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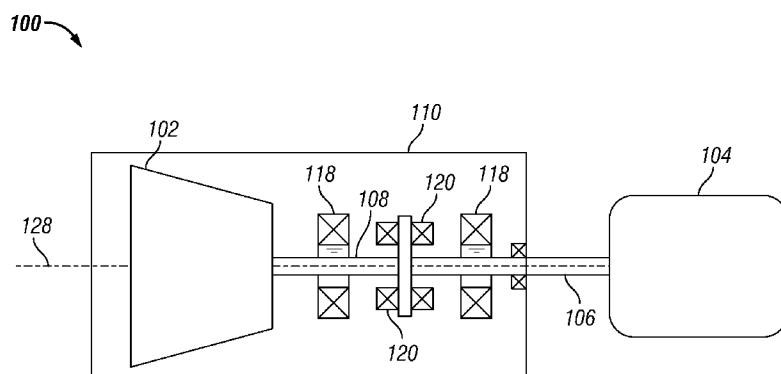


FIG. 1

(57) **Abstract:** A supersonic compressor including an inlet configured to receive and flow therethrough a process fluid. The supersonic compressor may further include a rotary shaft and a centrifugal impeller coupled therewith. The centrifugal impeller may be configured to impart energy to the process fluid received and to discharge the process fluid therefrom in at least a partially radial direction at an exit absolute Mach number of about one or greater. The supersonic compressor may further include a static diffuser circumferentially disposed about the centrifugal impeller and configured to receive the process fluid therefrom and convert the energy imparted. The supersonic compressor may further include a collector fluidly coupled to and configured to collect the process fluid exiting the diffuser, such that the supersonic compressor is configured to provide a compression ratio of at least about 8:1.

Apparatus, System, and Method for Compressing a Process Fluid

[0001] This invention was made with government support under Government Contract No. DOE-DE-FE0000493 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

[0002] This application claims the benefit of U.S. Provisional Patent Application having Serial No. 62/139,027, which was filed March 27, 2015 and U.S. Utility Patent Application having Serial No. 15/073,820, which was filed March 18, 2016. The aforementioned patent applications are hereby incorporated by reference in their entirety into the present application to the extent consistent with the present application.

[0003] Compressors and systems including compressors have been developed and are utilized in a myriad of industrial processes (e.g., petroleum refineries, offshore oil production platforms, and subsea process control systems) to compress gas, typically by applying mechanical energy to the gas in a low pressure environment and transporting the gas to and compressing the gas within a higher pressure environment. The compressed gas may be utilized to perform work or for operation of one or more downstream process components. As conventional compressors are increasingly used in offshore oil production facilities and other environments facing space constraints, there is an ever-increasing demand for smaller, lighter, and more compact compressors. In addition to the foregoing, it is desirable for commercial purposes that the compact compressors achieve higher compression ratios (e.g., 10:1 or greater) while maintaining a compact arrangement.

[0004] In view of the foregoing, skilled artisans may often attempt to achieve the higher compression ratios by increasing the number of compression stages within the compact compressor. Increasing the number of compression stages, however, increases the overall number of components (e.g., impellers and/or other intricate parts) required to achieve the desired compressor throughput (e.g., mass flow) and pressure rise to achieve the higher compression ratios. Increasing the number of components required in these compact compressors may often increase length requirements for the rotary shaft and/or increase distance requirements between rotary shaft bearings. The imposition of these requirements often results in larger, less compact compressors as compared to compact compressors utilizing fewer compression stages. Further, in many cases, increasing the number of compression stages in the compact compressors may still not provide the desired higher compression ratios, or if the desired compression ratios are achieved, the compact compressors may exhibit decreased efficiencies that make the compact compressors commercially undesirable.

[0005] What is needed, therefore, is an efficient compression system that provides increased compression ratios in a compact arrangement that is economically and commercially viable.

[0006] Embodiments of the disclosure may provide a supersonic compressor. The supersonic compressor may include a housing and an inlet coupled to or integral with the housing and defining an inlet passageway configured to receive and flow therethrough a process fluid. The supersonic compressor may also include a plurality of inlet guide vanes coupled to the housing and extending into the inlet passageway. The supersonic compressor may further include a rotary shaft configured to be driven by a driver, and a centrifugal impeller coupled with the rotary shaft and fluidly coupled to the inlet passageway via a plurality of flow passages formed by the centrifugal impeller. The centrifugal impeller may have a tip and be configured to impart energy to the process fluid received via the inlet passageway and to discharge the process fluid from the tip via the

plurality of flow passages in at least a partially radial direction at an exit absolute Mach number of about one or greater. The supersonic compressor may also include a balance piston configured to balance an axial thrust generated by the centrifugal impeller. The supersonic compressor may further include a static diffuser circumferentially disposed about the tip of the centrifugal impeller and bounded in part by a shroud wall and a hub wall defining an annular diffuser passageway therebetween. The static diffuser may be configured to receive the process fluid from the plurality of flow passages of the centrifugal impeller and convert, within the annular diffuser passageway, the energy imparted. The supersonic compressor may further include a collector fluidly coupled to the annular diffuser passageway and configured to collect the process fluid exiting the annular diffuser passageway, such that the supersonic compressor is configured to provide a compression ratio of at least about 8:1.

[0007] Embodiments of the disclosure may further provide a compression system. The compression system may include a driver including a drive shaft, the driver configured to provide the drive shaft with rotational energy, and a supersonic compressor operatively coupled to the driver via a rotary shaft integral with or coupled with the drive shaft. The supersonic compressor may include a compressor chassis and an inlet defining an inlet passageway configured to flow a process fluid therethrough. The process fluid may have a first velocity and a first pressure energy. The supersonic compressor may also include a plurality of inlet guide vanes pivotally coupled to the compressor chassis and extending into the inlet passageway, and a centrifugal impeller coupled with the rotary shaft and fluidly coupled to the inlet passageway via a plurality of flow passages formed by the centrifugal impeller. The centrifugal impeller may have a tip and may be configured to increase the first velocity and the first pressure energy of the process fluid received via the inlet passageway and to discharge the process fluid from the tip via the plurality of flow passages in at least a partially radial direction having a second velocity and a second pressure energy. The second velocity may be a supersonic velocity having an exit absolute Mach number of about one or greater. The supersonic compressor may further include a static diffuser circumferentially disposed about the tip of the centrifugal impeller and defining an annular diffuser passageway fluidly coupled to the plurality of flow passages. The annular diffuser passageway may be configured to receive and reduce the second velocity of the process fluid to a third velocity and increase the second pressure energy to a third pressure energy, the third velocity being a subsonic velocity. The supersonic compressor may also include a discharge volute fluidly coupled to the annular diffuser passageway and configured to receive the process fluid flowing therefrom, such that the supersonic compressor is configured to provide a compression ratio of at least about 8:1.

[0008] Embodiments of the disclosure may further provide a method for compressing a process fluid. The method may include driving a rotary shaft of a supersonic compressor via a driver operatively coupled with the supersonic compressor. The method may also include establishing a fluid property of the process fluid flowing through an inlet passageway defined by an inlet of the supersonic compressor via at least one moveable inlet guide vane pivotally coupled to a housing of the supersonic compressor and extending into the inlet passageway. The method may further include rotating a centrifugal impeller mounted about the rotary shaft, such that the process fluid flowing through the inlet passageway of the supersonic compressor is drawn into the centrifugal impeller and discharged from a tip of the centrifugal impeller via a plurality of flow passages. The discharged process fluid may have a supersonic velocity with an exit absolute Mach number of about 1.0

or greater. The method may also include flowing the discharged process fluid having a supersonic velocity through an annular diffuser passageway defined by a static diffuser and fluidly coupled to the plurality of flow passages such that a pressure energy of the discharged process fluid is increased, thereby compressing the discharged process fluid at a compression ratio of about 8:1 or greater.

[0009] 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.

[0010] Figure 1 illustrates a schematic view of an exemplary compression system, according to one or more embodiments.

[0011] Figure 2 illustrates a cross-sectional view of an exemplary compressor, which may be included in the compression system of Figure 1, according to one or more embodiments.

[0012] Figure 3 illustrates a perspective view of an exemplary impeller, which may be included in the compressor of Figure 2, according to one or more embodiments.

[0013] Figure 4 illustrates a front view of a portion of the impeller of Figure 3 and a portion of an exemplary vaneless static diffuser that may be included in the compressor of Figure 2, according to one or more embodiments.

[0014] Figure 5 illustrates a front view of a portion of the impeller of Figure 3 and a portion of an exemplary vaned static diffuser that may be included in the compressor of Figure 2, according to one or more embodiments.

[0015] Figure 6 is a flowchart depicting an exemplary method for compressing a process fluid, according to one or more embodiments.

[0016] 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.

[0017] 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.

[0018] Figure 1 illustrates a schematic view of an exemplary compression system 100, according to one or more embodiments. The compression system 100 may include one or more compressors 102 (one is shown) configured to pressurize a process fluid. In an exemplary embodiment, the compression system 100 may have a compression ratio of at least about 6:1 or greater. For example, the compression system 100 may compress the process fluid to a compression ratio of about 6:1, about 6.1:1, about 6.2:1, about 6.3:1, about 6.4:1, about 6.5:1, about 6.6:1, about 6.7:1, about 6.8:1, about 6.9:1, about 7:1, about 7.1:1, about 7.2:1, about 7.3:1, about 7.4:1, about 7.5:1, about 7.6:1, about 7.7:1, about 7.8:1, about 7.9:1, about 8:1, about 8.1:1, about 8.2:1, about 8.3:1, about 8.4:1, about 8.5:1, about 8.6:1, about 8.7:1, about 8.8:1, about 8.9:1, about 9:1, about 9.1:1, about 9.2:1, about 9.3:1, about 9.4:1, about 9.5:1, about 9.6:1, about 9.7:1, about 9.8:1, about 9.9:1, about 10:1, about 10.1:1, about 10.2:1, about 10.3:1, about 10.4:1, about 10.5:1, about 10.6:1, about 10.7:1, about 10.8:1, about 10.9:1, about 11:1, about 11.1:1, about 11.2:1, about 11.3:1, about 11.4:1, about 11.5:1, about 11.6:1, about 11.7:1, about 11.8:1, about 11.9:1, about 12:1, about 12.1:1, about 12.2:1, about 12.3:1, about 12.4:1, about 12.5:1, about 12.6:1, about 12.7:1, about 12.8:1, about 12.9:1, about 13:1, about 13.1:1, about 13.2:1, about 13.3:1, about 13.4:1, about 13.5:1, about 13.6:1, about 13.7:1, about 13.8:1, about 13.9:1, about 14:1, or greater.

[0019] The compression system 100 may also include, amongst other components, a driver 104 operatively coupled to the compressor 102 via a drive shaft 106. The driver 104 may be configured to provide the drive shaft 106 with rotational energy. In an exemplary embodiment, the drive shaft 106 may be integral with or coupled with a rotary shaft 108 of the compressor 102, such that the rotational energy of the drive shaft 106 is imparted to the rotary shaft 108. The drive shaft 106 may be coupled with the rotary shaft 108 via a gearbox (not shown) including a plurality of gears configured to transmit the rotational energy of the drive shaft 106 to the rotary shaft 108 of the compressor 102, such that the drive shaft 106 and the rotary shaft 108 may spin at the same speed, substantially similar speeds, or differing speeds and rotational directions.

[0020] The driver 104 may be a motor and more specifically may be an electric motor, such as a permanent magnet motor, and may include a stator (not shown) and a rotor (not shown). It will be appreciated, however, that other embodiments may employ other types of electric motors including, but not limited to, synchronous motors, induction motors, and brushed DC motors. The driver 104 may also be a hydraulic motor, an internal combustion engine, a steam turbine, a gas turbine, or any other device capable of driving the rotary shaft 108 of the compressor 102 either directly or through a power train.

[0021] In an exemplary embodiment, the compressor 102 may be a direct-inlet centrifugal compressor. In other embodiments, the compressor 102 may be a back-to-back compressor. The direct-inlet centrifugal compressor may be, for example, a version of a Dresser-Rand Pipeline Direct Inlet (PDI) centrifugal compressor manufactured by the Dresser-Rand Company of Olean, New York. The compressor 102 may have a center-hung rotor configuration or an overhung rotor configuration, as illustrated in Figure 1. In an exemplary embodiment, the compressor 102 may be an axial-inlet centrifugal compressor. In another embodiment, the compressor 102 may be a radial-inlet centrifugal compressor. As previously discussed, the compression system 100 may include one or more compressors 102. For example, the compression system 100 may include a plurality of compressors (not shown). In another example, illustrated in Figure 1, the compression system 100 may include a single compressor 102. The compressor 102 may be a supersonic compressor or a subsonic compressor. In at least one embodiment, the compression system 100 may include a plurality of compressors (not shown), and at least one compressor of the plurality of compressors is a subsonic compressor. In another embodiment, illustrated in Figure 1, the compression system 100 includes a single compressor 102, and the single compressor 102 is a supersonic compressor.

[0022] The compressor 102 may include one or more stages (not shown). In at least one embodiment, the compressor 102 may be a single-stage compressor. In another embodiment, the compressor 102 may be a multi-stage centrifugal compressor. Each stage (not shown) of the compressor 102 may be a subsonic compressor stage or a supersonic compressor stage. In an exemplary embodiment, the compressor 102 may include a single supersonic compressor stage. In another embodiment, the compressor 102 may include a plurality of subsonic compressor stages. In yet another embodiment, the compressor 102 may include a subsonic compressor stage and a supersonic compressor stage. Any one or more stages of the compressor 102 may have a compression ratio greater than about 1:1. For example, any one or more stages of the compressor 102 may have a compression ratio of about 1.1:1, about 1.2:1, about 1.3:1, about 1.4:1, about 1.5:1, about 1.6:1, about 1.7:1, about 1.8:1, about 1.9:1, about 2:1, about 2.1:1, about 2.2:1, about 2.3:1, about 2.4:1, about 2.5:1, about 2.6:1, about 2.7:1, about 2.8:1, about 2.9:1, about 3:1, about 3.1:1, about 3.2:1, about 3.3:1, about 3.4:1, about 3.5:1, about 3.6:1, about 3.7:1, about 3.8:1, about 3.9:1, about 4:1, about 4.1:1, about 4.2:1, about 4.3:1, about 4.4:1, about 4.5:1, about 4.6:1, about 4.7:1, about 4.8:1, about 4.9:1, about 5:1, about 5.1:1, about 5.2:1, about 5.3:1, about 5.4:1, about 5.5:1, about 5.6:1, about 5.7:1, about 5.8:1, about 5.9:1, about 6:1, about 6.1:1, about 6.2:1, about 6.3:1, about 6.4:1, about 6.5:1, about 6.6:1, about 6.7:1, about 6.8:1, about 6.9:1, about 7:1, about 7.1:1, about 7.2:1, about 7.3:1, about 7.4:1, about 7.5:1, about 7.6:1, about 7.7:1, about 7.8:1, about 7.9:1, about 8:1, about 8.1:1, about 8.2:1, about 8.3:1, about 8.4:1, about 8.5:1, about 8.6:1, about 8.7:1, about 8.8:1, about 8.9:1, about 9:1, about 9.1:1, about 9.2:1, about 9.3:1, about 9.4:1, about 9.5:1, about 9.6:1, about 9.7:1, about 9.8:1, about 9.9:1, about 10:1, about 10.1:1, about 10.2:1, about 10.3:1, about 10.4:1, about 10.5:1, about 10.6:1, about 10.7:1, about 10.8:1, about 10.9:1, about 11:1, about 11.1:1, about 11.2:1, about 11.3:1, about 11.4:1, about 11.5:1, about 11.6:1, about 11.7:1, about 11.8:1, about 11.9:1, about 12:1, about 12.1:1, about 12.2:1, about 12.3:1, about 12.4:1, about 12.5:1, about 12.6:1, about 12.7:1, about 12.8:1, about 12.9:1, about 13:1, about 13.1:1, about 13.2:1, about 13.3:1, about 13.4:1, about 13.5:1, about 13.6:1, about 13.7:1, about 13.8:1, about 13.9:1, about 14:1, or greater. In an exemplary embodiment, the compressor 102 may include a plurality of compressor

stages, where a first stage (not shown) of the plurality of compressor stages may have a compression ratio of about 1.75:1 and a second stage (not shown) of the plurality of compressor stages may have a compression ratio of about 6.0:1.

[0023] Figure 2 illustrates a cross-sectional view of an embodiment of the compressor 102, which may be included in the compression system 100 of Figure 1. As shown in Figure 2, the compressor 102 includes a housing 110 forming or having an axial inlet 112 defining an inlet passageway 114, a static diffuser 116 fluidly coupled to the inlet passageway 114, and a collector 117 fluidly coupled to the static diffuser 116. Although illustrated as an axial inlet in Figure 2, in one or more other embodiments, the inlet 112 may be a radial inlet. The driver 104 may be disposed outside of (as shown in Figure 1) or within the housing 110, such that the housing 110 may have a first end, or compressor end, and a second end (not shown), or driver end. The housing 110 may be configured to hermetically seal the driver 104 and the compressor 102 within, thereby providing both support and protection to each component of the compression system 100. The housing 110 may also be configured to contain the process fluid flowing through one or more portions or components of the compressor 102.

[0024] The drive shaft 106 of the driver 104 and the rotary shaft 108 of the compressor 102 may be supported, respectively, by one or more radial bearings 118, as shown in Figure 1 in an overhung configuration. The radial bearings 118 may be directly or indirectly supported by the housing 110, and in turn provide support to the drive shaft 106 and the rotary shaft 108, which carry the compressor 102 and the driver 104 during operation of the compression system 100. In one embodiment, the radial bearings 118 may be magnetic bearings, such as active or passive magnetic bearings. In other embodiments, however, other types of bearings (e.g., oil film bearings) may be used. In addition, at least one axial thrust bearing 120 may be provided to manage movement of the rotary shaft 108 in the axial direction. In an embodiment in which the driver 104 and the compressor 102 are hermetically-sealed within the housing 110, the thrust bearing 120 may be provided at or near the end of the rotary shaft 108 adjacent the compressor end of the housing 110. The axial thrust bearing 120 may be a magnetic bearing and may be configured to bear axial thrusts generated by the compressor 102.

[0025] As shown in Figure 2, the axial inlet 112 defining the inlet passageway 114 of the compressor 102 may include one or more inlet guide vanes 122 of an inlet guide vane assembly configured to condition a process fluid flowing therethrough to achieve predetermined or desired fluid properties and/or fluid flow attributes. Such fluid properties may include flow pattern (e.g., swirl distribution), velocity, mass flow rate, pressure, temperature, and/or any suitable fluid property and fluid flow attribute to enable the compressor 102 to function as described herein. The inlet guide vanes 122 may be disposed within the inlet passageway 114 and may be static or moveable, *i.e.*, adjustable. In an exemplary embodiment, a plurality of inlet guide vanes 122 may be arranged about a circumferential inner surface 124 of the axial inlet 112 in a spaced apart orientation, each extending into the inlet passageway 114. The spacing of the inlet guide vanes 122 may be equidistant or may vary depending on the predetermined process fluid property and/or fluid flow attribute desired. With reference to shape, the inlet guide vanes 122 may be airfoil shaped, streamline shaped, or otherwise shaped and configured to at least partially impart the one or more fluid properties and/or fluid flow attributes on the process fluid flowing through the inlet passageway 114.

[0026] In one or more embodiments, the inlet guide vanes 122 may be moveably coupled to the housing 110 and disposed within the inlet passageway 114 as disclosed in U.S. 8,632,302, the subject matter of which is incorporated by reference herein to the extent consistent with the present disclosure. The inlet guide vanes 122 may be further coupled to an annular inlet guide vane actuation member (not shown), such that upon actuation of the annular inlet vane actuation member, each of the inlet guide vanes 122 coupled to the annular inlet guide vane actuation member may pivot about the respective coupling to the housing 110, thereby adjusting the flow incident on components of the compressor 102. As configured, the inlet guide vanes 122 may be adjusted without disassembling the housing 110 in order to adjust the performance of the compressor 102. Doing so without disassembly of the compressor 102 saves time and effort in optimizing the compressor 102 for a particular operating condition. Furthermore, the impact of alternate vane angles on overall flow range and/or peak efficiency may be assessed and optimized for increased performance, and a matrix of inlet guide vane angles may be produced on a relatively short cycle time relative to conventional compressors such that the data may be analyzed to determine the best combination of inlet guide vane angles for any given application.

[0027] The compressor 102 may include a centrifugal impeller 126 configured to rotate about a center axis 128 within the housing 110. In an exemplary embodiment, the centrifugal impeller 126 includes a hub 130 and is open or “unshrouded.” In another embodiment, the centrifugal impeller 126 may be a shrouded impeller. The hub 130 may include a first meridional end portion 132, generally referred to as the eye of the centrifugal impeller 126, and a second meridional end portion 134 having a disc shape, the outer perimeter of the second meridional end portion 134 generally referred to as the tip 136 of the centrifugal impeller 126. The disc-shaped, second meridional end portion 134 may taper inwardly to the first meridional end portion 132 having an annular shape. The hub 130 may define a bore 138 configured to receive a coupling member 140, such as a tie-bolt, to couple the centrifugal impeller 126 to the rotary shaft 108. In another embodiment, the bore 138 may be configured to receive the rotary shaft 108 extending therethrough.

[0028] As shown in Figure 2, the compressor 102 may include a balance piston 142 configured to balance an axial thrust generated by the centrifugal impeller 126 during operation. In an exemplary embodiment, the balance piston 142 may be integral with the centrifugal impeller 126, such that the balance piston 142 and the centrifugal impeller 126 are formed from a single or unitary piece. In another embodiment, the balance piston 142 and the centrifugal impeller 126 may be separate components. For example, the balance piston 142 and the centrifugal impeller 126 may be separate annular components coupled with one another. One or more seals, e.g., labyrinth seals, may be implemented to isolate the balance piston 142 from external contaminants or lubricants.

[0029] The centrifugal impeller 126 may be operatively coupled to the rotary shaft 108 such that the rotary shaft 108, when acted upon by the driver 104 via the drive shaft 106, rotates, thereby causing the centrifugal impeller 126 to rotate such that process fluid flowing into the inlet passageway 114 is drawn into the centrifugal impeller 126 and accelerated to the tip 136, or periphery, of the centrifugal impeller 126, thereby increasing the velocity of the process fluid. In one or more embodiments, the process fluid at the tip 136 of the centrifugal impeller 126 may be subsonic and have an absolute Mach number less than one. For example, the process fluid at the tip 136 of the centrifugal impeller 126 may have an exit absolute Mach

number less than one, less than 0.9, less than 0.8, less than 0.7, less than 0.6, or less than 0.5. Accordingly, in such embodiments, the compressor 102 discussed herein may be "subsonic," as the centrifugal impeller 126 may be configured to rotate about the center axis 128 at a speed sufficient to provide the process fluid at the tip 136 thereof with an exit absolute Mach number of less than one.

[0030] In one or more embodiments, the process fluid at the tip 136 of the centrifugal impeller 126 may be supersonic and have an exit absolute Mach number of one or greater. For example, the process fluid at the tip 136 of the centrifugal impeller 126 may have an exit absolute Mach number of at least one, at least 1.1, at least 1.2, at least 1.3, at least 1.4, or at least 1.5. Accordingly, in such embodiments, the compressor 102 discussed herein may be "supersonic," as the centrifugal impeller 126 may be configured to rotate about the center axis 128 at a speed sufficient to provide the process fluid at the tip 136 thereof with an exit absolute Mach number of one or greater or with a fluid velocity greater than the speed of sound. In a supersonic compressor or a stage thereof, the rotational or tip speed of the centrifugal impeller 126 may be about 500 meters per second (m/s) or greater. For example, the tip speed of the centrifugal impeller 126 may be about 510 m/s, about 520 m/s, about 530 m/s, about 540 m/s, about 550 m/s, about 560 m/s, or greater.

[0031] Referring now to Figures 3-5, with continued reference to Figure 2, Figure 3 illustrates a perspective view of the centrifugal impeller 126 that may be included in the compressor 102, according to one or more embodiments. Figure 4 illustrates a front view of a portion of the centrifugal impeller 126 of Figure 3 and a portion of the static diffuser 116 that may be included in the compressor 102 of Figure 2, according to one or more embodiments. Figure 5 illustrates a front view of a portion of the centrifugal impeller 126 of Figure 3 and a portion of another static diffuser 216 that may be included in the compressor 102 of Figure 2 and utilized in place of the static supersonic diffuser 116, according to one or more embodiments.

[0032] As shown in Figure 2 and more clearly in Figures 3-5, the centrifugal impeller 126 may include a plurality of aerodynamic surfaces or blades 144a,b coupled or integral with the hub 130 and configured to increase the velocity and energy of the process fluid. As illustrated in Figures 3-5, the blades 144a,b of the centrifugal impeller 126 may be curved, such that the process fluid may be urged in a tangential and radial direction by the centrifugal force through a plurality of flow passages 146, 148 formed by the blades 144a,b and discharged from the blade tips of the centrifugal impeller 126 (cumulatively, the tip 136 of the centrifugal impeller 126) in at least partially radial directions that extend 360 degrees around the centrifugal impeller 126.

It will be appreciated that the contour or amount of curvature of the blades 144a,b is not limited to the shaping illustrated in Figures 3-5 and may be determined based, at least in part, on desired operating parameters.

[0033] The plurality of blades 144a,b may include main blades 144a spaced equidistantly apart and circumferentially about the center axis 128. Each main blade 144a may extend from a leading edge 150 disposed adjacent the first meridional end portion 132 of the centrifugal impeller 126 to a trailing edge 152 disposed adjacent the second meridional end portion 134 of the centrifugal impeller 126. Further, based on rotation of the centrifugal impeller 126, each main blade 144a may define a pressure surface on one side 154 of the main blade 144a and a suction surface on the opposing side 156 of the main blade 144a. As shown most clearly in Figure 3, the centrifugal impeller 126 may include thirteen main blades 144a; however, other

embodiments including more than or less than thirteen main blades are contemplated herein. The number of main blades 144a may be determined based, at least in part, on desired operating parameters.

[0034] The plurality of blades 144a,b may also include one or more splitter blades 144b configured to reduce aerodynamic choking conditions that may occur in the compressor 102 depending on the number of blades 144a,b employed with respect to the centrifugal impeller 126. The splitter blades 144b may be spaced equidistantly apart and circumferentially about the center axis 128. Each splitter blade 144b may extend from a leading edge 158, meridionally spaced and downstream from the first meridional end portion 132, to a trailing edge 160 disposed adjacent the second meridional end portion 134 of the centrifugal impeller 126. The leading edge 158 of each splitter blade 144b may be disposed meridionally outward from the leading edges 150 of the main blades 144a such that the respective leading edges 150, 158 of the main blades 144a and splitter blades 144b are staggered and not coplanar. Further, based on rotation of the centrifugal impeller 126, each splitter blade 144b may define a pressure surface on one side 162 of the splitter blade 144b and a suction surface on the opposing side 164 of the splitter blade 144b.

[0035] As most clearly illustrated in Figures 2 and 3, each of the main blades 144a and the splitter blades 144b extends meridionally from the second meridional end portion 134 of the centrifugal impeller 126 toward the first meridional end portion 132 thereof. The configuration of the respective meridional extents of the main blades 144a and the splitter blades 144b may be substantially similar proximal the respective trailing edges 152, 160 of the main blades 144a and the splitter blades 144b. The configuration of the respective meridional extents of the main blades 144a and the splitter blades 144b may differ from the second meridional end portion 134 to the respective leading edges 150, 158 of the main blades 144a and the splitter blades 144b. In an exemplary embodiment, the meridional extent of each of the main blades 144a may be greater than the meridional extent of each of the splitter blades 144b, such that the respective leading edges 158 of the splitter blades 144b may be disposed meridionally offset toward the second meridional end portion 134 of the centrifugal impeller 126 from the respective leading edges 150 of the main blades 144a.

[0036] The splitter blades 144b and main blades 144a may be arranged circumferentially about the center axis 128 in a pattern such that a splitter blade 144b is disposed between adjacent main blades 144a. As arranged, each splitter blade 144b may be disposed between the pressure surface side 154 of an adjacent main blade 144a and the suction surface side 156 of the other adjacent main blade 144a. Further, the splitter blades 144b may be "clocked" with respect to the main blades 144a, such that each splitter blade 144b is circumferentially offset or not equidistant from the respective adjacent main blades 144a and thus is not circumferentially centered between the adjacent main blades 144a. By clocking the splitter blades 144b, e.g., displacing the splitter blades 144b from a position equidistant from adjacent main blades 144a, the operating characteristics of the centrifugal impeller 126 may be improved.

[0037] In one or more embodiments, the splitter blades 144b and main blades 144a may be arranged circumferentially about the center axis 128 in a pattern such that a plurality of splitter blades 144b may be disposed between adjacent main blades 144a. Accordingly, in one embodiment, at least two splitter blades 144b are disposed between adjacent main blades 144a. The leading edges 158 of the respective splitter blades 144b may be offset meridionally from one another such that the respective leading edges 158 of the splitter blades 144b are staggered and not coplanar.

[0038] As positioned between the adjacent main blades 144a, each splitter blade 144b may be oriented such that the splitter blade 144b is canted, such that the leading edge 158 of the splitter blade 144b is circumferentially offset from a position equidistant from the adjacent main blades 144a a different percentage amount than the trailing edge 160 of the splitter blade 144b. Accordingly, in an exemplary embodiment, the leading edge 158 of the splitter blade 144b may be displaced from a position equidistant from the adjacent main blades 144a by a distance of a first percentage amount of one half the angular distance θ between the adjacent main blades 144a. The trailing edge 160 of the splitter blade 144b may be displaced from the position equidistant the adjacent main blades 144a by a distance of a second percentage amount of one half the angular distance θ between the adjacent main blades 144a.

[0039] In an exemplary embodiment, the first percentage amount may be greater than the second percentage amount. In another embodiment, the first percentage amount may be less than the second percentage amount. For example, the difference in displacement between the leading edge 158 and the trailing edge 160 from the position equidistant the adjacent main blades 144a may be a percentage amount of about one percent, about two percent, about three percent, about four percent, about five percent, about ten percent, about fifteen percent, about twenty percent, or greater. In another example, the difference in displacement between the leading edge 158 and the trailing edge 160 from the position equidistant the adjacent main blades 144a may be a percentage amount of between about one percent and about two percent, about three percent and about five percent, about five percent and about ten percent, or about ten percent and about twenty percent. The differences in distance related to the percentage amounts, *e.g.*, the amount the splitter blade 144b is canted, may be determined based, at least in part, on desired operating parameters.

[0040] As shown in Figures 3-5, a plurality of flow passages 146, 148 may be formed between the splitter blades 144b and the adjacent main blades 144a as arranged about the center axis 128. In an exemplary embodiment, the plurality of flow passages 146, 148 may include a first flow passage 146 formed between the pressure surface side 162 of the splitter blade 144b and the suction surface side 156 of one of the adjacent main blades 144a and a second flow passage 148 between the suction surface side 164 of the splitter blade 144b and the pressure surface side 154 of the other adjacent main blade 144a. The mass flow of the process fluid through the first and second flow passages 146, 148 may be determined based on the displacement of the splitter blade 144b in relation to the adjacent main blades 144b. For example, it has been determined that disposing the splitter blade 144b equidistantly between the adjacent main blades 144a may not result in equal mass flow through the first flow passage 146 and the second flow passage 148. Accordingly, in an exemplary embodiment, the splitter blade 144b may be circumferentially offset from a position centered between adjacent main blades 144a, such that the suction surface side 164 of the splitter blade 144b is disposed in a direction closer to the pressure surface side 154 of one of the adjacent main blades 144a and further from the suction surface side 156 of the other adjacent main blade 144a, thereby substantially equalizing the mass flow through the respective flow passages 146, 148.

[0041] As will be appreciated by those of skill in the art, the desired displacement of the splitter blades 144b may depend on various factors, such as the shape of the blades 144a,b, the angle of incidence of the blades 144a,b, the size of the blades 144a,b and of the centrifugal impeller 126, the operating speed range, etc.

However, the displacement necessary to equalize the mass flow through the first flow passage 146 and the second flow passage 148 may be determined for a given design of the centrifugal impeller 126 and corresponding blades 144a,b by measurement of the mass flow, such as by use of a mass flow meter.

[0042] As shown in Figure 2, the compressor 102 may include a shroud 170 coupled to the housing 110 and disposed adjacent the plurality of blades 144a,b of the centrifugal impeller 126. In particular, a surface 172 of the shroud 170 may include an abradable material and may be contoured to substantially align with the silhouette of the plurality of blades 144a,b, thus substantially reducing leakage flow of the process fluid in a gap defined therebetween. The abradable material is arranged on the surface 172 of the shroud 170 and configured to be deformed and/or removed therefrom during incidental contact of the rotating centrifugal impeller 126 with the abradable material of the stationary shroud 170 during axial movement of the rotary shaft 108, thereby preventing damage to the blades 144a,b and resulting in a loss of a sacrificial amount of the abradable material.

[0043] In an embodiment, illustrated most clearly in Figure 4 with continued reference to Figure 2, the compressor 102 may include the static diffuser 116 fluidly coupled to the axial inlet 112 and configured to receive the radial process fluid flow exiting the tip 136 of the centrifugal impeller 126. In an exemplary embodiment, the static diffuser 116 may be a vaneless diffuser. The static diffuser 116 may be configured to convert kinetic energy of the process fluid from the centrifugal impeller 126 into increased static pressure. In an exemplary embodiment, the static diffuser 116 may be located downstream of the centrifugal impeller 126 and may be statically disposed circumferentially about the periphery, or tip 136, of the centrifugal impeller 126.

[0044] The static diffuser 116 may be coupled with or integral with the housing 110 of the compressor 102 and may form an annular diffuser passageway 174 having an inlet end 176 adjacent the tip 136 of the centrifugal impeller 126 and a radially outer outlet end 178. In an exemplary embodiment, the annular diffuser passageway 174 may be formed, at least in part, by portions of the housing 110, namely a shroud wall 180 and a hub wall 182, forming the confining sidewalls of the static diffuser 116. The shroud wall 180 and the hub wall 182 may each be a straight wall or a contoured wall, such that the annular diffuser passageway 174 may be formed from straight walls, contoured walls, or a combination thereof. In addition, the annular diffuser passageway 174 may have a reduced width as the shroud wall 180 and the hub wall 182 extend radially outward. Such a "pinched" diffuser may provide for lower choke and surge limits and, thus, improve the efficiency of the centrifugal impeller 126.

[0045] In another embodiment, illustrated most clearly in Figure 5 with continued reference to Figure 2, a static diffuser 216 may be utilized in the compressor 102 in place of the static diffuser 116 disclosed above. The static diffuser 216 illustrated in Figure 5 may be similar in some respects to the static diffuser 116 described above and therefore may be best understood with reference to the description of Figures 2 and 4, where like numerals may designate like components and will not be described again in detail. The static diffuser 216 may be fluidly coupled to the axial inlet 112 and configured to receive the radial process fluid flow exiting the centrifugal impeller 126.

[0046] The static diffuser 216 may be configured to convert kinetic energy of the process fluid from the centrifugal impeller 126 into increased static pressure. In an exemplary embodiment, the static diffuser 216 may be located downstream of the centrifugal impeller 126 and may be statically disposed circumferentially

about the periphery, or tip 136, of the centrifugal impeller 126. The static diffuser 216 may be coupled with or integral with the housing 110 of the compressor 102 and may further form the annular diffuser passageway 174 having the inlet end 176 adjacent the tip 136 of the centrifugal impeller 126 and the radially outer outlet end 178. In an exemplary embodiment, the annular diffuser passageway 174 may be formed, at least in part, by the shroud wall 180 and the hub wall 182 of the housing 110.

[0047] In an exemplary embodiment, the static diffuser 216 may be a vaned diffuser, e.g., wedge diffuser, or a vaned diffuser as shown in Figure 5. The static diffuser 216 may have a plurality of diffuser vanes 184, 186 arranged in a plurality of concentric rings 188, 190 about the center axis 128 and extending from the shroud wall 180 or the hub wall 182 or from both the shroud wall 180 and the hub wall 182 of the static diffuser 216. As shown in Figure 5, the plurality of diffuser vanes 184, 186 may include first row vanes 184 arranged in a first ring 188 about the center axis 128 and extending from the hub wall 182 of the static diffuser 216. The first row vanes 184 each include a leading edge 192 disposed proximal the inlet end 176 and a trailing edge 194 radially and circumferentially offset from the leading edge 192. The first row vanes 184 may be low solidity diffuser vanes, where the chord to pitch ratio of the first row vanes 184 is less than one. As provided herein, diffuser vanes having a chord to pitch ratio of less than one are referred to as low solidity diffuser vanes. In the illustrated embodiment of Figure 5, the first ring 188 includes seventeen low solidity diffuser vanes; however, embodiments including more or less than seventeen low solidity diffuser vanes are contemplated herein. Each of the first row vanes 184 may be airfoils or shaped substantially similar thereto.

[0048] As shown in Figure 5, the plurality of diffuser vanes 184, 186 may include second row vanes 186 arranged in a second ring 190 about the center axis 128 and extending from the hub wall 182 of the static diffuser 216. The plurality of diffuser vanes 184, 186 is arranged in tandem, such that the second ring 190 of second row vanes 186 is disposed radially outward from the first ring 188 of first row vanes 184. The second row vanes 186 include respective leading edges 196 disposed proximal the trailing edges 194 of the first row vanes 184 and respective trailing edges 198 radially and circumferentially offset from the leading edges 196. The second row vanes 186 may have a greater solidity than the first row vanes 184, where the chord to pitch ratio of the second row vanes 186 is generally greater than the chord to pitch ratio of the first row vanes 184. In an exemplary embodiment, the chord to pitch ratio of the second row vanes 186 is one or greater. As provided herein, diffuser vanes having a chord to pitch ratio of one or greater are referred to as high solidity diffuser vanes. In the illustrated embodiment of Figure 5, the second ring 190 includes a multiple of the number of first row vanes 184, and more specifically, twice the number of first row vanes 184. Thus, in an embodiment in which the first ring 188 includes seventeen first row vanes 184, the second ring 190 may include thirty-four diffuser vanes; however, embodiments including more or less than thirty-four diffuser vanes are contemplated herein. Each of the second row vanes 186 may be airfoils or shaped substantially similar thereto.

[0049] In an exemplary embodiment, the first row vanes 184 of the first ring 188 may be proximal the tip 136 of the centrifugal impeller 126 and may be spaced therefrom via an inner vaneless space 200. Accordingly, the inner vaneless space 200 may be provided between the centrifugal impeller tip diameter 202 and the leading edge diameter 204 of the first ring 188. In an exemplary embodiment, the inner vaneless space 200 may be formed from the leading edge diameter 204 being about five to about ten percent greater than the

centrifugal impeller tip diameter 202. In another embodiment, the inner vaneless space 200 may be formed from the leading edge diameter 204 being about six to about eight percent greater than the centrifugal impeller tip diameter 202. Similarly, an outer vaneless space 206 may be provided between the diameter 208 formed by the trailing edges 194 of the first row vanes 184 of the first ring 188 and the diameter 210 of the leading edges 196 of the second row vanes 186 of the second ring 190. In an exemplary embodiment, the outer vaneless space 206 may be formed from the leading edge diameter 210 of the second ring 190 being about five to about ten percent greater than the trailing edge diameter 208 of the first ring 188. In another embodiment, the outer vaneless space 206 may be formed from the leading edge diameter 210 of the second ring 190 being about six to about eight percent greater than the trailing edge diameter 208 of the first ring 188.

[0050] In an exemplary embodiment, the incidence of the first row vanes 184 of the first ring 188 may be determined for controlling the exit absolute Mach number and reducing supersonic flow introduced at the inlet end 176 of the static diffuser 216 to a subsonic flow at the trailing edges 194 of the first ring 188. As configured, shock waves created by the leading edges 192 of the first ring 188 do not propagate to the second row vanes 186; however, the leading edges 192 of the first ring 188 provide for a communication path from the downstream portion of the static diffuser 216 toward an upstream portion of the centrifugal impeller 126 to back pressure the centrifugal impeller 126, thereby obtaining a wider range. The incidence of the second row vanes 186 of the second ring 190 may be determined by placing the second ring 190 in the "shadow" or flow path of the first ring 188. Accordingly, the second row vanes 186 may be arranged such that two second row vanes 186 are provided in the wake of each first row vane 184 and are provided to alter the direction of the process fluid flow.

[0051] In another embodiment, the static diffuser 216 may include third row vanes (not shown) arranged in a third ring (not shown) about the center axis 128 and disposed radially outward of the first ring 188 and the second ring 190, where the first ring 188, the second ring 190, and the third ring are concentric. The third row vanes may have a chord to pitch ratio less than the chord to pitch ratio of the second row vanes 186 of the second ring 190. In another embodiment, the third row vanes may have a chord to pitch ratio substantially equal to the chord to pitch ratio of the first row vanes 184 of the first ring 188. The third row vanes may be configured to provide additional turning of the process fluid flow.

[0052] As discussed above, in one or more embodiments, the compressor 102 provided herein may be referred to as "supersonic" because the centrifugal impeller 126 may be designed to rotate about the center axis 128 at high speeds such that a moving process fluid encountering the inlet end 176 of the static diffuser 116 is said to have a fluid velocity which is above the speed of sound of the process fluid being compressed. Thus, in an exemplary embodiment, the moving process fluid encountering the inlet end 176 of the static diffuser 116 may have an exit absolute Mach number of about one or greater. However, to increase total energy of the fluid system, the moving process fluid encountering the inlet end 176 of the static diffuser 116 may have an exit absolute Mach number of at least about 1.1, at least about 1.2, at least about 1.3, at least about 1.4, or at least about 1.5. In another example, the process fluid at the tip 136 of the centrifugal impeller 126 may have an exit absolute Mach number from about 1.1 to about 1.5, or about 1.2 to about 1.4.

[0053] The process fluid flow leaving the outlet end 178 of the static diffuser 116, 216 may flow into the collector 117, as most clearly seen in Figure 2. The collector 117 may be configured to gather the process fluid flow from the static diffuser 116, 216 and to deliver the process fluid flow to a downstream pipe and/or process component (not shown). In an exemplary embodiment, the collector 117 may be a discharge volute or specifically, a scroll-type discharge volute. In another embodiment, the collector 117 may be a plenum. The collector 117 may be further configured to increase the static pressure of the process fluid flow by converting the kinetic energy of the process fluid to static pressure. The collector 117 may have a round tongue (not shown). In another embodiment, the collector may have a sharp tongue (not shown). It will be appreciated that the tongue of the collector 117 may form other shapes known to those of ordinary skill in the art without varying from the scope of this disclosure.

[0054] One or more exemplary operational aspects of an exemplary compression system 100 will now be discussed with continued reference to Figures 1-5. A process fluid may be provided from an external source (not shown), having a low pressure environment, to the compression system 100. The compression system 100 may include, amongst other components, the compressor 102 having the centrifugal impeller 126 coupled with the rotary shaft 108 and the static diffuser 116 disposed circumferentially about the rotating centrifugal impeller 126. In another embodiment, the compression system 100 may include, amongst other components, the compressor 102 having the centrifugal impeller 126 coupled with the rotary shaft 108 and the static diffuser 216 disposed circumferentially about the rotating centrifugal impeller 126.

[0055] The process fluid may be drawn into the axial inlet 112 of the compressor 102 with a velocity ranging, for example, from about Mach 0.05 to about Mach 0.40. The process fluid may flow through the inlet passageway 114 defined by the axial inlet 112 and across the inlet guide vanes 122 extending into the inlet passageway 114. The process fluid flowing across the inlet guide vanes 122 may be provided with an increased velocity and imparted with at least one fluid property (e.g., swirl) prior to being drawn into the rotating centrifugal impeller 126. The inlet guide vanes 122 may be adjusted in order to vary the one or more fluid properties imparted to the process fluid.

[0056] The process fluid may be drawn into the rotating centrifugal impeller 126 and may contact the curved centrifugal impeller blades 144a,b, such that the process fluid may be accelerated in a tangential and radial direction by centrifugal force and may be discharged from the flow passages 146, 148 via the blade tips of the centrifugal impeller 126 (cumulatively, the tip 136 of the centrifugal impeller 126) in at least partially radial directions that extend 360 degrees around the rotating centrifugal impeller 126. The rotating centrifugal impeller 126 increases the velocity and static pressure of the process fluid, such that the velocity of the process fluid discharged from the blade tips (cumulatively, the tip 136 of the centrifugal impeller 126) may be supersonic in some embodiments and have an exit absolute Mach number of at least about one, at least about 1.1, at least about 1.2, at least about 1.3, at least about 1.4, or at least about 1.5.

[0057] In an embodiment, the static diffuser 116 may be disposed circumferentially about the periphery, or tip 136, of the centrifugal impeller 126 and may be coupled with or integral with the housing 110 of the compressor 102. In another embodiment, the static diffuser 216 may be disposed circumferentially about the periphery, or tip 136, of the centrifugal impeller 126 and may be coupled with or integral with the housing 110 of the compressor 102. The radial process fluid flow discharged from the rotating centrifugal impeller 126 may

be received by the static diffuser 116, 216 such that the velocity of the flow of process fluid discharged from the tip 136 of the rotating centrifugal impeller 126 is substantially similar to the velocity of the process fluid entering the inlet end 176 of the static diffuser 116, 216. Accordingly, the process fluid may enter the inlet end 176 of the static diffuser 116, 216 with a supersonic velocity having, for example, an exit absolute Mach number of at least one, and correspondingly, may be referred to as supersonic process fluid.

[0058] The velocity of the supersonic process fluid flowing into the inlet end 176 of the static diffuser 116, 216 decreases with increasing radius of the annular diffuser passageway 174 as the process fluid flows from the inlet end 176 to the radially outer outlet end 178 of the static diffuser 116, 216 as the velocity head is converted to static pressure. In at least one embodiment including the static diffuser 216, the tangential velocity of the supersonic process fluid may decelerate from supersonic to subsonic velocities across the first row vanes 184 without shock losses. The static diffuser 116, 216 may reduce the velocity and increase the pressure energy of the process fluid.

[0059] The process fluid exiting the static diffuser 116, 216 may have a subsonic velocity and may be fed into the collector 117 or discharge volute. The collector 117 may increase the static pressure of the process fluid by converting the remaining kinetic energy of the process fluid to static pressure. The process fluid may then be routed to perform work or for operation of one or more downstream processes or components (not shown).

[0060] The process fluid pressurized, circulated, contained, or otherwise utilized in the compression system 100 may be a fluid in a liquid phase, a gas phase, a supercritical state, a subcritical state, or any combination thereof. The process fluid may be a mixture, or process fluid mixture. The process fluid may include one or more high molecular weight process fluids, one or more low molecular weight process fluids, or any mixture or combination thereof. As used herein, the term "high molecular weight process fluids" refers to process fluids having a molecular weight of about 30 grams per mole (g/mol) or greater. Illustrative high molecular weight process fluids may include, but are not limited to, hydrocarbons, such as ethane, propane, butanes, pentanes, and hexanes. Illustrative high molecular weight process fluids may also include, but are not limited to, carbon dioxide (CO₂) or process fluid mixtures containing carbon dioxide. As used herein, the term "low molecular weight process fluids" refers to process fluids having a molecular weight less than about 30 g/mol. Illustrative low molecular weight process fluids may include, but are not limited to, air, hydrogen, methane, or any combination or mixtures thereof.

[0061] In an exemplary embodiment, the process fluid or the process fluid mixture may be or include carbon dioxide. The amount of carbon dioxide in the process fluid or the process fluid mixture may be at least about 80%, at least about 85%, at least about 90%, at least about 95%, at least about 96%, at least about 97%, at least about 98%, at least about 99%, or greater by volume. Utilizing carbon dioxide as the process fluid or as a component or part of the process fluid mixture in the compression system 100 may provide one or more advantages. For example, the high density and high heat capacity or volumetric heat capacity of carbon dioxide with respect to other process fluids may make carbon dioxide more "energy dense." Accordingly, a relative size of the compression system 100 and/or the components thereof may be reduced without reducing the performance of the compression system 100.

[0062] The carbon dioxide may be of any particular type, source, purity, or grade. For example, industrial grade carbon dioxide may be utilized as the process fluid without departing from the scope of the disclosure.

Further, as previously discussed, the process fluids may be a mixture, or process fluid mixture. The process fluid mixture may be selected for one or more desirable properties of the process fluid mixture within the compression system 100. For example, the process fluid mixture may include a mixture of a liquid absorbent and carbon dioxide (or a process fluid containing carbon dioxide) that may enable the process fluid mixture to be compressed to a relatively higher pressure with less energy input than compressing carbon dioxide (or a process fluid containing carbon dioxide) alone.

[0063] Figure 6 is a flowchart depicting an exemplary method 300 for compressing a process fluid, according to one or more embodiments. The method 300 may include driving a rotary shaft of a supersonic compressor via a driver operatively coupled with the supersonic compressor, as at 302. The drive shaft may be driven by a driver, such as, for example, an electric motor.

[0064] The method 300 may also include establishing a fluid property of the process fluid flowing through an inlet passageway defined by an inlet of the supersonic compressor via at least one moveable inlet guide vane pivotally coupled to a housing of the supersonic compressor and extending into the inlet passageway, the process fluid including carbon dioxide, as at 304. The method may also include adjusting the at least one moveable inlet guide vane to establish the fluid property of the process fluid, where the fluid property is a flow pattern, a first velocity, a mass flow rate, a pressure, or a temperature.

[0065] The method 300 may further include rotating a centrifugal impeller mounted about the rotary shaft, such that the process fluid flowing through the inlet passageway of the supersonic compressor is drawn into the centrifugal impeller and discharged from a tip of the centrifugal impeller via a plurality of flow passages, the discharged process fluid having a supersonic velocity with an exit absolute Mach number of about one or greater, as at 306. The method 300 may also include flowing the discharged process fluid having a supersonic velocity through an annular diffuser passageway defined by a static diffuser and fluidly coupled to the plurality of flow passages such that a pressure energy of the discharged process fluid is increased, thereby compressing the discharged process fluid at a compression ratio of about 8:1 or greater, as at 308.

[0066] The static diffuser may be a vaneless diffuser bounded in part by a shroud wall and a hub wall defining the annular diffuser passageway therebetween. The shroud wall bounding the annular diffuser passageway may be a straight wall, a contoured wall, or a combination thereof, and the hub wall bounding the annular diffuser passageway may be a straight wall, a contoured wall, or a combination thereof. In another embodiment, the static diffuser may be a vaned diffuser bounded in part by a shroud wall and a hub wall defining the annular diffuser passageway therebetween, and the vaned diffuser may include a plurality of low solidity diffuser vanes extending into the annular diffuser passageway from either or both the shroud wall and the hub wall.

[0067] 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.

[0068] Certain embodiments and features have been described using a set of numerical upper limits and a set of numerical lower limits. It should be appreciated that ranges including the combination of any two values, *e.g.*, the combination of any lower value with any upper value, the combination of any two lower values, and/or the combination of any two upper values are contemplated unless otherwise indicated.

[0069] 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

We claim:

1. A supersonic compressor comprising:
 - a housing;
 - an inlet coupled to or integral with the housing and defining an inlet passageway configured to receive and flow therethrough a process fluid;
 - a plurality of inlet guide vanes coupled to the housing and extending into the inlet passageway;
 - a rotary shaft configured to be driven by a driver;
 - a centrifugal impeller coupled with the rotary shaft and fluidly coupled to the inlet passageway via a plurality of flow passages formed by the centrifugal impeller, the centrifugal impeller having a tip and configured to impart energy to the process fluid received via the inlet passageway and to discharge the process fluid from the tip via the plurality of flow passages in at least a partially radial direction at an exit absolute Mach number of about one or greater;
 - a balance piston configured to balance an axial thrust generated by the centrifugal impeller;
 - a static diffuser circumferentially disposed about the tip of the centrifugal impeller and bounded in part by a shroud wall and a hub wall defining an annular diffuser passageway therebetween, the static diffuser configured to receive the process fluid from the plurality of flow passages of the centrifugal impeller and convert, within the annular diffuser passageway, the energy imparted; and
 - a collector fluidly coupled to the annular diffuser passageway and configured to collect the process fluid exiting the annular diffuser passageway,wherein the supersonic compressor is configured to provide a compression ratio of at least about 8:1.
2. The supersonic compressor of claim 1, wherein:
 - the plurality of inlet guide vanes are pivotably coupled to the housing;
 - the balance piston is integral with the centrifugal impeller; and
 - the collector is a discharge volute configured to discharge the process fluid to a downstream processing component.
3. The supersonic compressor of claim 2, wherein the plurality of inlet guide vanes are configured to condition the process fluid flowing therethrough to yield one or more predetermined fluid properties selected from the group consisting of a flow pattern, a velocity, a mass flow rate, a pressure, and a temperature.
4. The supersonic compressor of claim 1, wherein:
 - the supersonic compressor is configured to provide a compression ratio of at least about 10:1;
 - the process fluid comprises carbon dioxide;
 - the centrifugal impeller is configured to discharge the process fluid from the tip via the plurality of flow passages in at least a partially radial direction at an exit absolute Mach number of about 1.3 or greater; and

the centrifugal impeller is further configured to rotate via the rotary shaft at a rotational speed of about 500 meters per second or greater.

5. The supersonic compressor of claim 1, wherein the static diffuser is a vaneless diffuser configured to discharge the process fluid flowing therethrough at a subsonic velocity.
6. The supersonic compressor of claim 1, wherein the centrifugal impeller comprises a hub and a plurality of blades extending therefrom and forming the plurality of flow passages, each of the plurality of blades comprising a leading edge and at least one leading edge of the plurality of blades is meridionally spaced from at least one other leading edge of the plurality of blades.
7. The supersonic compressor of claim 1, further comprising a shroud having an abradable material disposed adjacent a plurality of blades extending from a hub of the centrifugal impeller.
8. The supersonic compressor of claim 1, wherein the process fluid comprises carbon dioxide.
9. The supersonic compressor of claim 8, wherein the process fluid comprises about ninety percent carbon dioxide.
10. The supersonic compressor of claim 1, wherein the centrifugal impeller is an open-faced impeller.
11. A compression system comprising:
 - a driver comprising a drive shaft, the driver configured to provide the drive shaft with rotational energy;
 - a supersonic compressor operatively coupled to the driver via a rotary shaft integral with or coupled with the drive shaft, the supersonic compressor comprising:
 - a compressor chassis;
 - an inlet defining an inlet passageway configured to flow a process fluid therethrough, the process fluid having a first velocity and a first pressure energy;
 - a plurality of inlet guide vanes pivotally coupled to the compressor chassis and extending into the inlet passageway;
 - a centrifugal impeller coupled with the rotary shaft and fluidly coupled to the inlet passageway via a plurality of flow passages formed by the centrifugal impeller, the centrifugal impeller having a tip and configured to increase the first velocity and the first pressure energy of the process fluid received via the inlet passageway and to discharge the process fluid from the tip via the plurality of flow passages in at least a partially radial direction having a second velocity and a second pressure energy, the second velocity being a supersonic velocity having an exit absolute Mach number of about one or greater;
 - a static diffuser circumferentially disposed about the tip of the centrifugal impeller and defining an annular diffuser passageway fluidly coupled to the plurality of flow passages, the annular diffuser

passageway configured to receive and reduce the second velocity of the process fluid to a third velocity and increase the second pressure energy to a third pressure energy, the third velocity being a subsonic velocity; and

a discharge volute fluidly coupled to the annular diffuser passageway and configured to receive the process fluid flowing therefrom,

wherein the supersonic compressor is configured to provide a compression ratio of at least about 8:1.

12. The compression system of claim 11, wherein the supersonic compressor further comprises:

a shroud having an abradable material disposed adjacent a plurality of blades extending from a hub of the centrifugal impeller and forming the plurality of flow passages fluidly coupled to the annular diffuser passageway and the inlet passageway; and

a balance piston integral with the centrifugal impeller and configured to balance an axial thrust generated by the centrifugal impeller, wherein

the supersonic compressor is configured to provide a compression ratio of at least about 10:1,

the process fluid comprises carbon dioxide, and

the second velocity has an exit absolute Mach number of about 1.3 or greater.

13. The compression system of claim 11, wherein the static diffuser is a vaneless diffuser bounded in part by a shroud wall and a hub wall defining the annular diffuser passageway therebetween.

14. The compression system of claim 13, wherein either or both the shroud wall and the hub wall are contoured, such that an axial width of the annular diffuser passageway is reduced as the shroud wall and the hub wall extend radially outward.

15. The compression system of claim 11, wherein the static diffuser comprises a plurality of low solidity diffuser vanes extending into the annular diffuser passageway.

16. The compression system of claim 15, wherein the static diffuser is bounded in part by a shroud wall and a hub wall defining the annular diffuser passageway therebetween, and the plurality of low solidity diffuser vanes are arranged in tandem within the annular diffuser passageway and extend into the annular diffuser passageway from the shroud wall, the hub wall, or both the shroud wall and the hub wall.

17. A method for compressing a process fluid, comprising:

driving a rotary shaft of a supersonic compressor via a driver operatively coupled with the supersonic compressor;

establishing a fluid property of the process fluid flowing through an inlet passageway defined by an inlet of the supersonic compressor via at least one moveable inlet guide vane pivotally coupled to a housing of the supersonic compressor and extending into the inlet passageway;

rotating a centrifugal impeller mounted about the rotary shaft, such that the process fluid flowing through the inlet passageway of the supersonic compressor is drawn into the centrifugal impeller and discharged from a tip of the centrifugal impeller via a plurality of flow passages, the discharged process fluid having a supersonic velocity with an exit absolute Mach number of about 1.0 or greater; and

flowing the discharged process fluid having a supersonic velocity through an annular diffuser passageway defined by a static diffuser and fluidly coupled to the plurality of flow passages such that a pressure energy of the discharged process fluid is increased, thereby compressing the discharged process fluid at a compression ratio of about 8:1 or greater.

18. The method of claim 17, further comprising:

adjusting the at least one moveable inlet guide vane to establish the fluid property of the process fluid, wherein the fluid property is selected from the group consisting of a flow pattern, a first velocity, a mass flow rate, a pressure, and a temperature, and wherein the process fluid comprises carbon dioxide.

19. The method of claim 17, wherein:

the static diffuser is a vaneless diffuser bounded in part by a shroud wall and a hub wall defining the annular diffuser passageway therebetween,

the shroud wall bounding the annular diffuser passageway is a straight wall, a contoured wall, or a combination thereof, and

the hub wall bounding the annular diffuser passageway is a straight wall, a contoured wall, or a combination thereof.

20. The method of claim 17, wherein:

the static diffuser is a vaned diffuser bounded in part by a shroud wall and a hub wall defining the annular diffuser passageway therebetween, and

the static diffuser comprises a plurality of low solidity diffuser vanes extending into the annular diffuser passageway from either or both the shroud wall and the hub wall.

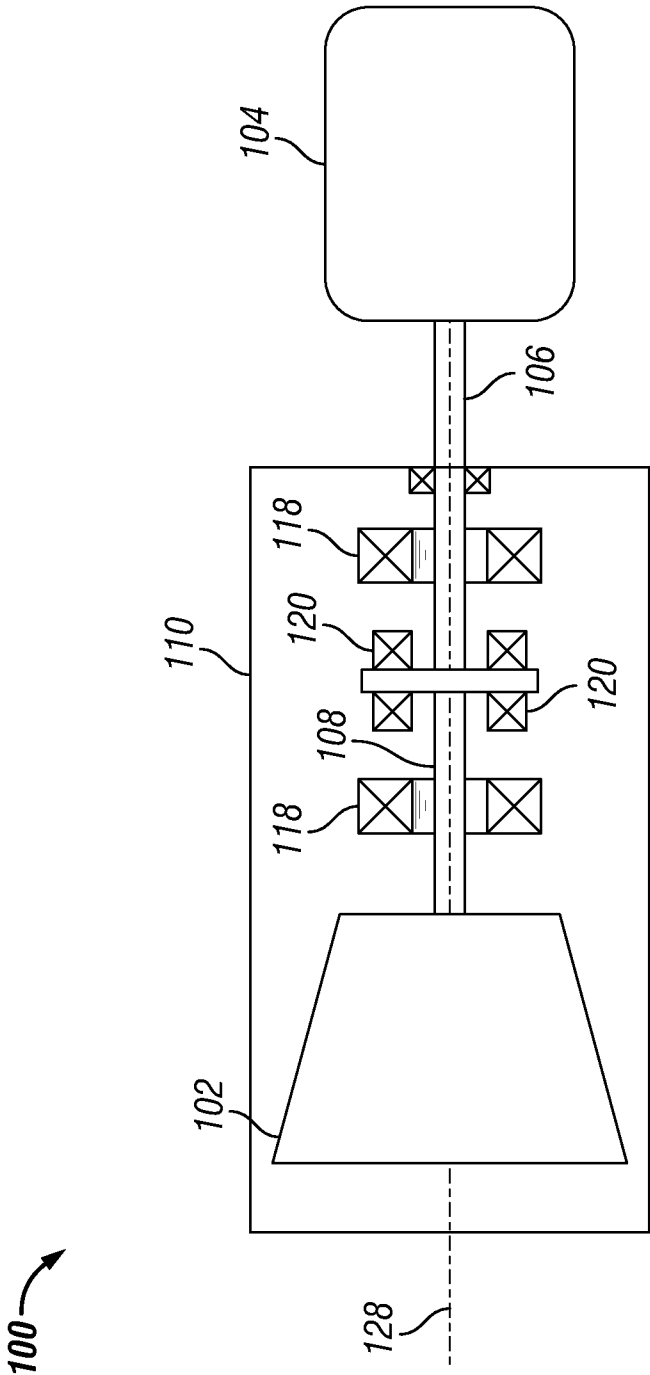


FIG. 1

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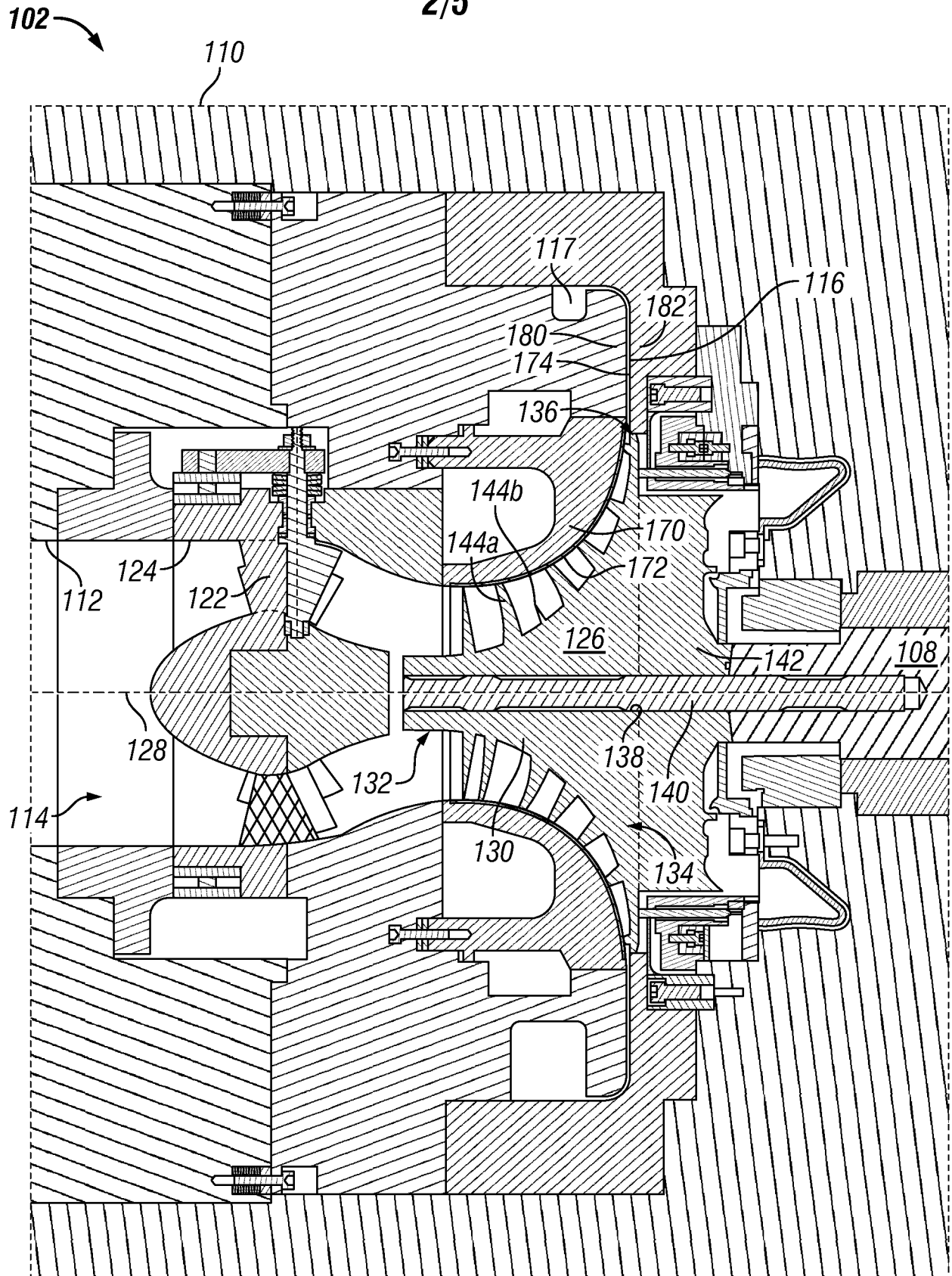


FIG. 2

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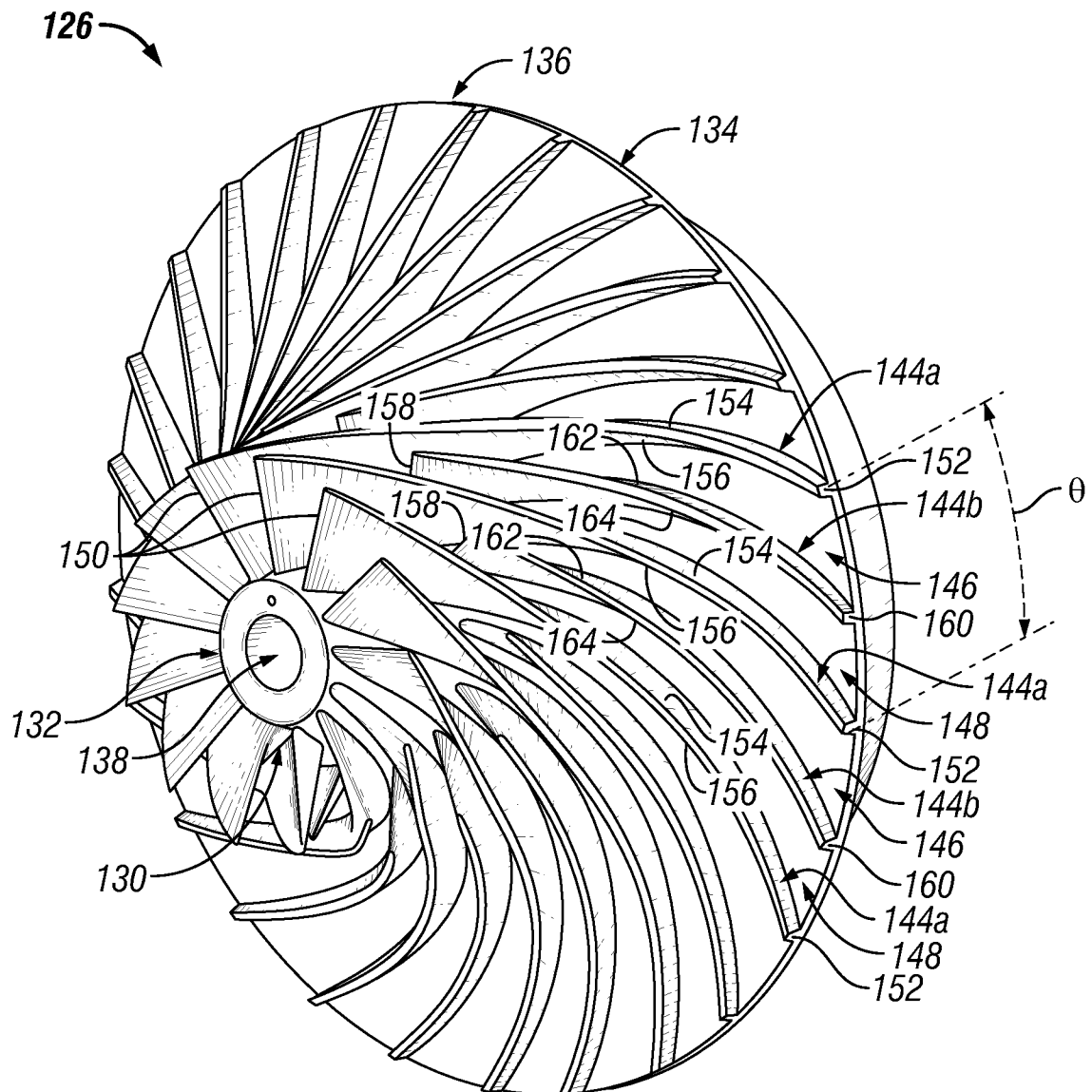


FIG. 3

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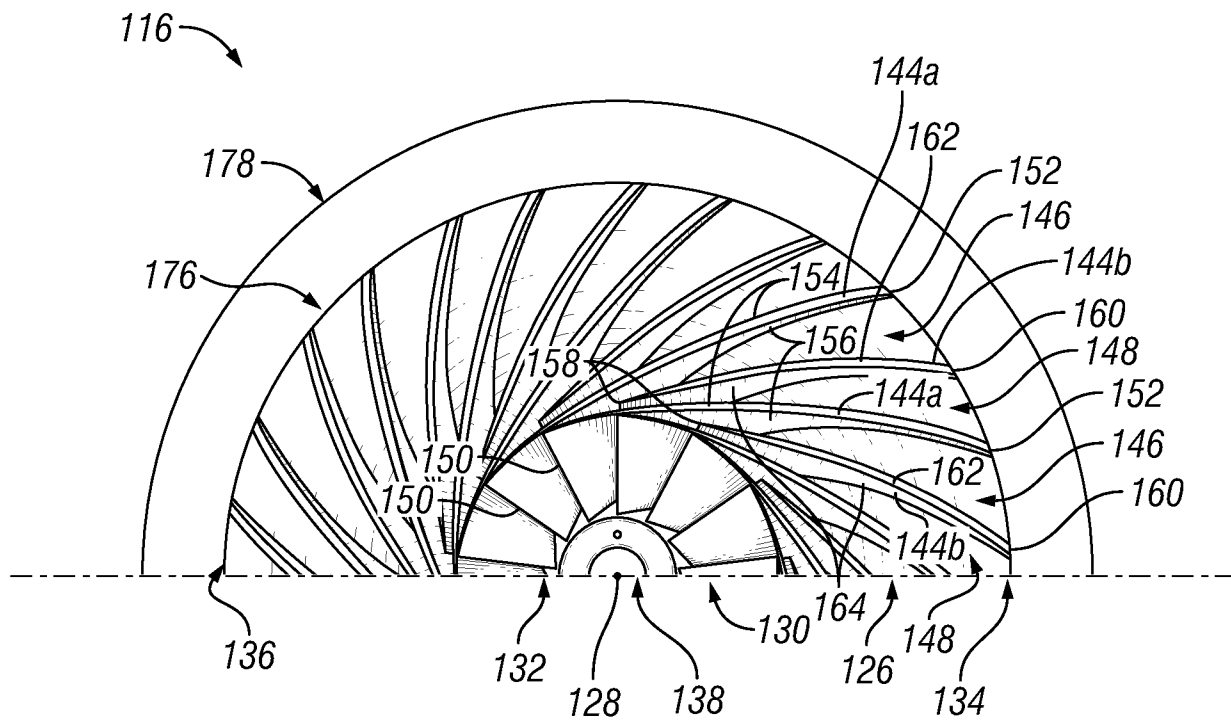


FIG. 4

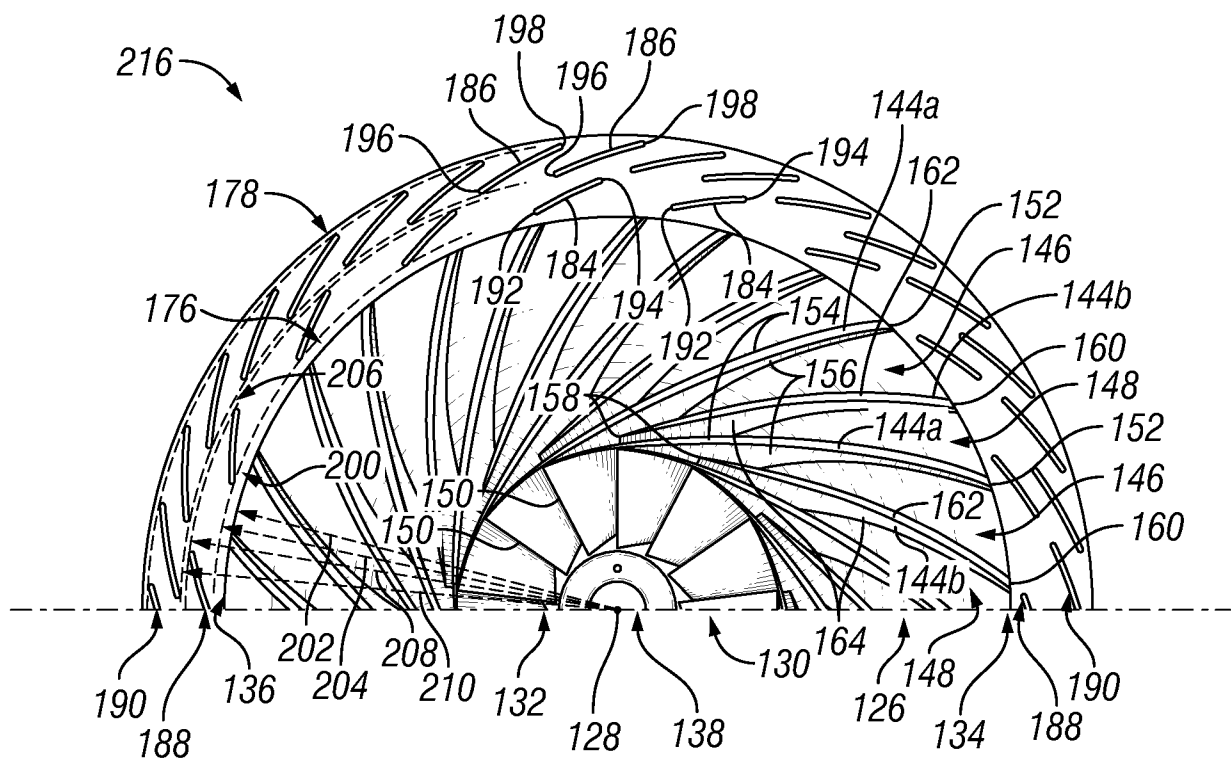


FIG. 5

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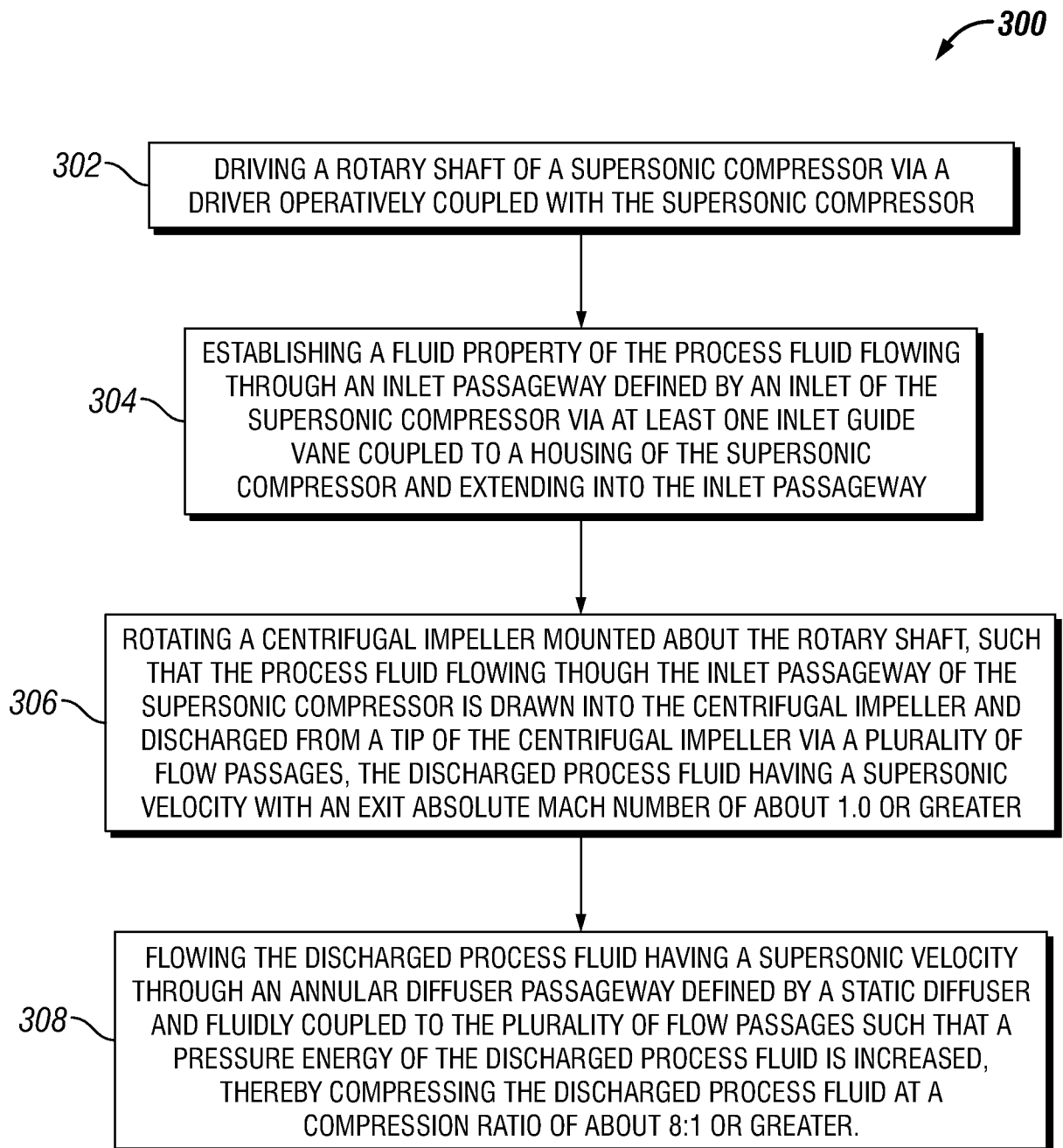


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/023568**A. CLASSIFICATION OF SUBJECT MATTER****F04D 29/44(2006.01)i, F04D 17/08(2006.01)i**

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

B. FIELDS SEARCHEDMinimum documentation searched (classification system followed by classification symbols)
F04D 29/44; F04D 21/00; F25B 9/06; B23P 11/00; B64C 27/18; F04D 17/12; F04D 17/08Documentation 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 modelsElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: supersonic, compressor, housing, inlet, vane, shaft, impeller, piston, diffuser, collector and compression-ratio**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2012-0224952 A1 (HOFER, DOUGLAS CARL et al.) 06 September 2012 See paragraphs [0022]-[0024], [0031]-[0032] and figures 1-2.	1-20
A	US 2013-0091869 A1 (BARDON, PATRICE et al.) 18 April 2013 See paragraph [0029] and claim 1.	1-20
A	US 2012-0301271 A1 (HOFER, DOUGLAS CARL et al.) 29 November 2012 See paragraphs [0005]-[0007] and claim 1.	1-20
A	KR 10-2014-0041498 A (GENERAL ELECTRIC CO.) 04 April 2014 See claims 1, 8 and figures 1-2.	1-20
A	US 2006-0034691 A1 (LAWLOR, SHAWN P. et al.) 16 February 2006 See claims 1, 21.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

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"&" document member of the same patent family

Date of the actual completion of the international search

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Date of mailing of the international search report

13 June 2016 (13.06.2016)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/023568

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