentially arranged about and placed in close proximity to a relatively smooth surface of a rotary shaft of the turbomachine such that a gap or clearance is defined therebetween. In instances in which the labyrinth seal includes a plurality of stationary teeth, each stationary tooth may be circumferentially arranged about the inner annular seal surface and axially offset from an adjacent stationary tooth, thereby forming respective grooves therebetween and providing a difficult and tortuous flowpath for leakage flow of the process fluid to traverse in the gap formed between the labyrinth seal and the rotary shaft.

[0003] Although used extensively in turbomachines, labyrinth seals may have certain drawbacks, one of which is an adverse effect on the stability of the rotordynamic system of the turbomachine. This adverse effect may be attributed to circumferential or swirl velocity induced into the leakage flow of the process fluid in the gap formed between the labyrinth seal and the rotary shaft due to frictional pumping by the rotating shaft. The effect on the stability of the rotordynamic system by the labyrinth seal may be especially problematic at higher operating pressures. Accordingly, several approaches have been proposed to address the above-mentioned drawback.

[0004] One such approach provides for the implementation of a swirl brake, which generally includes a circumferential array of fins machined into the upstream face of the labyrinth seal and arranged to arrest any swirl velocity in the leakage flow of the process fluid entering the

gap formed between the labyrinth seal and the rotary shaft. Although swirl brakes have been found to be effective in reducing swirl velocity, the array of fins machined into the upstream face of the labyrinth seal may reduce the area of the axial extent of the inner annular seal surface configurable to reduce leakage flow of the process fluid there across.

[0005] Another approach provides for the implementation of a hole-pattern seal to prevent the leakage flow of process fluid between regions within the turbomachine or between an internal region of the turbomachine and the external environment. In such an approach, the circumferential labyrinth teeth may be replaced by a network of ligaments formed between arrays of radially-oriented holes formed in the inner annular seal surface. Unlike the stationary teeth of a labyrinth seal, the ligaments in a hole-pattern seal may create effective process fluid leakage flow barriers in both the axial and circumferential direction, which generally results in effective fluid swirl abatement. Although the hole-pattern seals have been determined to be effective in fluid swirl abatement, the radial orientation of the holes may provide for an inner annular seal surface having an undesirable stiffness, which may result in damage to the inner annular seal surface or the rotary shaft if contact is made with one another.

[0006] What is needed, therefore, is a non-contacting rotating member seal capable of reducing leakage flow of the process fluid between regions within the turbomachine or between an internal region of the turbomachine and the external environment while addressing the aforementioned drawbacks.

[0007] Embodiments of the disclosure may provide a non-contacting rotary member seal for a turbomachine. The non-contacting rotary member seal may include an annular seal body having a seal body center axis extending axially from a first axial end to a second axial end, a radial axis extending radially outward from the seal body center axis, and an inner annular surface radially opposing an outer annular surface. The inner annular surface may define a plurality of apertures extending into the annular seal body from the inner annular surface. An aperture of the plurality of apertures may have an aperture center axis extending into the annular seal body from the inner annular surface and axially from the radial axis at a first angle. The aperture center axis may further extend into the annular seal body from the inner annular surface and circumferentially from the radial axis at a second angle.

[0008] Embodiments of the disclosure may further provide a non-contacting rotary member seal for a turbomachine. The non-contacting rotary member seal may include an annular seal body having an inner annular surface extending axially from a first axial end to a second axial end. The inner annular surface may define a plurality of apertures extending into the annular seal body from the inner annular surface, where an aperture of the plurality of apertures has a first end portion at the inner annular surface and terminates at a second end portion axially offset, circumferentially offset, or both from the first end portion.

[0009] Embodiments of the disclosure may further provide a turbomachine. The turbomachine may include a rotary member arranged for rotation within the turbomachine, and a non-contacting rotary member seal radially offset from an outer circumferential surface of the rotary member such that a gap is defined therebetween. The non-contacting rotary member seal may include an annular seal body having an inner annular surface defining a plurality of apertures extending into the annular seal body from the inner annular surface. An aperture of the plurality of apertures may have a first end portion at the inner annular surface and a second end portion axially offset, circumferentially offset, or both from the first end portion.

[0010] The present disclosure is best understood from the following detailed description when read with the accompanying Figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0011] Figure 1 illustrates a schematic cross-sectional view of a portion of an exemplary turbomachine including exemplary non-contacting rotating member seals disposed in exemplary locations within the turbomachine, according to one or more embodiments of the disclosure.

[0012] Figure 2 illustrates a perspective view of an exemplary non-contacting rotating member seal that may be included in the turbomachine of Figure 1, according to one or more embodiments of the disclosure.

[0013] Figure 3 illustrates an enlarged perspective cutaway view of a portion of the non-contacting rotating member seal of Figure 2.

[0014] Figure 4 illustrates another enlarged perspective view of another portion of the non-contacting rotating member seal of Figure 2.

[0015] Figure 5 illustrates a perspective view of a portion of another exemplary non-contacting rotating member seal that may be included in the turbomachine of Figure 1, according to one or more embodiments of the disclosure.

[0016] Figure 6 illustrates an enlarged perspective view of a portion of an inner annular surface of the exemplary non-contacting rotating member seal of Figure 5.

[0017] Figure 7 illustrates a perspective view of a portion of another exemplary non-contacting rotating member seal that may be included in the turbomachine of Figure 1, according to one or more embodiments of the disclosure.

[0018] Figure 8 illustrates a front view of another portion of the exemplary non-contacting rotating member seal of Figure 7.

[0019] It is to be understood that the following disclosure describes several exemplary embodiments for implementing different features, structures, or functions of the invention. Exemplary embodiments of components, arrangements, and configurations are described below to simplify the present disclosure; however, these exemplary embodiments are provided merely as examples and are not intended to limit the scope of the invention. Additionally, the present disclosure may repeat reference numerals and/or letters in the various exemplary embodiments and across the Figures provided herein. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various exemplary embodiments and/or configurations discussed in the various Figures. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact. Finally, the exemplary embodiments presented below may be combined in any combination of ways, *i.e.*, any element from one exemplary embodiment may be used in any other exemplary embodiment, without departing from the scope of the disclosure.

[0020] Additionally, certain terms are used throughout the following description and claims to refer to particular components. As one skilled in the art will appreciate, various entities may refer to the same component by different names, and as such, the naming convention for the elements described herein is not intended to limit the scope of the invention, unless otherwise specifically defined herein. Further, the naming convention used herein is not intended to distinguish between components that differ in name but not function. Additionally, in the following discussion and in the claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to." All numerical values in this disclosure may be exact or approximate values unless otherwise specifically stated. Accordingly, various embodiments of the disclosure may deviate from the numbers, values, and ranges disclosed herein without departing from the intended scope. Furthermore, as it is used in the claims or specification, the term "or" is intended to encompass both exclusive and inclusive cases, *i.e.*, "A or B" is intended to be synonymous with "at least one of A and B," unless otherwise expressly specified herein.

[0021] Figure 1 shows a schematic cross-sectional view of a portion of an exemplary turbomachine 10 that may be implemented with any of non-contacting rotating member seals 100, 200, 300, according to one or more embodiments of the present disclosure. As shown in Figure 1, the turbomachine may be a centrifugal compressor; however, in other embodiments, the turbomachine 10 may be or include a gas turbine, a steam turbine, an axial flow compressor, a back-to-back compressor, or any other turbomachine in which the reduction or elimination of process fluid leakage from a high pressure region to a low pressure region is desired. Illustrative process fluids may include, but are not limited to, methane, natural gas, air, oxygen, nitrogen, hydrogen, and carbon dioxide.

[0022] The turbomachine 10, illustrated as a centrifugal compressor in Figure 1, generally includes one or more impellers 12 (two are shown) disposed in a housing 14 and coupled to a rotary shaft 16. The impellers 12 may be disposed in respective chambers 18 defined in the housing 14 and forming flowpaths upstream and downstream from each of the impellers 12 to facilitate controlled movement of the process fluids through the impellers 12. In the illustrated turbomachine 10, the impellers 12 are arranged in a cascading fashion such that one of the chambers 18 may couple the output of one impeller 12 to the input of the other

impeller 12. The turbomachine 10 may further include a balance piston 20 disposed about the rotary shaft 16 and configured to counteract the thrust generated by the pressure rise through the impellers 12. The balance piston 20, the rotary shaft 16, and the impellers 12 may be individually or collectively referred to as rotating members.

[0023] To prevent or reduce process fluid leakage from the chambers 18, one or more of the non-contacting rotating member seals 100, 200, 300 according to the teachings of the present disclosure may be incorporated. The non-contacting rotating member seals 100, 200, 300 may be configured with any rotating member of the turbomachine 10 to provide a sealing action to process fluid moving from a higher pressure region to a lower pressure region. As configured with any of the rotating members, a gap or clearance 22 may be formed between the respective non-contacting rotating member seal 100, 200, 300 and the respective outer circumferential surface of the rotating member to allow the rotating member to freely rotate while in operation. The non-contacting rotating member seals 100, 200, 300 may be configured to provide a tortuous flowpath for the process fluid to traverse in the gap, thereby providing a sealing action to the moving process fluid.

[0024] According to the teachings of the present disclosure, the non-contacting rotating member seals 100, 200, 300 may be disposed in various locations within the housing 14 including, but not limited to, the illustrative locations of Figure 1. As shown in the embodiment of Figure 1, any of the non-contacting rotating member seals 100, 200, 300 may be disposed adjacent the rotary shaft 16 at location 24a. At this location 24a, the non-contacting rotating member seal 100, 200, 300 may be generally referred to as a shaft seal. In another embodiment, any of the non-contacting rotating member seals 100, 200, 300 may be configured with a balance piston 20 at location 24b, where the non-contacting rotating member seal 100, 200, 300 may be referred to as a balance piston seal when used with a straight-through compressor or a division-wall seal when used with a back-to-back compressor. In another embodiment, any of the non-contacting rotating member seals 100, 200, 300 may be configured on the front shroud portion of each of the impellers 12 at location 24c, where the non-contacting rotating member seal 100, 200, 300 may be referred to as an eye packing shaft seal.

[0025] Referring now to Figures 2-4, with continued reference to Figure 1, Figure 2 illustrates a perspective view of an embodiment of the non-contacting rotating member seal

100 that may be included in the turbomachine of Figure 1 and utilized at one or more of the locations 24a-c therein to reduce or prevent process fluid leakage from the chambers 18 and to provide a sealing action to the process fluid moving from a higher pressure region to a lower pressure region. Figures 3 and 4 illustrate differing enlarged perspective views of respective portions of the non-contacting rotating member seal 100. The non-contacting rotating member seal 100 may separate a high pressure region or side from a low pressure region or side within the turbomachine 10 as the rotary shaft 16 rotates about a shaft center axis 26.

[0026] The non-contacting rotating member seal 100 generally includes an annular seal body 102 having an inner annular surface 104 defining a borehole 106 through which a rotating member, such as the rotary shaft 16, may extend, and an outer annular surface 108 radially opposing the inner annular surface 104 and configured to couple with the housing 14. The annular seal body 102 may also include a first axial end 110 and a second axial end 112 separated from and axially opposing the first axial end 110 by an axial extent 114 of the inner annular surface 104. As positioned in the turbomachine 10, the non-contacting rotating member seal 100 may be disposed concentrically with the rotary shaft 16 or other rotating member and may have a seal body center axis 116 extending axially from the first axial end 110 to the second axial end 112 and a radial axis 118 extending radially outward from the seal body center axis 116.

[0027] The inner annular surface 104 may define a plurality of apertures 120 axially arrayed along the axial extent 114 from the first axial end 110 and to the second axial end 112 of the annular seal body 102. In an exemplary embodiment, the plurality of apertures 120 may be arrayed circumferentially in the inner annular surface 104 in addition to being axially arrayed along the axial extent 114 from the first axial end 110 to the second axial end 112, as shown in Figure 2. Accordingly, a plurality of annular rows may be formed along the axial extent 114 of the inner annular surface 104. In between respective apertures 120, the inner annular surface 104 may form ligaments 122 defining the sidewalls of the respective apertures 120. To form the plurality of apertures 120 and the respective ligaments 122 therebetween in the inner annular surface 104, each of the apertures 120 may be machined or otherwise milled into the inner annular surface 104 of the annular seal body 102.

[0028] As shown in respective enlarged views in Figures 3 and 4, the plurality of apertures 120 may extend into the annular seal body 102 from the inner annular surface 104. For clarity purposes, only the first three rows of the plurality of annular rows are illustrated in Figures 3 and 4; however, it will be appreciated that the respective illustrated embodiments contemplate a plurality of annular rows extending arrayed along the axial extent 114 from the first axial end 110 to the second axial end 112. Each aperture 120 may include a first end portion 124 at the inner annular surface 104 and a second end portion 126 in the annular seal body 102 at which the aperture 120 terminates. As shown most clearly in Figure 3, in one embodiment, the first end portion 124 and the second end portion 126 of one or more of the apertures 120 are arranged such that the first end portion 124 and the second end portion 126 are axially offset from one another. As shown most clearly in Figure 4, in another embodiment, the first end portion 124 and the second end portion 126 of one or more of the apertures 120 are arranged such that the first end portion 124 and the second end portion 126 are circumferentially offset from one another. In another embodiment, the first end portion 124 and the second end portion 126 of one or more of the apertures 120 are arranged such that the first end portion 124 and the second end portion 126 are circumferentially offset from one another and axially offset from one another.

[0029] Accordingly, the plurality of apertures 120 may extend into the inner annular surface 104 in a non-radial direction, e.g., at a direction diverging from the radial axis 118. Although a single radial axis 118 is shown in Figures 2-4, it will be appreciated that the non-contacting rotating member seal 100 may have a multitude of radial axes 118 extending radially outward from the seal body center axis 116, such that each aperture 120 may be oriented with respect to a corresponding radial axis 118 extending radially into the annular seal body 102 from the first end portion 124 of the aperture 120. Accordingly, as shown in most clearly in Figure 3, each aperture center axis 128 of the plurality of apertures 120 may extend into the annular seal body 102 from the inner annular surface 104 and axially from a respective radial axis 118 at an acute angle β . In an exemplary embodiment, the acute angle β may be about 30 degrees. In another embodiment, the acute angle β may be less than about 40 degrees, less than about 35 degrees, less than about 30 degrees, less than about 25 degrees, less than about 20 degrees, less than about 15 degrees, less than about 10 degrees, or less than about 5 degrees. It should be appreciated that all numerical values and ranges disclosed herein are approximate values and ranges, whether "about" is

used in conjunction therewith. It should also be appreciated that the term "about," as used herein, in conjunction with a numeral refers to a value that is $\pm 5\%$ (inclusive) of that numeral, $\pm 10\%$ (inclusive) of that numeral, or $\pm 15\%$ (inclusive) of that numeral. It should further be appreciated that when a numerical range is disclosed herein, any numerical value falling within the range is also specifically disclosed.

[0030] As shown in most clearly in Figure 4, each aperture center axis 128 of the plurality of apertures 120 may also extend into the annular seal body 102 from the inner annular surface 104 and circumferentially from a respective radial axis 118 at an angle θ . In an exemplary embodiment, the angle θ may be less than 90 degrees. In another embodiment, the angle θ may be less than about 75 degrees. In another embodiment, the angle θ may be less than about 60 degrees. In another embodiment, the angle θ may be less than about 45 degrees, less than about 35 degrees, less than about 30 degrees, less than about 20 degrees, less than about 15 degrees, less than about 10 degrees, or less than about 5 degrees. The angle θ may be determined based, at least in part, on the amount of swirl dissipation desired relative to the reduction in axial leakage flow. For example, an angle θ of zero degrees maximizes the axial leakage flow, whereas a greater angle θ , e.g., 45 degrees, has a greater influence on swirl reduction. Accordingly, an optimum value may be arranged by factoring the rotary shaft size, the rotary shaft rotational speed, and a nominal amount of axial leakage flow.

[0031] One or more of the plurality of apertures 120 may terminate in the annular seal body 102 such that the second end portion 126 of the respective apertures 120 forms a conical end portion in the annular seal body 102. The formation of the conical end portion in one or more of the apertures 120 provides for improved dissipation of kinetic energy in the process leakage flow as the process leakage flow expands into the volume of each aperture 120. Although depicted in Figures 2-4 as terminating in a conical end portion, those of ordinary skill in the art will appreciate that the second end portion 126 of the respective apertures 120 may terminate in any other profile capable of dissipating kinetic energy in the process leakage flow as the process leakage flow expands into the volume of each aperture 120. For example, the respective apertures 120 may terminate in a planar end surface, such as a cylindrical end surface.

[0032] In an exemplary embodiment, the plurality of annular rows formed from the arrayed apertures 120 includes a first annular row 130 of the plurality of apertures 120 that may be circumferentially arrayed in the inner annular surface 104 at the first axial end 110 and configured to reduce swirl in the process leakage flow. Each of the apertures 120 in the first annular row 130 may extend further into the annular seal body 102 from the inner annular surface 104 than the remaining annularly arrayed rows of apertures 120 along the axial extent 114 of the inner annular surface 104. A portion of the first axial end 110 may be removed via machining or milling at the first annular row 130 of the plurality of apertures 120 to about the aperture center axis 128 of each of the apertures 120 such that about half of the axial extent of the first annular row 130 of the plurality of apertures 120 may be removed and the remaining half of the first annular row 130 remains after the removal of the portion of the first axial end 110. The portions of the ligaments 122 and apertures 120 remaining in the first annular row 130 may form a circumferential array of scalloped fins capable of reducing swirl and thereby functioning as a swirl brake. By incorporating the function of the first annular row 130 of apertures 120 as a swirl brake, the axial extent 114 of the annular seal body 102 configurable to provide a sealing action to the moving process fluid is maximized.

[0033] As shown most clearly in Figure 4, the plurality of apertures 120 may be circumferentially and axially arrayed such that the apertures 120 are arranged in triangular arrays 132. The arrangement of the apertures 120 in such triangular arrays 132 is provided to maximize the number of ligaments 122 per unit length (and circumference) of the non-contacting rotating member seal 100, thereby reducing the amount of process fluid leakage.

[0034] Figure 5 illustrates a perspective view of an embodiment of the non-contacting rotating member seal 200 that may be included in the turbomachine of Figure 1 and utilized at one or more of the locations 24a-c therein to prevent process fluid leakage from the chambers 18 and to provide a sealing action to the process fluid moving from a higher pressure region to a lower pressure region. Figure 6 illustrates an enlarged perspective view of another portion of the exemplary non-contacting rotating member seal 200 of Figure 5. The non-contacting rotating member seal 200 illustrated in Figures 5 and 6 may be similar in some respects to the non-contacting rotating member seal 100 described above and therefore may be best understood with reference to the description of Figures 2-4,

where like numerals may designate like components and will not be described again in detail. As illustrated in Figures 5 and 6, the non-contacting rotating member seal 200 may include a plurality of scalloped fins formed from the ligaments 122 and apertures 120 remaining in the first annular row 130. In addition to the plurality of scalloped fins, the non-contacting rotating member seal 200 may include a plurality of vanes or brake fins 202 formed in the annular seal body 102 and circumferentially arrayed at the first axial end 110 of the non-contacting rotating member seal 200. The plurality of brake fins 202 may extend radially between the inner annular surface 104 and the outer annular surface 108 and may be configured to reduce swirl in the process fluid leakage flow. The brake fins 202 may be machined or milled from the first axial end 110 and at least a portion of each of the brake fins 202 may be radially offset from the plurality of scalloped fins.

[0035] Figure 7 illustrates a perspective view of a portion of an embodiment of the non-contacting rotating member seal 300 that may be included in the turbomachine of Figure 1 and utilized at one or more of the locations 24a-c therein to prevent process fluid leakage from the chambers 18 and to provide a sealing action to the process fluid moving from a higher pressure region to a lower pressure region. Figure 8 illustrates a front view of another portion of the exemplary non-contacting rotating member seal 300 of Figure 7. The non-contacting rotating member seal 300 illustrated in Figures 7 and 8 may be similar in some respects to the non-contacting rotating member seals 100, 200 described above and therefore may be best understood with reference to the description of Figures 2-6, where like numerals may designate like components and will not be described again in detail. As illustrated in Figures 7 and 8, the non-contacting rotating member seal 300 may include a plurality of scalloped fins formed from the ligaments 122 and apertures 120 remaining in the first annular row 130. In addition to the plurality of scalloped fins, the non-contacting rotating member seal 300 may include a plurality of vanes or brake fins 302 formed in the annular seal body 102 and circumferentially arrayed at the first axial end 110 of the non-contacting rotating member seal 300. The plurality of brake fins 302, as arranged, may be configured to reduce swirl in the leakage flow of the process fluid. Each brake fin 302 may include a first brake fin end portion 304 and a second brake fin end portion 306. Each brake fin 302 may extend between the inner annular surface 104 and the outer annular surface 108, such that the first brake fin end portion 304 and the second brake fin end portion 306 are circumferentially offset, and thus, are angled or non-radial in orientation.

Such angling may provide for an increased reduction in swirl velocity. The brake fins 302 may be machined or milled from the first axial end 110 and at least a portion of each of the brake fins 302 may be radially offset from the plurality of scalloped fins.

[0036] As disclosed herein, each of the non-contacting rotating member seals 100, 200, 300 provides for maximizing the axial extent 114 of the inner annular surface 104 extending from the first axial end 110 to the second axial end 112 to reduce leakage flow of process fluids while providing a swirl brake to reduce circumferential velocity of the leakage flow. The orientation of the apertures 120 in a non-radial orientation provides for a reduction in radial stiffness of the ligaments 122, thereby minimizing damage to the rotary member, *e.g.*, rotary shaft 16, and/or non-contacting rotating member seal 100, 200, 300 in instances of contact with one another. In addition, the orientation of the apertures 120 in a non-radial orientation provides improved reduction in leakage of process fluid flow over a radial orientation of the apertures 120. Without being bound by theory, the improvement in leakage flow reduction may be attributed to a larger free jet expansion of the flow into the apertures 120, causing more through flow blockage. Further, because of the combined usage of the apertures 120 to reduce both leakage flow and circumferential velocity of the process fluid, the additional cost of manufacturing separate swirl brake vanes may be eliminated.

[0037] The foregoing has outlined features of several embodiments so that those skilled in the art may better understand the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions and alterations herein without departing from the spirit and scope of the present disclosure.

Claims

I claim:

1. A non-contacting rotary member seal for a turbomachine, comprising:
an annular seal body comprising:
a seal body center axis extending axially from a first axial end to a second axial end;
a radial axis extending radially outward from the seal body center axis; and
an inner annular surface radially opposing an outer annular surface, the inner annular surface defining a plurality of apertures extending into the annular seal body from the inner annular surface, wherein an aperture of the plurality of apertures has an aperture center axis that extends into the annular seal body from the inner annular surface and axially from the radial axis at a first angle and further extends into the annular seal body from the inner annular surface and circumferentially from the radial axis at a second angle.
2. The non-contacting rotary member seal of claim 1, wherein the plurality of apertures are axially arrayed along an axial extent of the inner annular surface of the annular seal body.
3. The non-contacting rotary member seal of claim 2, wherein the plurality of apertures are further circumferentially arrayed in the inner annular surface along the axial extent and about the seal body center axis, thereby forming a plurality of annular rows of apertures.
4. The non-contacting rotary member seal of claim 3, wherein the plurality of apertures are arranged in a triangular array.
5. The non-contacting rotary member seal of claim 3, wherein the plurality of annular rows of apertures comprises a first annular row of apertures disposed at the first axial end of the annular seal body, each aperture of the first annular row of apertures separated from an adjacent aperture by a respective ligament formed in the annular seal body, the ligaments and the apertures of the first annular row of apertures forming an array of

scalloped fins configured to redirect circumferential flow of process fluid leakage flowing therethrough.

6. The non-contacting rotary member seal of claim 5, further comprising a plurality of vanes extending between the inner annular surface and the outer annular surface and further arranged circumferentially about the seal body center axis, the plurality of vanes configured to redirect the circumferential flow of process fluid leakage.

7. The non-contacting rotary member seal of claim 6, wherein one or more vanes of the plurality of vanes are circumferentially offset from the inner annular surface to the outer annular surface.

8. The non-contacting rotary member seal of claim 1, wherein the aperture of the plurality of apertures extending into the annular seal body from the inner annular surface terminates in a conical end portion.

9. The non-contacting rotary member seal of claim 1, wherein the aperture of the plurality of apertures extending into the annular seal body from the inner annular surface terminates in a cylindrical end surface.

10. The non-contacting rotary member seal of claim 1, wherein the first angle is less than about ninety degrees, and the second angle is less than about ninety degrees.

11. The non-contacting rotary member seal of claim 1, wherein the first angle is about thirty degrees, and the second angle is less than about forty-five degrees.

12. A non-contacting rotary member seal for a turbomachine, comprising:
an annular seal body comprising an inner annular surface extending axially from a first axial end to a second axial end, the inner annular surface defining a plurality of apertures extending into the annular seal body from the inner annular surface, wherein an aperture of the plurality of apertures has a first end portion at the inner annular surface and

terminates at a second end portion axially offset, circumferentially offset, or both from the first end portion.

13. The non-contacting rotary member seal of claim 12, wherein the second end portion forms a conical end portion in the annular seal body.

14. The non-contacting rotary member seal of claim 12, wherein the plurality of apertures are axially and circumferentially arrayed in the inner annular surface of the annular seal body, such that the plurality of apertures form a plurality of annular rows of apertures arranged to form a triangular array.

15. The non-contacting rotary member seal of claim 14, wherein the plurality of annular rows of apertures comprises a first annular row of apertures disposed at the first axial end of the annular seal body, each aperture of the first annular row of apertures separated from an adjacent aperture by a respective ligament formed in the annular seal body, the ligaments and the apertures of the first annular row of apertures forming an array of scalloped fins configured to redirect circumferential flow of process fluid leakage flowing therethrough.

16. The non-contacting rotary member seal of claim 15, further comprising a plurality of vanes extending between the inner annular surface and an outer annular surface radially opposing the inner annular surface, the plurality of vanes further arranged circumferentially about the seal body center axis and configured to redirect the circumferential flow of process fluid leakage.

17. The non-contacting rotary member seal of claim 16, wherein each of the plurality of vanes extends radially between the inner annular surface and the outer annular surface.

18. The non-contacting rotary member seal of claim 16, wherein one or more vanes of the plurality of vanes are circumferentially offset from the inner annular surface to the outer annular surface.

19. A turbomachine comprising:

a rotary member arranged for rotation within the turbomachine; and

a non-contacting rotary member seal radially offset from an outer circumferential surface of the rotary member such that a gap is defined therebetween, the non-contacting rotary member seal comprising:

an annular seal body comprising an inner annular surface defining a plurality of apertures extending into the annular seal body from the inner annular surface, wherein an aperture of the plurality of apertures has a first end portion at the inner annular surface and a second end portion axially offset, circumferentially offset, or both from the first end portion.

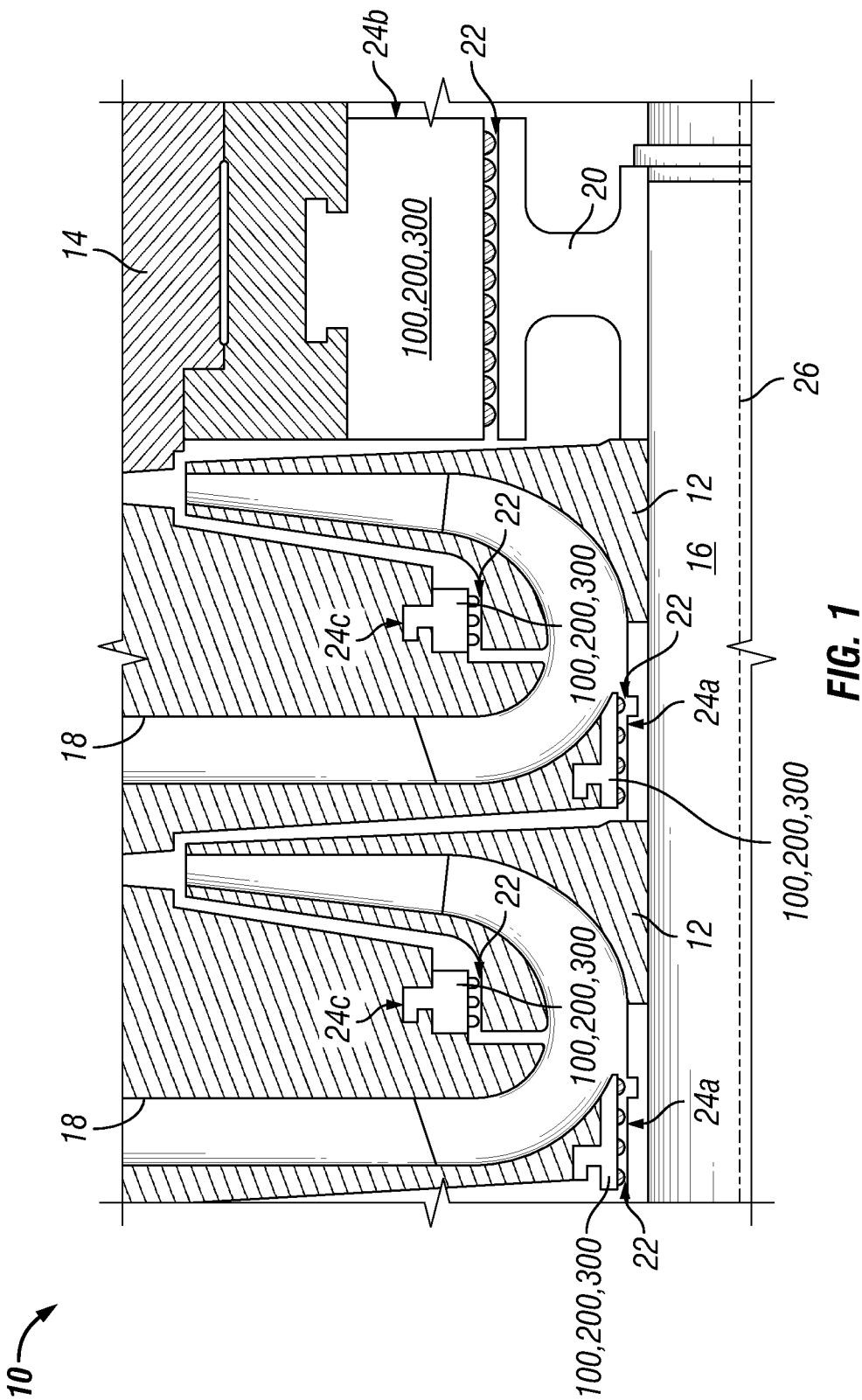
20. The turbomachine of claim 19, wherein the non-contacting rotary member seal further comprises:

a plurality of vanes extending between the inner annular surface and the outer annular surface and further arranged circumferentially about the seal body center axis, the plurality of vanes configured to redirect circumferential flow of process fluid leakage,

wherein the plurality of apertures are axially and circumferentially arrayed in the inner annular surface of the annular seal body, such that the plurality of apertures forms a plurality of annular rows of apertures arranged to form a triangular array;

wherein the plurality of annular rows of apertures comprises a first annular row of apertures disposed at the first axial end of the annular seal body, each aperture of the first annular row of apertures separated from an adjacent aperture by a respective ligament formed in the annular seal body, the ligaments and the apertures of the first annular row of apertures forming an array of scalloped fins configured to redirect the circumferential flow of process fluid leakage flowing therethrough; and

wherein the aperture terminates in the second end portion and forms a conical end portion in the annular seal body.



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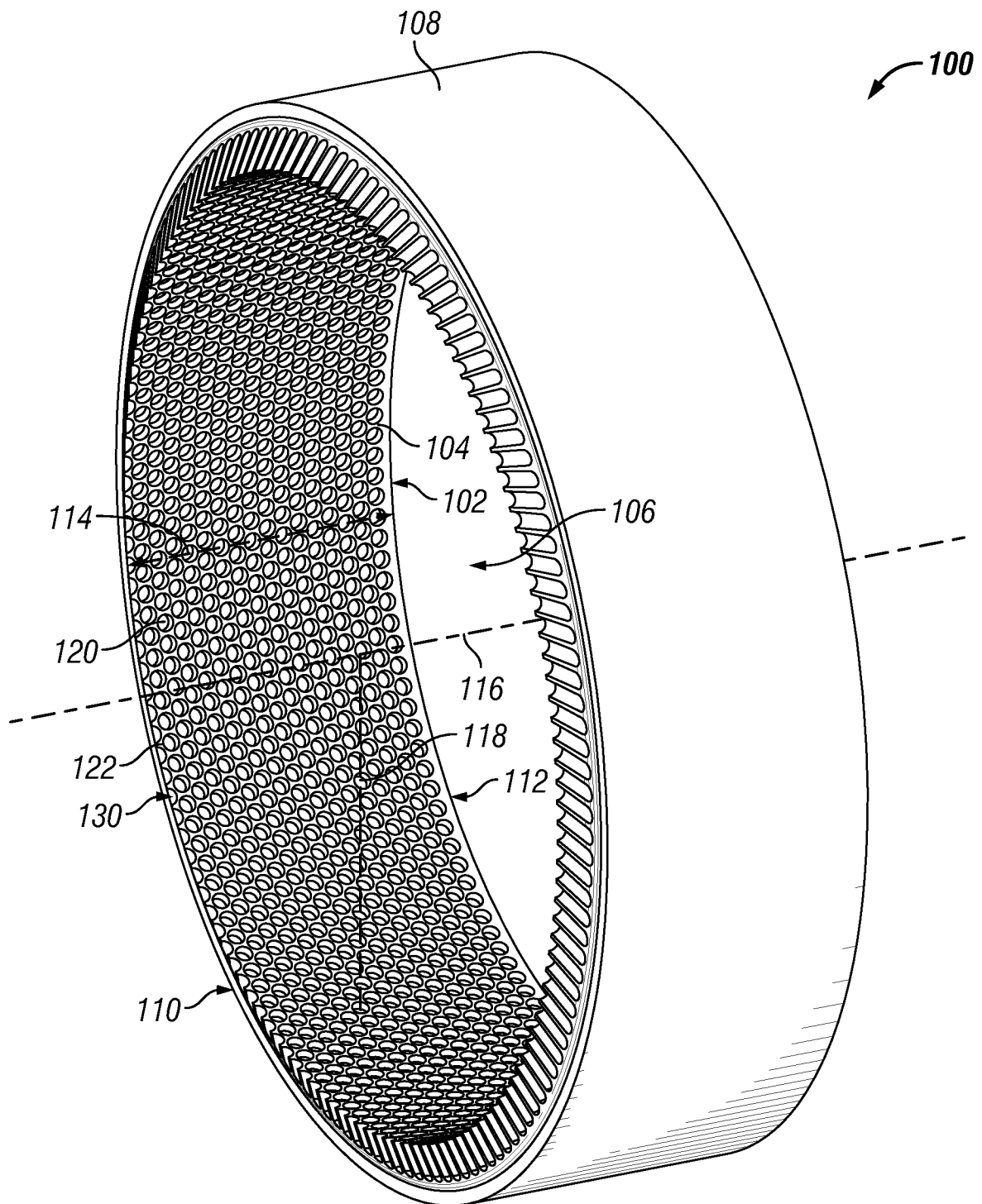
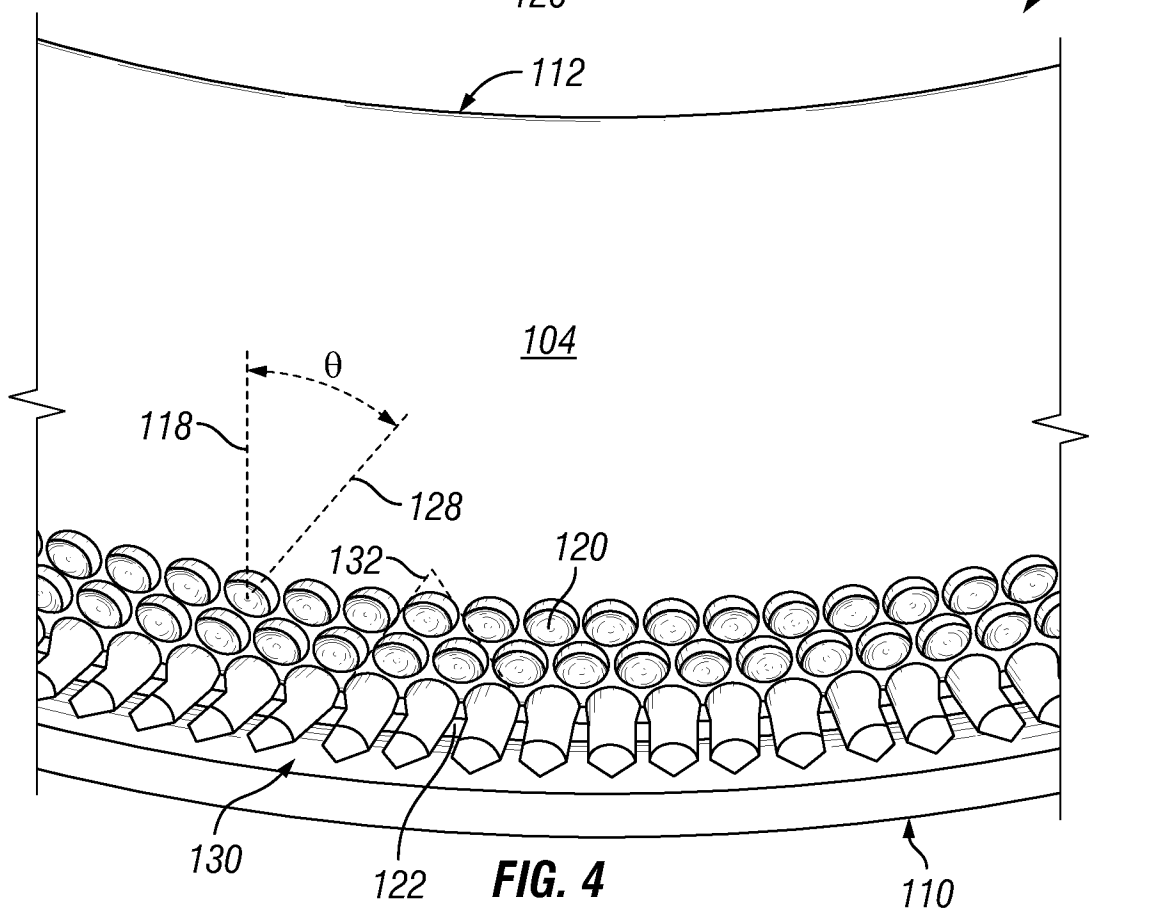
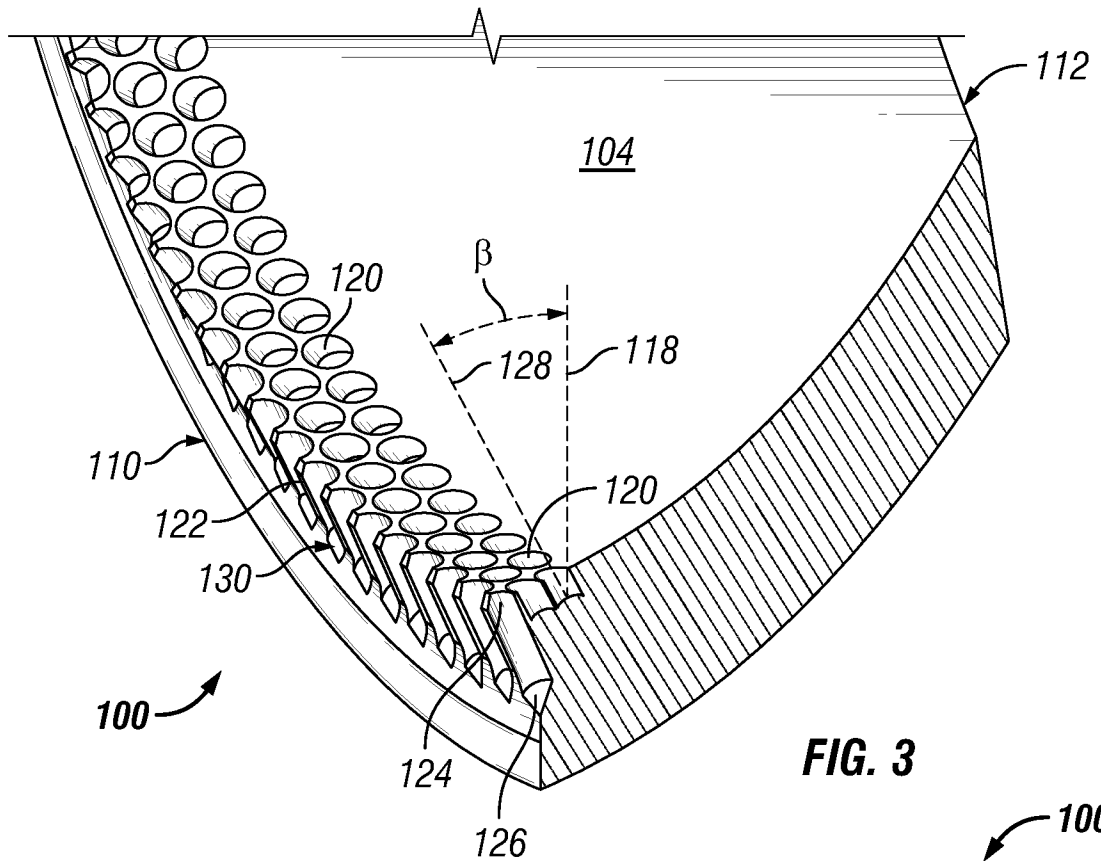


FIG. 2

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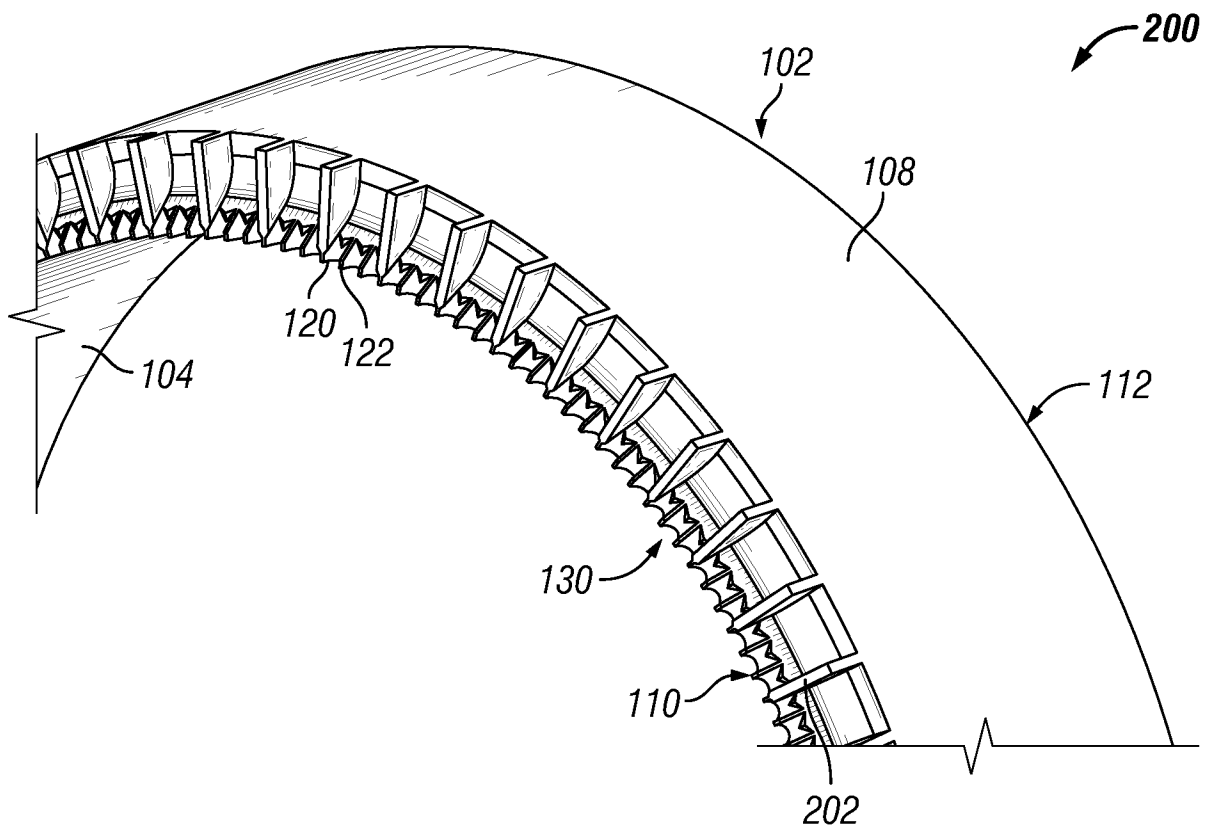
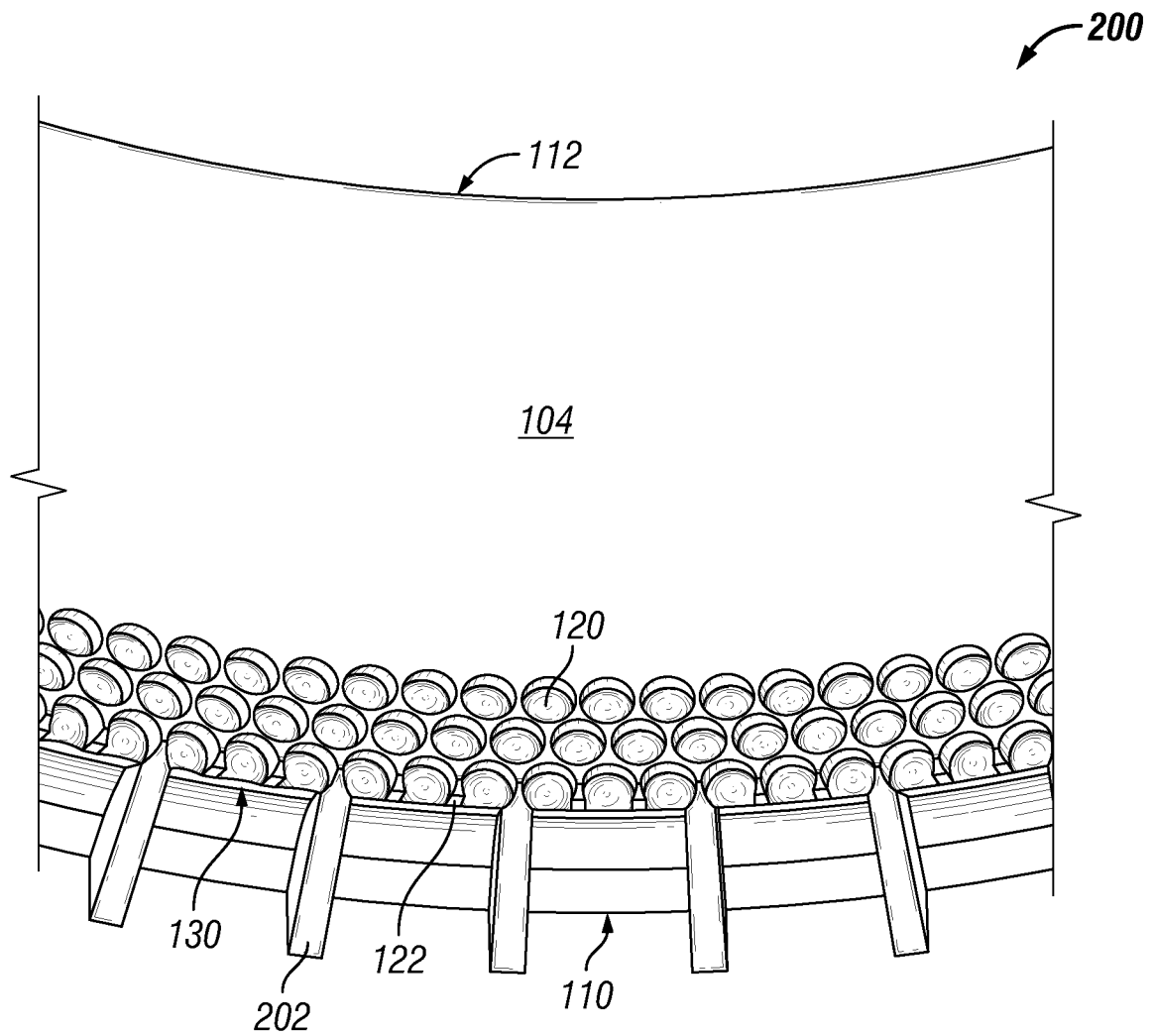


FIG. 5

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**FIG. 6**

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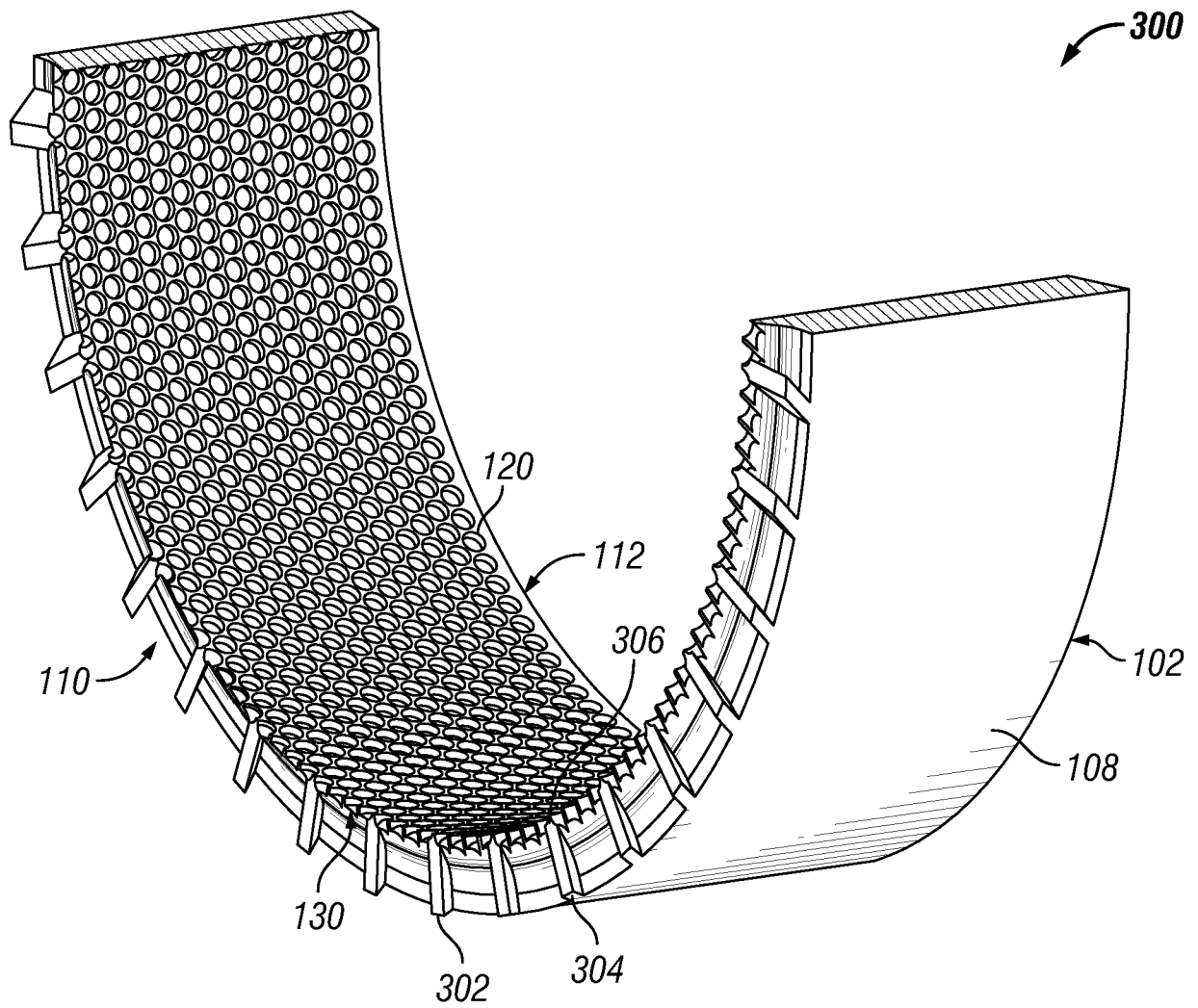


FIG. 7

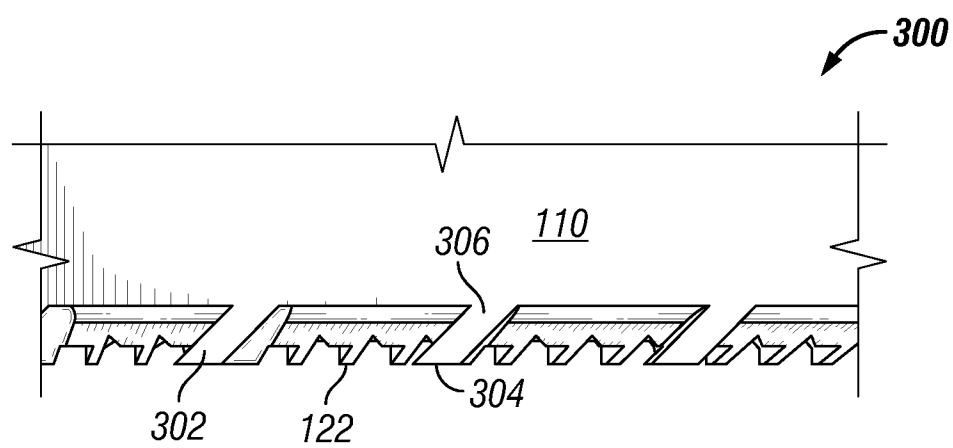


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/014833**A. CLASSIFICATION OF SUBJECT MATTER****F16J 15/44(2006.01)i, F02C 7/28(2006.01)i, F01D 11/02(2006.01)i, F04D 29/10(2006.01)i**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F16J 15/44; F16J 15/447; F16J 15/34; F04D 29/16; F04D 29/10; F04D 29/08; F02C 7/28; F01D 11/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & keywords: hole, aperture, annular, seal, noncontact, and shaft

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2014-109263 A (MITSUBISHI HEAVY IND. LTD. et al.) 12 June 2014 See paragraphs [0048]-[0063] and figures 1-6.	1-5, 8-15, 19
Y		6-7, 16-18, 20
Y	US 2015-0016988 A1 (GRIFFIN, DANIEL J.) 15 January 2015 See paragraphs [0028]-[0031] and figure 2.	6-7, 16-18, 20
A	US 2007-0257444 A1 (CHILDS, DARA W.) 08 November 2007 See paragraphs [0019]-[0027] and figures 1-2.	1-20
A	JP 08-178083 A (MITSUBISHI HEAVY IND. LTD.) 12 July 1996 See paragraphs [0020]-[0026], claim 1, and figures 1-2.	1-20
A	US 5492341 A (PECHT et al.) 20 February 1996 See column 13, line 18 - column 14, line 14 and figures 3-4.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

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Date of the actual completion of the international search

10 May 2016 (10.05.2016)

Date of mailing of the international search report

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Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/014833

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