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Inventor(s) Swartzlander; Matthew Gareld

OPTIMIZED ENERGY RECOVERY DEVICE

Abstract

A Roots-type device can include a housing assembly having a first opening and a second opening in fluid communication with an internal cavity; a pair of identical rotors oppositely arranged within the housing internal cavity, each of the pair of rotors having a longitudinal axis and plurality of lobes, each of the lobes defining an end face extending between a first longitudinal side of the rotor lobe and a second longitudinal side of the rotor lobe; and a recess port defined within the housing assembly and being axially spaced from the end faces of the rotor lobes, the recess port placing the first longitudinal side of one of the rotor lobes in fluid communication with the second longitudinal side of the rotor lobe such that the housing first opening is placed in fluid communication with the housing second opening. The device can also be provided be provided with an inlet nozzle structure in fluid communication with the first opening, the inlet nozzle tapering towards the first opening and being configured such that a nozzle velocity of a working fluid passing through the nozzle is at least equal to the rotor mesh axial lead velocity.

Inventors: **Swartzlander; Matthew Gareld (Battle Creek, MI)**

Applicant: **Eaton Intelligent Power Limited** (Dublin 4, IE)

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Background/Summary

RELATED APPLICATIONS [0001] This application is being filed on Apr. 14, 2023, as a PCT International Patent application and claims the benefit of and priority to U.S. Provisional application Nos. 63/363,024, filed Apr. 14, 2022; 63/336,483, filed Apr. 29, 2022; and 63/493,606, filed on Mar. 31, 2023, the entireties of each being incorporated by reference herein.

TECHNICAL FIELD
[0002] This disclosure relates to Roots-type devices used in expander and compressor applications.
BACKGROUND
[0003] Roots-type expanders utilize the energy in the fluid stream applied to the rotor surfaces to create rotational work. By increasing the time within the device, the pressure differential applied to the rotors can improve the efficiency of the device. One way to increase this "time" is to twist the rotors more than the ideal twist. However, conventional methods of designing rotors of Roots-type expanders have limitations of hardware constraints. Improvements are desired.
SUMMARY
[0004] In general terms, this disclosure is directed to a volumetric fluid expander. Various aspects are described in this disclosure, which include, but are not limited to, the following aspects.
[0005] In one aspect of the disclosure, a volumetric fluid expander is provided to generate useful work by expanding a working fluid. In one application, the volumetric fluid expander can be utilized to recover waste energy from a power plant, such as waste heat energy from a fuel cell or an internal combustion engine. The power plant may be provided in a vehicle or may be provided in a stationary application such as could be the case when the power plant is used as a generator. In one possible configuration and by non-limiting example, the volumetric fluid expander is employed in an exhaust gas recirculation system of an internal combustion engine.
[0006] In one example, the working fluid is all or part of the exhaust gas stream from an internal combustion engine or a fuel cell. In another example, the working fluid is separate from and heated by a waste heat stream from an internal combustion engine or a fuel cell, such as is disclosed in International Publication Number WO 2013/130774, which is incorporated herein by reference. WO 2013/130774 discloses that the working fluid can be used in a Rankine cycle where the working fluid may be a solvent such as ethanol, n-pentane, or toluene.
[0007] A Roots-type device can include a housing assembly having a first opening and a second opening in fluid communication with an internal cavity; a pair of identical rotors oppositely arranged within the housing internal cavity, each of the pair of rotors having a longitudinal axis and a plurality of lobes, each of the lobes defining an end face extending between a first longitudinal side of the rotor lobe and a second longitudinal side of the rotor lobe; and a recess port defined within the housing assembly and being axially spaced from the end faces of the rotor lobes, the recess port placing the first longitudinal side of one of the rotor lobes in fluid communication with the second longitudinal side of the rotor lobe such that the housing first opening is placed in fluid communication with the housing second opening.

[0008] In some examples, the housing assembly includes a main housing and a bearing plate secured to the main housing, and wherein the recess port is defined within the bearing plate.
[0009] In some examples, the end face of at least one rotor lobe faces the recess port in all rotational angles of the rotors.
[0010] In some examples, each of the pair of rotors has a twist angle that is less than or equal to an ideal twist angle of the rotors defined without the presence of the recess port.
[0011] In some examples, each of the pair of rotors has three lobes.
[0012] In some examples, the rotors are located axially between the housing first opening and the recess port.
[0013] In some examples, the pair of rotors are each supported by rotatable shafts located between the housing second opening and the recess port.
[0014] In some examples, the pair of rotors are each supported by shafts having longitudinal axes aligned along a first longitudinal plane, wherein a housing outlet is located on a first side of the first longitudinal plane, and wherein the recess port is located on a second side of the first longitudinal plane.
[0015] In some examples, the first opening is orthogonal to the longitudinal axes of the rotors.
[0016] In some examples, the second opening is parallel to the longitudinal axes of the rotors.
[0017] A Roots-type device can include a pair of rotors and a housing assembly within which the rotors are disposed, the housing assembly having a first opening and a second opening, and having a recess port placing the housing first opening in fluid communication with the housing second opening.
[0018] In some examples, the recess port is located at a first axial end of the pair of rotors.
[0019] In some examples, the recess port defines a leak path around an axial end of at least one lobe of the pair of rotors in at least some rotational positions of the pair of rotors.
[0020] In some examples, the recess port places a first longitudinal side of one of the rotor lobes in fluid communication with a second longitudinal side of the rotor lobe.
[0021] In some examples, the housing assembly includes a main housing and a bearing plate secured to the main housing, and wherein the recess port is defined within the bearing plate.
[0022] In some examples, an end face of at least one lobe of the pair of rotors faces the recess port in all rotational angles of the rotors.
[0023] In some examples, each of the pair of rotors has a twist angle that is less than or equal to an ideal twist angle of the rotors defined without the presence of the recess port.
[0024] In some examples, each of the pair of rotors has three lobes.
[0025] In some examples, the rotors are located axially between the housing first opening and the recess port.
[0026] In some examples, the pair of rotors are each supported by rotatable shafts located between the housing second opening and the recess port.
[0027] In some examples, the pair of rotors are each supported by shafts having longitudinal axes aligned along a first longitudinal plane, wherein a housing outlet is located on a first side of the first longitudinal plane, and wherein the recess port is located on a second side of the first longitudinal plane.
[0028] In some examples, the first opening is orthogonal to the longitudinal axes of the rotors.
[0029] In some examples, the second opening is parallel to the longitudinal axes of the rotors.
[0030] A bearing plate for a Roots-type device can include a main body extending along a longitudinal axis from a first side to a second side; a pair of cavities for supporting bearing and seal assemblies, the cavities extending between the first and second sides of the main body; a primary surface at least partially defining the first side and being orthogonal to the longitudinal axis; and a recess area at least partially defining the first side and being axially recessed from the primary surface in a direction towards the second side, the recess area being configured to provide a leak path for the Roots-type device.

[0031] In some examples, the recess area is located entirely on a first side of a plane extending centrally through the pair of cavities and parallel to the longitudinal axis.
[0032] In some examples, the recess area extends to an outer edge of the main body.
[0033] In some examples, the main body includes a second recess area at least partially defining the first side and being axially recessed from the primary surface in a direction towards the second side, the second recess area being located entirely on a second side of the plane.
[0034] In some examples, the recess area has a V-shape.
[0035] A method for retrofitting a supercharger for an expander application can include providing a supercharger having a pair of rotors and a housing assembly within which the rotors are disposed, the housing assembly having a first opening and a second opening; removing a first bearing plate of the supercharger; and installing a second bearing plate onto the supercharger, the second bearing plate including a recess port placing the housing first opening in fluid communication with the housing second opening.
[0036] A Roots-type device can include a housing assembly having a first opening and a second opening in fluid communication with an internal cavity; a pair of identical rotors oppositely arranged within the internal cavity, each of the pair of rotors having a longitudinal axis and a plurality of lobes, wherein the rotors are intermeshed and, when rotating, define a rotor mesh axial lead velocity; and an inlet nozzle structure in fluid communication with the first opening, the inlet nozzle structure tapering towards the first opening and being configured such that a nozzle velocity of a working fluid passing through the inlet nozzle structure is at least equal to the rotor mesh axial lead velocity.
[0037] In some examples, the inlet nozzle structure is oriented generally parallel to the longitudinal axis.
[0038] In some examples, the inlet nozzle structure is oriented at an oblique angle to the longitudinal axis.
[0039] In some examples, the cross-sectional area of the nozzle structure decreases by at least 20 percent.
[0040] In some examples, a volumetric flow rate through the inlet nozzle structure is increased by at least double.
[0041] In some examples, each of the rotors includes four lobes.
[0042] In some examples, the nozzle velocity is greater than the rotor mesh axial lead velocity.
[0043] In some examples, the nozzle velocity is at least 1.1 times the rotor mesh axial lead velocity.
[0044] In some examples, the nozzle velocity is at least 1.6 times the rotor mesh axial lead velocity.
[0045] Additional objects and advantages will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the teachings presented herein. The objects and advantages will also be realized and attained by means of the elements and combinations particularly pointed out in the appended claims. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the claimed invention.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0046] FIG. **1** is a perspective view of a Roots-type device having features that are examples of aspects in accordance with the principles of the present disclosure.
[0047] FIG. **2** is a second perspective view of the Roots-type device shown in FIG. **1**.
[0048] FIG. **3** is a top view of the Roots-type device shown in FIG. **1**.
[0049] FIG. **4** is a bottom view of the Roots-type device shown in FIG. **1**.
[0050] FIG. **5** is a first side view of the Roots-type device shown in FIG. **1**.

[0051] FIG. **6** is a second side view of the Roots-type device shown in FIG. **1**.
[0052] FIG. **7** is a first end view of the Roots-type device shown in FIG. **1**.
[0053] FIG. **8** is a second end view of the Roots-type device shown in FIG. **1**.
[0054] FIG. **9** is a first cross-sectional view of the Roots-type device shown in FIG. **1**, taken along line **9-9** in FIG. **7**.
[0055] FIG. **10** is a second cross-sectional view of the Roots-type device shown in FIG. **1**, taken along line **10-10** in FIG. **7**.
[0056] FIG. **11** is a third cross-sectional view of the Roots-type device shown in FIG. **1**, taken along line **11-11** in FIG. **5**.
[0057] FIG. **12** is a partial perspective view of the Roots-type device shown in FIG. **1**, illustrating a leak path within the device.
[0058] FIG. **13** is a perspective view of a bearing plate of the Roots-type device shown in FIG. **1**.
[0059] FIG. **14** is a second perspective view of the bearing plate shown in FIG. **13**.
[0060] FIG. **15** is a first end view of the bearing plate shown in FIG. **13**.
[0061] FIG. **16** is a second end view of the bearing plate shown in FIG. **13**.
[0062] FIG. **17** is a cross-sectional view of the bearing plate shown in FIG. **13**, taken along line **17-17** in FIG. **16**.
[0063] FIG. **18** is a perspective view of a rotor of the Roots-type device shown in FIG. **1**.
[0064] FIG. **19** is an end view of the rotor shown in FIG. **18**.
[0065] FIG. **20** is a perspective view of a second example of a rotor usable with the Roots-type device shown in FIG. **1**.
[0066] FIG. **21** is an end view of the rotor shown in FIG. **20**.
[0067] FIG. **22** is a schematic cross-sectional view of the Roots-type expander shown in FIG. **1**.
[0068] FIG. **23** is a schematic perspective view of a variation of the Roots-type expander shown in FIG. **1**.
[0069] FIG. **24** is a schematic cross-sectional side view of variation of the Roots-type expander shown in FIG. **1**.
[0070] FIG. **25** is a side view of a second embodiment of a volumetric fluid expander having features that are examples of aspects in accordance with the principles of the present disclosure.
[0071] FIG. **26** is a cross-sectional side view of the volumetric fluid expander shown in FIG. **25**.
[0072] FIG. **27** is a cross-sectional side view of a portion of the fluid expander shown in FIG. **25**.
[0073] FIG. **28** is a top view of the portion of the fluid expander shown in FIG. **27**.
[0074] FIG. **29** is a perspective view of the portion of the fluid expander shown in FIG. **27**.
[0075] FIG. **30** is a perspective view of the rotors of the fluid expander shown in FIG. **25**.
[0076] FIG. **31** is a schematic perspective view of the volumetric fluid expander shown in FIG. **25**.
[0077] FIG. **32** is a schematic showing geometric parameters of the rotors of the volumetric fluid expanders shown in FIGS. **1**, **23**, and **24**.

DETAILED DESCRIPTION

[0078] This disclosure is related to energy recovery devices for use in multiple applications. In one, the disclosed energy recovery devices are usable in vehicle power plant applications where waste heat energy from the vehicle power plant is captured and returned to the power plant. In some examples, the working fluid used by the expander is a compressible fluid such as air. The disclosed energy recovery devices can be used in other applications as well, for example, in marine and agricultural industries.
[0079] Referring to FIGS. **1-12** and **23-25**, a Roots-type device **20**, also called energy recovery device, in accordance with the present teachings is shown. FIGS. **1-12** present the Roots-type device **20** in a physical embodiment, while FIGS. **23-25** present the Roots-type device **20** in schematic cross-sectional form.
[0080] In one aspect, the Roots-type device **20** includes a main housing **102** that defines an internal cavity or first working fluid passageway **106** extending between a first opening **108** and a second

opening **110**. Disposed within the working fluid passageway **106** is a pair of intermeshed rotors **30**, **32** extending between end faces **30***a*, **30***b* and **32***a*, **32***b*. In the example presented, the rotors **30**, **32** are three-lobe rotors with lobes **30-1**, **30-2**, **30-3** and **32-1**, **32-2**, **32-3**, such as the rotor **30**, **32** shown in isolation at FIGS. **18** and **19**. As presented, the number of lobes is the same for each rotor **30** and **32**. This is in contrast to the construction of typical rotary screw devices and other similarly configured rotating equipment which have a dissimilar number of lobes (e.g., a male rotor with "n" lobes and a female rotor with "n+1" lobes). Furthermore, one of the distinguishing features of the Roots-type device **20** is that the rotors **30** and **32** are identical, wherein the rotors **30**, **32** are oppositely arranged so that, as viewed from one axial end, the lobes of one rotor are twisted clockwise while the lobes of the meshing rotor are twisted counter-clockwise. Other configurations are possible, such as the four-lobe rotor **30**, **32** schematically presented at FIGS. **20** and **21**.

[0081] In the example presented, the first opening **108** is disposed generally parallel to a longitudinal axis X of the energy recovery device while the second opening **110** is disposed generally orthogonally to the longitudinal axis X. Other opening configurations are possible. In one example, the Roots-type device **20** is configured such that a working fluid **12** flows from the first opening **108**, which can be characterized as an inlet **108**, to the second opening **110**, which can be characterized as an outlet **110**. The Roots-type device **20** may be operated or configured such that flow in the opposite direction occurs as well. In some examples, the working fluid is a compressible fluid, such as atmospheric air or engine exhaust. In some applications, the Roots-type device **20** operates as an expander in which the working fluid flows through the passageway **106** to impart rotational energy onto the rotors **30**, **32** which can then be output by the device **20**. In some applications, the Roots-type device **20** operates as a compressor, such as in a supercharger application, in which the rotors **30**, **32** are rotated to generate and deliver a flow of the working fluid. In some applications, the same Roots-type device **20** is selectively operable in both an expander mode and a compressor mode.

[0082] In one aspect, and as most easily viewed at FIGS. **9** and **10**, each of the rotors **30**, **32** are respectively mounted to rotor shafts **38**, **40**. In the example shown, the shaft **38** has an extension portion **38***a* such that power can be transferred to and/or from the Roots-type device **20** via attached pulleys, gears, or the like. In the schematic example presented at FIG. **25**, a pulley or gear **200** is mounted to shaft **38** and operatively connected to an input/output location **16** via a belt, chain, or gear set **202**, such as a planetary gear set. The input/output location **16** can be any machine, device, or system capable of receiving, transferring, or generating energy such as a motor/generator or an internal combustion engine.

[0083] In one aspect, a timing gear **42**, **44** is respectively mounted to each shaft **38**, **40**. The timing gears **42**, **44** are intermeshed with each other to ensure that the rotors **30**, **32** rotate synchronously such that interference between the rotors **30**, **32** is avoided. Bearing and seal assemblies of a known type **46**, **48** and **50**, **52** are also provided at each shaft **38**, **40** on opposite sides of the rotors **30**, **32** to rotationally support the shafts **38**, **40** and to ensure that the working fluid within the housing passageway **106** does not leak past the shafts **38**, **40** as it exits the passageway **106**. In the example shown, the bearing assemblies **46**, **48** are supported within cavities **70**, **72** of a bearing plate **60** which is mounted to the housing **102**. The bearing plate **60** forms an end surface of the internal cavity of the housing and passageway **106**. The bearing assemblies **50**, **52** are shown as being supported in recess or cavity portions of the housing **102**.

[0084] The bearing plate **60**, when removed, provides an opening through which the rotors **30**, **32** can be installed and removed from the interior of the housing **102**. The bearing plate **60**, shown in isolation at FIGS. **13** to **17**, is shown as including an interior face **62** facing the interior of the housing **102** and passageway **106**. The interior face **62** includes a primary surface **64**, a first recessed area **66**, and a recess port **68**. The primary surface **64** is located in close proximity to the end faces **30***a*, **32***b* of the rotors **30**, **32** such that leakage between the primary surface **64** and the rotors **30**, **32** is minimized as much as possible. The first recessed area **66** is recessed in an axial direction away from the end faces **30***a*, **32***b* of the rotors **30**, **32** and is also open to the second opening **110**. Accordingly, the first recessed area **66** enlarges the area or volume through which the working fluid can enter or leave the passageway **106** and rotors **30**, **32**. The recess port **68**, located opposite the first recessed area **66** and opening **110**, which includes a first wall **68***a* parallel to the end faces **30***a*, **32***a* of the rotors **30**, **32**, is also recessed in an axial direction away from the end faces **30***a*, **32***b* of the rotors to create a gap **69** which is relatively larger than the gap between the end faces **30***a*, **32***b* and a bearing plate primary surface **64**. The recess port **68** also includes a second wall **68***b* extending from the primary surface **64** to the first wall **68***a*. Accordingly, the second wall **68***b* extends in a direction that is generally orthogonal to the ends faces **39***a*, **32***b* and parallel to the length of the rotors **30**, **32**. In one aspect, the second wall **68***b* can be characterized as having a V-shape or V-type shape having a center that is closer to the longitudinal axis X in comparison to the ends of the second wall **68***b*. This shape is advantageous as the leak path created by the recess port, discussed in more detail below, is more consistently maintained as the height of the rotor lobes necessarily changes as they rotate across the recess port **68**. Although the recess port **68** is shown as being integrated into the bearing plate **60**, other configurations are possible. For example, the recess port **68** could be incorporated into a surface of the housing **102**. In one aspect, the bearing plate **60** and main housing **102** can be characterized as being a housing assembly, while the recess port **68** can be characterized as being formed within the housing assembly. In one aspect, the recess port **68** can be characterized as being a metering port or orifice means. In one aspect, the housing **102**, rotors **30**, **32**, and recess port **68** of the bearing plate **60** collectively define the cross-sectional area or orifice area that defines the leak path. This area is to be considered the area perpendicular to the fluid flow through the port which should be parallel to the end face of the rotor. The shape and size of the recess port **68** can be determined or optimized for a specific application. For example, the depth of the recess port **68** (i.e., the distance between first wall **38***a* and end faces **30***a*, **32***b* and defined by the width of the second wall **68***b*) can be adjusted to result in a desired orifice area. For example, if it is desired to have a compressor mode and an expander mode for the device **20**, and the expander efficiency mode is more favorable, creating a leak path would favor this mode and the recess port **68** may be designed to be larger for an optimized leak. If the compressor mode is favored, then the recess port **68** and resulting leak path would be minimized to favor the compressor mode. Further, the pressure ratio and speed of the device **20** will also influence the cross-sectional area of the port.

[0085] During operation, as an individual rotor lobe **30-1**, **30-2**, **30-3** and **32-1**, **32-2**, **32-3** rotates across the recess port **68**, a passageway **107** is created that extends from one longitudinal side (e.g., side A) of the lobe, around the end face **30***a*, **32***b* of the lobe and into the recess port **68**, and to the other longitudinal side (e.g., side B) of the lobe. The pathway is schematically depicted at FIG. **25** and in partial view provided at FIG. **12**. By use of the term cross or crosses, it is meant that the end face of a lobe is exposed to and faces the recess port such that fluid communication exists at least between one side of the lobe and the recess port. By use of the term fully cross or fully crosses, it is meant that the end face of a lobe is exposed to and faces the recess port such that fluid communication exists between both sides of the lobe and the recess port.

[0086] When a rotor lobe fully crosses the recess port **68**, one side of the lobe is in fluid communication with the opening **108** while the other side of the lobe is in fluid communication with the opening **110**. As such, the recess port functions to create the orifice or passageway **107** extending between the openings **108**, **110**. In the example shown, the recess port **68** is shaped such that at least one rotor lobe **30-1**, **30-2**, **30-3** and **32-1**, **32-2**, **32-3** of one of the rotors **30**, **32** fully crosses the recess port **68** at all rotational angles such that the passageway **107** is continuously maintained. The passageway **107** can thus be characterized as an orifice or a strategic leak path. In some rotational angles, at least one lobe **30-1**, **30-2**, **30-3** of rotor **30** and at least one lobe **32-1**, **32-2**, **32-3** of rotor **32** cross the recess port **68** at the same time. In some rotational angles of the rotor **30**, none of the lobes **30-1**, **30-2**, **30-3** of rotor **30** cross the recess port **68**. In some rotational angles of the rotor **32**, none of the lobes **32-1**, **32-2**, **32-3** of rotor **32** cross the recessed port **68**. Other configurations are possible.

[0087] When the device **20** is operated as an expander, the creation of a strategic leak path **107** is advantageous in that the time or duration that the working fluid is exposed to the rotors **30**, **32** is increased. This allows additional working fluid to expand within the outlet to create a greater pressure drop which results in additional rotational work being imparted to the rotors **30**, **32**. Stated in other terms, the disclosed design advantageously allows the fluid velocity (i.e., fluid kinetic energy) of the working fluid to remain higher and to generate rotation within the energy recovery device. The increased fluid velocity flow assists in the conversion of energy in the fluid stream into the rotor's rotation by imparting an additional moment on the rotor shafts. The strategic leak path **107**, enabled by the recess port **68**, also ensures additional expansion occurs in the outlet ensuring the working fluid **12** continues to transfer out of the device.

[0088] Another advantage is that the recess port **68** allows for a strategic leak path **107** to be created without requiring an increase of the twist angle of the rotors **30**, **32** above the ideal twist angle, as would otherwise be necessary to ensure the openings **108**, **110** remain in fluid communication with each other but for the presence of the recess port **68**. For reference, the twist angle is known to those skilled in the art to be the angular displacement of the lobe, in degrees, which occurs in “traveling” the length L of the lobe from the rearward end of the rotor to the forward end of the rotor. A further discussion on the concepts of twist angle can be found at U.S. Pat. No. 7,488,164, the entirety of which is incorporated by reference herein. An illustration of the twist angle and related parameters is also provided at FIG. **32**. The “ideal twist” is the maximum twist angle through which the rotor **30**, **32** can twist without causing a leak will occur between the inlet and the outlet. Accordingly, rotors designed for a supercharger application having an ideal twist angle or less can be readily adapted for use in an expander application by providing the recess port **68** in the bearing plate **60** or in a modified housing **102**. In one example, a supercharger can be retrofitted for expander operation by replacing an existing bearing plate with a bearing plate **60** of the type disclosed herein having a recess port **68**. Even in cases where the rotors **30**, **32** are provided with a twist angle deviating from the ideal twist angle, the recess port **68** reduces the incremental deviation of the twist angle that would otherwise be expected without the presence of the recess port **68**, as the fluid will advantageously remain in contact with the rotors **30**, **32** within the outlet for much longer as the fluid **12** is allowed to expand.

[0089] Other configurations of the Roots-type device **20** are possible. For example, as schematically illustrated at FIG. **23**, the device **20** can be provided with a differently configured recess port which can also be characterized as a metering arrangement **68** that spans the inlet and outlet ends. As shown, there is a metering port **68** at the inlet end and a metering port **68** at the end opposite end of the inlet, wherein the two metering ports **68** create the crossover to the inlet and outlet, configured such that the recess port **68**, connecting the inlet **108** and the outlet **110**, extends along the length of the rotors **30**, **32**. As shown at FIG. **23**, each rotor **30**, **32** is provided with four lobes having 220 degrees of twist.

[0090] Yet another variation of the Roots-type device **20** is presented at FIG. **24** in which a nozzle section **24***d* is provided at the inlet **108** that tapers from a first dimension w**2**, defining a first cross-sectional area, to a second dimension w**3**, at least partially defining a second cross-sectional area that is less than the first cross-sectional area. The nozzle section **24***d*, described in further detail with respect to the embodiment shown at FIGS. **25** to **32**, operates to accelerate the velocity of the fluid **12** such that additional efficiencies of the Roots-type device **20** can be realized.

[0091] Incorporating a recess port **68** and the nozzle section **24***d* into the same Roots-type device **20**, as shown at FIG. **24**, can result in additional operational efficiencies and power output.

[0092] FIGS. **25** to **32** present another example of a Roots-type device **20** also including a nozzle section **24***d* in a housing configuration with a modified inlet and outlet, in comparison to those shown at FIGS. **1** to **24**. Although not illustrated at FIGS. **25** to **32**, the Roots-type device **20** of these figures can be provided with a recess port that creates a bypass passageway around the ends of the rotors to interconnect the device inlet and outlet. As noted previously, the following description of the nozzle section **24***d* is applicable to the nozzle section **24***d* schematically shown at FIG. **24**.

[0093] With continued reference to FIGS. **24** to **32**, Roots-type device **20** has a housing **22** with a fluid inlet structure **24** and a fluid outlet structure **26** through which a working fluid **12** undergoes a pressure drop to transfer energy to an output shaft **38**. The inlet structure **24** is configured to admit working fluid **12-1** at a first pressure whereas the outlet structure **26** is configured to discharge working fluid **12-2** at a second pressure lower than the first pressure. The output shaft **38** is driven by synchronously connected first and second interleaved counter-rotating rotors **30**, **32** which are disposed in a cavity **28** of the housing **22**. Each of the rotors **30**, **32** has lobes that are twisted or helically disposed along the length of the rotors **30**, **32**. Upon rotation of the rotors **30**, **32**, the lobes at least partially seal the fluid **12-1** against an interior side of the housing at which point expansion of the fluid **12-1** only occurs to the extent allowed by leakage which represents an inefficiency in the system. In contrast to some Roots-type devices that change the volume of the fluid when the fluid is sealed, the volume defined between the lobes and the interior side of the housing **22** of device **20** is constant as the fluid **12-1** traverses the length of the rotors **30**, **32**. Accordingly, the Roots-type device **20** is referred to as a “volumetric device” as the sealed or partially sealed fluid volume does not change.

[0094] As additionally shown schematically at FIG. **31**, each rotor **30**, **32** has four lobes, **30-1**, **30-2**, **30-3**, and **30-4** in the case of the rotor **30**, and **32-1**, **32-2**, **32-3**, and **32-4** in the case of the rotor **32**. Although four lobes are shown for each rotor **30** and **32**, each of the two rotors may have any number of lobes that is equal to or greater than two, for example three lobes. Additionally, the number of lobes is the same for each rotor **30** and **32**. This is in contrast to the construction of typical rotary screw devices and other similarly configured rotating equipment which have a dissimilar number of lobes (e.g., a male rotor with “n” lobes and a female rotor with “n+1” lobes). Furthermore, one of the distinguishing features of the Roots-type device **20** is that the rotors **30** and **32** are identical, wherein the rotors **30**, **32** are oppositely arranged so that, as viewed from one axial end, the lobes of one rotor are twisted clockwise while the lobes of the meshing rotor are twisted counter-clockwise. Accordingly, when one lobe of the rotor **30**, such as the lobe **30-1**, is leading with respect to the inlet structure **24**, a lobe of the rotor **32**, such as the lobe **30-2**, is trailing with respect to the inlet structure **24**, and, therefore with respect to a stream of the high-pressure fluid **12-1**.

[0095] As shown, the first and second rotors **30**, **32** are fixed to respective rotor shafts, the first rotor being fixed to the output shaft **38** and the second rotor being fixed to a shaft **40**. Each of the rotor shafts **38**, **40** is mounted for rotation on sets of bearings **43**, **45** about an axis X**1**, X**2**, respectively. It is noted that axes X**1** and X**2** are generally parallel to each other.

[0096] The first and second rotors **30**, **32** are interleaved and continuously meshed for unitary rotation with each other. With renewed reference to FIG. **1**, the expander **20** also includes meshed timing gears **42** and **44**, wherein the timing gear **42** is fixed for rotation with the rotor **30**, while the timing gear **44** is fixed for rotation with the rotor **32**. The timing gears **42**, **44** are also configured to maintain the relative position of the rotors **30**, **32** such that contact between the rotors is entirely prevented which could cause extensive damage to the rotors **30**, **32**. Rather, a close tolerance between the rotors **30**, **32** is maintained during rotation by the timing gears **42**, **44**. As the rotors **30**, **32** are non-contacting, a lubricant in the fluid **12** is not required for operation of the Roots-type device **20**, in contrast to typical rotary screw devices and other similarly configured rotating equipment having rotor lobes that contact each other.

[0097] The output shaft **38** is rotated by the working fluid **12** as the fluid undergoes expansion from the higher first pressure working fluid **12-1** to the lower second pressure working fluid **12-2**. As may additionally be seen in FIGS. **1**, **2**, and **7**, the output shaft **38** extends beyond the boundary of the housing **22**. Accordingly, the output shaft **38** is configured to capture the work or power generated by the expander **20** during the expansion of the fluid **12** that takes place in the rotor cavity **28** between the inlet structure **24** and the outlet structure **26** and transfer such work as output torque from the expander **20**. Although the output shaft **38** is shown as being operatively connected to the first rotor **30**, in the alternative, the output shaft **38** may be operatively connected to the second rotor **32**. The output shaft **38** can be coupled to an engine such that the energy from the exhaust can be recaptured.

[0098] In one aspect of the geometry of the expander **20**, each of the rotor lobes **30-1** to **30-4** and **32-1** to **32-4** has a lobe geometry in which the twist of each of the first and second rotors **30** and **32** is constant along their substantially matching length L. As shown schematically at FIG. **8**, one parameter of the lobe geometry is the helix angle HA. By way of definition, it should be understood that references hereinafter to “helix angle” of the rotor lobes is meant to refer to the helix angle at the pitch diameter PD (or pitch circle) of the rotors **30** and **32**. The term pitch diameter and its identification are well understood to those skilled in the gear and rotor art and will not be further discussed herein. As used herein, the helix angle HA can be calculated as follows: Helix Angle (HA)=(180/.pi.*arctan (PD/Lead)), wherein: PD=pitch diameter of the rotor lobes; and Lead=the lobe length required for the lobe to complete 360 degrees of twist. It is noted that the Lead is a function of the twist angle and the length L**1**, L**2** of the lobes **30**, **32**, respectively. The twist angle is known to those skilled in the art to be the angular displacement of the lobe, in degrees, which occurs in “traveling” the length of the lobe from the rearward end of the rotor to the forward end of the rotor. In some examples, the twist angle is about 120 degrees, although the twist angle may be fewer or more degrees.

[0099] In another aspect of the expander geometry, the inlet structure **24** includes an inlet angle **24-1**, as can be seen schematically at FIG. **26**. In one example, the inlet angle **24-1** is defined as the general or average angle of an inner surface **24***a* of the inlet structure **24**, for example an anterior inner surface. In one example, the inlet angle **24-1** is defined as the angle of the general centerline CL-**1** of the inlet structure **24**, for example as shown at FIG. **2**. In one example, the inlet angle **24-1** is defined as the general resulting direction of the fluid **12-1** entering the rotors **30**, **32** due to contact with the anterior inner surface **24***a*, as can be seen at FIG. **26**. As shown, the inlet angle **24-1** is neither perpendicular nor parallel to the rotational axes X**1**, X**2** of the rotors **30**, **32**. Accordingly, the anterior inner surface **24***a* of the inlet structure **24** causes a substantial portion of the fluid **12-1** to be shaped in a direction that is at an oblique angle with respect to the rotational axes X**1**, X**2** of the rotors **30**, **32**, and thus generally parallel to the inlet angle **24-1**.

[0100] Furthermore, and as shown in FIGS. **26** to **29**, the inlet structure **24** may be shaped such that the fluid **12-1** is directed to first axial ends of the rotors **30**, **32** and directed to the rotor lobe leading and trailing surfaces (discussed below) from a lateral direction. However, it is to be understood that the inlet angle **24-1** may be generally parallel or generally perpendicular to axes X**1**, X**2**, although an efficiency loss may be anticipated for certain rotor configurations. For example, as shown at FIG. **24**, the inlet angle **24-1** is generally parallel to axes X**1**, X**2**. By use of the term generally parallel, it is meant to refer angles that are within 10 to 15 degrees of each other. Furthermore, and as discussed in more detail later, it is noted that the inlet structure **24** may be shaped to narrow towards an inlet opening **24***b*, as shown in FIGS. **26** and **28**.

[0101] In another aspect of the expander geometry, the outlet structure **26** includes an outlet angle **26-1**, as can be seen schematically at FIG. **26**. In one example, the outlet angle **26-1** is defined as the general or average angle of an inner surface **26***a* of the outlet structure **26**. In one example, the outlet angle **26-1** is defined as the angle of the general centerline CL-**2** of the outlet structure **26**, for example as shown at FIGS. **26** and **27**. In one example, the outlet angle **26-1** is defined as the general resulting direction of the fluid **12-2** leaving the rotors **30**, **32** due to contact with the inner surface **26***a*, as can be seen at FIG. **26**. As shown, the outlet angle **26-1** is neither perpendicular nor parallel to the rotational axes X**1**, X**2** of the rotors **30**, **32**. Accordingly, the inner surface **26***a* of the outlet structure **26** receives the leaving fluid **12-2** from the rotors **30**, **32** at an oblique angle which can reduce backpressure at the outlet structure **26**. In one example, the inlet angle **24-1** and the outlet angle **26-1** are oblique with respect to each other, as is shown in the drawings. The inlet angle **24-1** and the outlet angle **26-1** can be generally equal or parallel, in alternative arrangements.

[0102] It is to be understood that the outlet angle **26-1** may be generally perpendicular to axes X**1**, X**2**, as is shown schematically at FIG. **24**. As configured, the orientation and size of the outlet structure **26-1** are established such that the leaving fluid **12-2** can evacuate each rotor cavity **28** as easily and rapidly as possible so that backpressure is reduced as much as possible. The output power of the shaft **38** is maximized to the extent that backpressure caused by the outlet can be minimized such that the fluid can be rapidly discharged. The efficiency of the expander **20** can be optimized by coordinating the geometry of the inlet angle **24-1** and the geometry of the rotors **30**, **32**. For example, the helix angle HA of the rotors **30**, **32** and the inlet angle **24-1** can be configured together in a complementary fashion. Because the inlet structure **24** introduces the fluid **12-1** to both the leading and trailing faces of each rotor **30**, **32**, the fluid **12-1** performs both positive and negative work on the expander **20**.

[0103] To illustrate, FIG. **31** shows that lobes **30-1**, **30-4**, **32-1**, and **32-2** are each exposed to the fluid **12-1** through the inlet structure opening **24***b*. Each of the lobes has a leading surface and a trailing surface, both of which are exposed to the fluid at various points of rotation of the associated rotor. The leading surface is the side of the lobe that is forward most as the rotor is rotating in a direction R**1**, R**2** while the trailing surface is the side of the lobe opposite the leading surface. For example, rotor **30** rotates in direction R**1** thereby resulting in the side **30-1***a* being the leading surface of lobe **30-1** and side **30-1***b* being the trailing surface. As rotor **32** rotates in a direction R**2** which is opposite direction R**1**, the leading and trailing surfaces are mirrored such that side **32-2***a* is the leading surface of lobe **32-2** while side **32-2***b* is the trailing surface.

[0104] In generalized terms, the fluid **12-1** impinges on the trailing surfaces of the lobes as they pass through the inlet structure opening **24***b* and positive work is performed on each rotor **30**, **32**. By use of the term positive work, it is meant that the fluid **12-1** causes the rotors to rotate in the desired direction: direction R**1** for rotor **30** and direction R**2** for rotor **32**. As shown, fluid **12-1** will operate to impart positive work on the trailing surface **32-2***b* of lobe **32-2**, for example on surface portion **47**. The fluid **12-1** is also imparting positive work on the trailing surface **30-1***b* of lobe **30-1**, for example of surface portion **46**. However, the fluid **12-1** also impinges on the leading surfaces of the lobes, for example surfaces **30-1***a* and **32-1***a*, as they pass through the inlet structure opening **24***b* thereby causing negative work to be performed on each rotor **30**, **32**. By use of the term negative work, it is meant that the fluid **12-1** causes the rotors to rotate opposite to the desired direction, R**1**, R**2**.

[0105] Accordingly, it is desirable to shape and orient the rotors **30**, **32** and to shape and orient the inlet structure **24** such that as much of the fluid **12-1** as possible impinges on the trailing surfaces of the lobes with as little of the fluid **12-1** impinging on the on the leading surfaces of the lobes such that the highest net positive work can be performed by the expander **20**.

[0106] In the example shown, the inlet structure **24** includes a first inlet section **24***c* and a nozzle section **24***d* located between the rotors **30**, **32** and the first inlet section **24***c*. In the example shown, the inlet section **24***c* has a generally constant diameter or dimension w**1**. In some examples, the inlet section **24***c* can be tapered. In the example shown, a transition section **24***e* is located between the first inlet section **24***c* and the nozzle section **24***d* and includes a radiused or tapering section transitioning to a diameter or dimension w**2**.

[0107] As shown, the nozzle section **24***d* tapers from the diameter or dimension w**2** proximate the first inlet section **24***c* to a diameter or dimension w**3** proximate the rotors **30**, **32**. In some examples, the taper between w**2** and w**3** results in at least a ten percent decrease in cross-sectional area of the nozzle section **24***d*. In the example shown, the nozzle section **24***d* includes a frustoconical taper such that the sidewalls of the nozzle section **24***d* are straight and define a

continuous, gradual taper, as is shown in the drawings. However, the nozzle section **24***d* may be provided with a taper that is curved in cross-section. In the example shown, and as most easily seen at FIGS. **27** to **29**, the first inlet section **24***c* and the nozzle section **24***d* each have a circular cross-sectional shape. However, other cross-sectional shapes are possible, such as oval, elliptical, rectangular, and obround shapes. The nozzle section **24***d* can also taper in a non-symmetrical manner, for example, wherein only one side of the nozzle section **24***d* forms the tapering cross-section such as is schematically shown at FIG. **24** wherein the nozzle section **24***d* is also arranged to direct fluid flow **12-1** into the ends of the rotors **30**, **32**.
[0108] In one aspect, the inlet velocity VN of the fluid **12-1** leaving the nozzle section **24***d* and entering the rotors **30**, **32** should at least equal to the rotor mesh axial lead velocity of the rotors **30**, **32** for best energy conversion. As schematically shown at FIG. **4**, the axial lead velocity VL is a well-known parameter in Roots-type devices and may also be referred to as the linear velocity of the lobe mesh. This parameter represents the speed with which the V-shape defined between the overlapping lobes of the intermeshed rotors **30**, **32** travels in a longitudinal direction (i.e., parallel with the longitudinal axis X). The axial lead velocity is further described and shown in U.S. Pat. No. 7,788,164, which is incorporated herein by reference. In some applications, increasing the twist angle of the rotors **30**, **32** results in further performance gains. In one example, as outlined in Table 1 below, an expander, having a displacement of 644 cc (cubic centimeters) and a rotor lead of 200 m, is provided such that dimension w**1** is 89 mm, dimension w**2** is 76 mm, and dimension w**3** is 60 mm. As such, the nozzle section **24***d* decreases in cross-sectional area by over 20 percent with a corresponding increase in fluid velocity.
TABLE-US-00001 TABLE 1 Expander dispacements 644 cc Rotor lead 200 mm RPM 2000 4000 6000 8000 10000 12000 14000 RPM 6.67 13.33 20.00 26.67 33.33 40.00 46.67 m/s Rotor axial lead velocity Volume flow rate 0.0215 0.0429 0.0644 0.0859 0.1073 0.1288 0.1503 m{circumflex over ( )}3/s Diameter 89 0.0062 3.45 6.90 10.35 13.80 17.25 20.70 24.15 m/s of flow 76 0.0045 4.73 9.46 14.20 18.93 23.66 28.39 33.12 section 60 0.0028 7.59 15.18 22.78 30.37 37.96 45.55 53.15 Velocity in port
[0109] As can be seen in Table 1, the nozzle section **24***d* increases the rotor axial lead velocity by over double throughout all operating rotational speeds of the rotors, thereby increasing the overall efficiency of the expander. As a result, the velocity in port value (VN) ranges from 7.59 m/s to 53.15 m/s and always exceeds the rotor axial lead velocity (VL) which ranges from 6.67 m/s to 46.67 m/s over the entire operating range of 2,000 to 14,000 rpm of the rotors. In the particular example shown, the nozzle velocity VN is about 1.1 times the rotor axial lead velocity VL. However, in some applications, such as lower pressure applications, the nozzle velocity VN can further exceed the rotor axial lead velocity VL. For example, the nozzle velocity VN can be about 1.6 times the rotor axial lead velocity VL, or more.
[0110] Other implementations will be apparent to those skilled in the art from consideration of the specification and practice of the examples and teachings presented herein. It is intended that the specification and examples be considered as exemplary only, with the true scope of the invention being indicated by the following claims.

Claims

1. A Roots-type device comprising: a) a housing assembly having a first opening and a second opening in fluid communication with an internal cavity; b) a pair of identical rotors oppositely arranged within the internal cavity, each of the pair of rotors having a longitudinal axis and a plurality of lobes, each of the lobes defining an end face extending between a first longitudinal side of the lobe and a second longitudinal side of the lobe; and c) a recess port defined within the housing assembly and being axially spaced from the end faces of the lobes, the recess port placing the first longitudinal side of one of the lobes in fluid communication with the second longitudinal

side of the lobe such that the first opening is placed in fluid communication with the second opening.
2. The Roots-type device of claim 1, wherein the housing assembly includes a main housing and a bearing plate secured to the main housing, and wherein the recess port is defined within the bearing plate.
3. The Roots-type device of claim 1, wherein the end face of at least one lobe faces the recess port in all rotational angles of the rotors.
4. The Roots-type device of claim 1, wherein each of the pair of rotors has a twist angle that is less than or equal to an ideal twist angle of the rotors defined without the presence of the recess port.
5. The Roots-type device of claim 1, wherein each of the pair of rotors has at least three lobes.
6. The Roots-type device of claim 1, wherein the rotors are located axially between the first opening and the recess port.
7. The Roots-type device of claim 1, wherein the pair of rotors are each supported by rotatable shafts located between the second opening and the recess port.
8. The Roots-type device of claim 1, wherein the pair of rotors are each supported by shafts having longitudinal axes aligned along a first longitudinal plane, wherein a housing outlet is located on a first side of the first longitudinal plane, and wherein the recess port is located on a second side of the first longitudinal plane.
9. The Roots-type device of claim 8, wherein the first opening is orthogonal to longitudinal axes of the rotors.
10. The Roots-type device of claim 9, wherein the second opening is parallel to the longitudinal axes of the rotors.
11-39. (canceled)
40. The Roots-type device of claim 1, further comprising: a) an inlet nozzle structure in fluid communication with the first opening, the inlet nozzle structure tapering towards the first opening and being configured such that a nozzle velocity of a working fluid passing through the inlet nozzle structure is at least equal to a rotor mesh axial lead velocity,
41. A bearing plate for a Roots-type device, the bearing plate comprising: a) a main body extending along a longitudinal axis from a first side to a second side; b) a pair of cavities for supporting bearing and seal assemblies, the cavities extending between the first and second sides of the main body; c) a primary surface at least partially defining the first side and being orthogonal to the longitudinal axis; and d) a first recessed area at least partially defining the first side and being axially recessed from the primary surface in a direction towards the second side, the recessed area being configured to provide a leak path for the Roots-type device.
42. The bearing plate of claim 41, wherein the first recessed area is located entirely on a first side of a plane extending centrally through the pair of cavities and parallel to the longitudinal axis.
43. The bearing plate of claim 41, wherein the first recessed area extends to an outer edge of the main body.
44. The bearing plate of claim 42, wherein the main body includes a second recessed area at least partially defining the first side and being axially recessed from the primary surface in a direction towards the second side, the second recessed area being located entirely on a second side of the plane.
45. The bearing plate of claim 41, wherein the first recessed area has a V-shape.
46. A Roots-type device comprising: a) a housing assembly having a first opening and a second opening in fluid communication with an internal cavity; b) a pair of identical rotors oppositely arranged within the internal cavity, each of the pair of rotors having a longitudinal axis and a plurality of lobes, wherein the rotors are intermeshed and, when rotating, define a rotor mesh axial lead velocity; and c) an inlet nozzle structure in fluid communication with the first opening, the inlet nozzle structure tapering towards the first opening and being configured such that a nozzle velocity of a working fluid passing through the inlet nozzle structure is at least equal to the rotor

mesh axial lead velocity.

47. The Roots-type device of claim 46, wherein the inlet nozzle structure is oriented generally parallel to the longitudinal axis.

48. The Roots-type device of claim 46, wherein the inlet nozzle structure is oriented at an oblique angle to the longitudinal axis.

49. The Roots-type device of claim 46, wherein a volumetric flow rate through the inlet nozzle structure is increased by at least double.