

BOUNDARY-LAYER TURBOMACHINE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63138649, filed on January 18, 2021; U.S. Provisional Application No. 63280396, filed on November 17, 2021; and U.S. Provisional Application No. 63285575, filed on December 3, 2021.

TECHNICAL FIELD

[0002] The following disclosure relates to turbomachinery and systems and methods of generating power using the same, and in particular, boundary-layer turbomachinery for extracting and injecting energy into a fluid.

BACKGROUND

[0003] Boundary-layer turbomachines may have advantages such as increased efficiency, and lower manufacturing and maintenance costs. Efficiency of such turbines may be less than what is theoretically achievable and manufacturing may require relatively high precision and/or costs.

[0004] Existing power generation systems have significant loss of energy to the environment. For example, heat may be lost when condensers are used to condense the working fluid of the power generation system. In other cases, heat may be lost in electric generators, where the associated heat buildup may also degrade performance of generators. Heat recuperators and combined heating and power (CHP) cycles have been proposed to reduce inefficiencies.

[0005] However, various drawbacks have been recognized previously. Heat recuperators do not address all types of heat loss and may not operate

efficiently in regimes common to low-grade heat applications, and CHP cycles are not useful where there is no need for heating in the local environment.

[0006] Turbomachinery, such as pumps and/or compressors, may be used to establish a power-generating flow of working fluids through power generating systems. However, such turbomachinery may be a source of parasitic loading that may reduce the efficiency of power generation systems.

[0007] Multiphase flow in turbomachinery may impart excessive structural loads on components of such turbomachines. To avoid structural failure due to such loads, large weight and cost penalties may be incurred in the design of the turbomachines. As such, working fluids are typically reduced to a single phase before compression and/or pumping. While this may reduce the design requirements on turbomachines, the need for complete phase change incur other penalties in terms of heat loss and a consequent loss in efficiency.

[0008] For example, inducers and screw compressors may be used for fluid compression and may generally comprise a stationary outer housing containing an inner rotating impeller having a curved helicoid blade defined thereon. A small tip clearance may be provided between the stationary outer housing and the inner rotating impeller. In some cases, the tip clearance may be a region liable to cavitation or condensation, which may result in structurally catastrophic consequences. The stationary outer housing may be configured to seal the turbomachinery without contacting moving components, such as the rotating impeller, to avoid seizing of turbomachinery, e.g. due to contact between stationary and moving components.

[0009] Improvement is desired.

SUMMARY

[0010] Pressing environmental concerns have led to demands to reduce energy consumption and emissions.

[0011] Emission and efficiency standards on turbomachinery, such as power generating turbine equipment pumps/compressors, are being raised at a rapid pace, e.g. to meet targets for greenhouse gas emissions. Carbon pricing has introduced strong market drivers for addressing sustainability challenges with respect to power generation and consumption.

[0012] Net overall energy consumption may be reduced by recovering energy. For example, in industrial processes, energy may be recovered from exit fluids with elevated temperature and/or pressure. Energy may be extracted from high temperature or high-pressure gas using let-down expanders, also referred to as turbo-expanders or expansion turbines. Turbo-expanders may entrain or form multiphase fluid therein. Such fluids may exert excessive stresses on structures of the turbo-expanders, e.g. blade-based turbo-expanders may have a limited operational envelope to avoid damage to blades. In some cases, cavitation may occur on blades. For example, turbo-expanders may be employed in natural gas refineries and oxygen manufacturing plants.

[0013] New approaches to generating energy that are better for the environment, e.g. Organic Rankine Cycle (ORC) power generation, may require higher turbomachine efficiencies to be feasible or may require lower cost turbomachines to offset increased costs elsewhere (e.g. in downstream carbon-capture and sequestration systems). Costs associated with designing, manufacturing, and maintaining turbomachinery, which are already high, may therefore increase even more rapidly.

[0014] For example, axial turbomachines may have more than three stages for achieving sufficiently high efficiency levels. Each such stage introduces a significant number of new (moving) parts, which drives up costs of manufacturing and maintenance. Additional, improvements in turbomachines have tended towards diminished returns, i.e. increased resources expended towards improvements have been rewarded with relatively lower increases in efficiency and cost-effectiveness.

[0015] Current efforts at improving turbomachines face the long-term challenge of consistently increasing efficiency while decreasing cost of manufacturing and maintenance.

[0016] Significant improvements in turbomachines, particular turbines and expanders, are critical for long-term sustainability.

[0017] Adhesion-based (or cohesion-based) turbomachines that exploit the boundary-layer effect may have the potential for significantly higher efficiencies relative to other types of turbomachines, and to operate with far fewer moving parts.

[0018] An early prototype of a boundary-layer turbomachine was the Tesla turbine (or pump). This is a bladeless centripetal flow turbine wherein fluid flows through the turbine radially inwardly in a spiral flow path. The Tesla turbine has extremely high sturdiness. However, it had drawbacks, e.g. in some cases such turbines had relatively limited range of power output, thereby limiting the potential for scaling up to large power levels to compete with existing axial turbomachine. For example, increasing rotation frequencies would increase turbulence levels, and often output flow would retain a significant amount of residual energy that could yet be extracted. Unsuccessful attempts over several decades involved trying to adapt the Tesla turbine and take advantage of the boundary-layer effect to achieve desired efficiencies at the required power outputs.

[0019] A drawback with the Tesla turbine is the inability to control the fluid as it spirals from a radially outward position to a radially inward position towards a turbine outlet. Thus, balancing of fluid speeds across the fluid as it spirals down may not be possible.

[0020] Aspects disclosed herein may provide for efficient turbomachines that operate at desired (high) power output levels. For example, aspects disclosed herein may provide for efficient turbines that extract relatively larger amounts of energy from the working fluid while retaining benefits such as relatively high efficiencies, mild operating conditions, high levels of sturdiness.

In some cases, aspects disclosed herein provide the ability to synchronize rotors driven by the boundary-layer effect, e.g. in turbine embodiments, the rotors may also generate positive torque.

[0021] In various embodiments of turbomachine turbines disclosed herein, a boundary-layer effect may be used to drive a plurality of concentrically nested generally tubular rotors engaged in common rotation around a longitudinal axis and defining ducts therebetween. Generally the ducts may be dimensioned or adapted to efficiently utilize the boundary-layer effect, e.g. in some cases the duct (radial) widths may be dimensioned by reference to the boundary-layer thickness therein.

[0022] In some embodiments, jets of working fluid may be azimuthally injected via nozzles around the longitudinal axis at a longitudinal end of the plurality of ducts to “drag” the rotors in rotation around the longitudinal axis. The jets so injected may cause the working fluid to spiral around the ducts in a helical path towards an opposing longitudinal end of the ducts containing a plurality of blades integrally formed with the rotors. The fluid jets may be directed against portions of adjacent ducts to create a fluid bearing seal between adjacent ducts.

[0023] In some embodiments, fluid may enter the ducts in such a way to encourage desired behaviour from the tubular rotors, e.g. nozzles may vary orientation, speed, pressure of inlets jets to achieve positive torque generation from the tubular rotors to prevent any of tubular rotors consuming power to pump fluid instead of generating power via flowing fluid. The width of the ducts and the length thereof may be varied to achieve positive torque generation.

[0024] Each duct may have a plurality of blades, e.g. which partially obstruct flow in the duct to extract residual energy from the fluid while maintaining the benefits of boundary-layer turbomachines. The plurality of blades may be oriented to receive the partially azimuthally aligned working fluid to extract further energy therefrom and realign the flow more towards the

longitudinal axis. More energy may be extracted from the working fluid using an axial flow turbine stage disposed downstream of the plurality of blades.

[0025] A relatively larger size of the jets and the plurality of blades, compared to the duct (radial) width, may be desirable due to manufacturability, costs, mass-flow rate, and/or fluid behaviour. In some aspects, ducts may be smoothly tapered at upstream and downstream ends to define respective converging and diverging flow zones (restriction and expansion, respectively) which efficiently merge jets and the bladed portions with adhesion portions of the duct. Such zones may provide fluid dynamical advantages.

[0026] Configurations disclosed herein may lead to high efficiencies, allowing milder operating conditions, and reduce the number of moving parts. Overall, lower costs and reduced energy consumption may be achieved.

[0027] Aspects disclosed herein may prevent catastrophic damage to blades in expansion turbines by employing an elongated adhesive section which extracts energy from the working fluid before contact with any blades.

[0028] Aspects disclosed herein may address limitations of turbomachines and provide for efficiencies surpassing those of other turbomachines, particularly in a configuration typical of gas turbines, jet engines and Tesla type boundary layer machinery. Embodiments disclosed herein may be particularly suitable for Organic Rankine Cycle (ORC) turbine generators, and particularly wherein the inlet fluid is hot pressurized, supercritical fluid configured to undergo at least partial phase change across the turbomachine.

[0029] In some aspects, turbomachines disclosed herein may surpass prior turbomachines by being able to maintain precise geometry under stress conditions generated by very high rotational speeds, accommodate thermal growth of the materials under high temperature, overcome material warpage which is a known flaw in disc-type boundary turbines. Such turbomachine may operate based on combining expansion properties, as in a conventional turbine

(radial inflow or axial), and surfaces with adhesive properties, as in a Tesla disc turbine.

[0030] Other advantages may include eliminating the need for forgings, castings, and multi axis machining operations inherent in conventional turbine designs, providing a low manufacturing cost and still maintain high durability, dependability with increased efficiency, utilizing new materials and manufacturing methods— high temperature plastics and composites, carbon fibers, 3D printed parts, and increase overall efficiency due to the ability to adjust the length of the tubes thereby increasing the residence time of the working fluid and corresponding energy extraction/recovery.

[0031] As well, aspects disclosed herein may eliminate exit losses of the compressor and the inlet losses of the turbine, as well as reduce inlet losses of the compressor, allowing for very high rotational speeds by utilizing ‘fluid bearings’ and external shaft bearings as well as longitudinal carrier bearings supporting the outside of the tube assembly at different positions along the length. For example, tubes may be cantilevered and overall retained in pressurized surroundings wherein fluid bearing effects may be achieved via pressurized slots configured to receive ends of the tubes.

[0032] In some embodiments, a tube within a tube type construction of the turbine may provide fluid bearings at the ‘hot’ end, and longitudinal bearings along the length. External ‘cool’ end bearings may allow for a relatively strong and durable rotating assembly able to endure very high temperatures and rotational speeds. Such an assembly may be able to accommodate dirty or contaminated motive fluids ranging from gas phase fluids to full liquids with any combination in-between.

[0033] Higher efficiencies may allow for a higher feasible output at milder operating conditions. In some aspects, lower rotational frequency (RPM) of the components may be possible. Ceramic ball bearings may be used to support the rotating components, which may otherwise be inappropriate for high power output operations.

[0034] In one aspect, the disclosure describes a boundary-layer turbomachine configured to receive fluid via an inlet end and discharge the fluid via an outlet end, comprising: a plurality of ducts concentrically arranged around a longitudinal axis of the boundary-layer turbomachine between the inlet end and the outlet end to convey the fluid from the inlet end towards the outlet end, the plurality of ducts at least partially defined by corresponding duct walls configured to rotate about the longitudinal axis; and one or more flow inlets disposed at the inlet end and configured to receive the fluid into the plurality of ducts at least partially azimuthally around the longitudinal axis towards the outlet end in accordance with rotation of the duct walls of the plurality of ducts, the fluid being frictionally engaged with the duct walls to transfer mechanical energy to, or from, the fluid flowing in the plurality of ducts.

[0035] There is an increasing emphasis on increasing the energy efficiency of power generation, for reducing costs and emissions. For example, two approaches include increasing the efficiency of power generating systems and reducing heat loss from industrial processes, e.g. by converting low grade heat into usable power. ORC systems have been proposed as one way of captured low-grade heat. However, in many cases, such systems are inefficient and expensive. For example, energy may be lost in ORC systems since the working fluid may need to be condensed during the cycle.

[0036] It is found that using a plurality of boundary-layer turbines arranged in series, with possible turbine stages in-between, may obviate the need for a separate condenser. For example, one or more of these boundary-layer turbines may be able to extract low-grade heat to liquefy the working fluid, e.g. propane.

[0037] Furthermore, it is found that using such a configuration may allow the working fluid to achieve sufficiently low temperatures to act as a coolant for downstream components such as electric generators to further reduce heat loss to the environment (by preheating). Finally, the low temperatures achieved by the working fluid may allow transfer of heat from very low grade heat

sources. For example, in some embodiments, heat from sea water may be harvested for energy.

[0038] In some aspects, there is disclosed a method of generating power using a working fluid configured to at least partially change phase for generating power, comprising: imparting heat to condensate to cause at least partial vaporization of the condensate to generate the working fluid; receiving the working fluid flowing at least partially azimuthally into a duct extending longitudinally between radially-separated duct walls; and driving rotatably a duct wall of the radially-separated duct walls via frictionally engaging the duct wall with the working fluid in the duct to exchange energy with the working fluid to cause condensation of the working fluid to generate the condensate.

[0039] In some further aspects, there is disclosed a system for generating power, comprising: a heater for transferring heat to condensate to generate fluid that is at least partially vaporized; a first boundary-layer turbine including a first plurality of ducts configured to receive the fluid from the heater and at least partially defined by corresponding first duct walls that are configured for drivable rotation about a longitudinal axis of the first boundary-layer turbine by the fluid frictionally dragging the first duct walls at least partially azimuthally around the longitudinal axis of the first boundary-layer turbine, the first duct walls configured to transfer energy from the fluid flowing in the first plurality of ducts; an axial turbine coupled to the first boundary-layer turbine to receive the fluid from the first boundary-layer turbine to extract energy from the fluid; and a second boundary-layer turbine coupled to the axial turbine to receive the fluid from the axial turbine into a second plurality of ducts at least partially defining the second boundary-layer turbine, the second plurality of ducts at least partially defined by corresponding second duct walls that are configured for drivable rotation about a longitudinal axis of the second boundary-layer turbine by the fluid frictionally dragging the second duct walls at least partially azimuthally around the longitudinal axis of the second boundary-layer turbine, the second duct walls configured to transfer energy

from the fluid flowing in the second plurality of ducts to condense the fluid to generate the condensate for the heater.

[0040] In yet further aspects, there is disclosed a system for generating power, comprising: a heater for transferring heat to condensate to generate fluid that is at least partially vaporized; a first boundary-layer turbine including a first plurality of ducts configured to receive the fluid from the heater and at least partially defined by corresponding first duct walls that are configured for drivable rotation about a longitudinal axis of the first boundary-layer turbine by the fluid frictionally dragging the first duct walls at least partially azimuthally around the longitudinal axis of the first boundary-layer turbine, the first duct walls configured to transfer energy from the fluid flowing in the first plurality of ducts; and a second boundary-layer turbine spaced apart from and coupled to the first boundary-layer turbine to receive the fluid from the first boundary-layer turbine into a second plurality of ducts at least partially defining the second boundary-layer turbine, the second plurality of ducts at least partially defined by corresponding second duct walls that are configured for drivable rotation about a longitudinal axis of the second boundary-layer turbine by the fluid frictionally dragging the second duct walls at least partially azimuthally around the longitudinal axis of the second boundary-layer turbine, the second duct walls configured to transfer energy from the fluid flowing in the second plurality of ducts to condense the fluid to generate the condensate for the heater.

[0041] Vapor compression and liquid pumping in power generation may be a significant source of parasitic loading in a power generation system. Such parasitic loading can reduce the efficiency of power generation and impact the viability of power generation systems that are important for reducing greenhouse gas emissions. For example, power generation systems configured to extract energy from low-grade heat sources may need high efficiencies to achieve sufficient net power generation. In some cases, low-grade heat sources may include sea water.

[0042] It is found that compression and/or pumping may be achieved efficiently by using a boundary-layer turbomachine configured for multiphase compression and/or pumping. In some cases, such a boundary-layer turbomachine may also be configured for energy extraction. For example, energy extraction and compression (and/or pump) may occur in sequence in the same duct of the boundary-layer turbomachine.

[0043] In some cases, the boundary-layer turbomachine comprises a plurality of coupled bodies elongated along, circumferentially surrounding, and concentrically arranged around, a longitudinal axis for common rotation about the longitudinal axis. The cylindrical bodies may define a plurality of (elongated) annuli therebetween, wherein each of the annuli has a corresponding protrusion disposed therein. The protrusion may spirally extend around and along the longitudinal axis to draw working fluid into the respective annulus.

[0044] In some aspects, the disclosure describes a method of generating power using a working fluid configured to change phase for generating power, comprising: imparting heat to condensate to cause at least partial vaporization of the condensate to generate the working fluid; receiving the working fluid on blades of a turbine rotor to drivably rotate the turbine rotor to generate shaft power; receiving the working fluid flowing at least partially azimuthally from the turbine rotor into a duct defined between a first duct wall and a second duct wall, the first duct wall and second duct wall circumferentially extending around a longitudinal axis and elongated along the longitudinal axis, the first duct wall being radially-separated from the second duct wall; and driving rotatably the first duct wall and the second duct wall via frictionally engaging the first duct wall and the second duct wall with the working fluid in the duct to exchange energy with the working fluid to cause condensation of the working fluid to generate the condensate.

[0045] In another aspect, the disclosure describes a system for generating power, comprising: a heater for transferring heat to condensate to

generate fluid that is at least partially vaporized; a first boundary-layer turbine including a first plurality of ducts configured to receive the fluid from the heater and at least partially defined by a corresponding plurality of first duct walls that are configured for drivable rotation about a longitudinal axis of the first boundary-layer turbine by the fluid frictionally dragging the first plurality of duct walls at least partially azimuthally around the longitudinal axis of the first boundary-layer turbine, the first plurality of duct walls configured to transfer energy from the fluid flowing in the first plurality of ducts; an axial turbine coupled to the first boundary-layer turbine to receive the fluid from the first boundary-layer turbine to extract energy from the fluid; and a second boundary-layer turbomachine coupled to the axial turbine to receive the fluid from the axial turbine into a second plurality of ducts at least partially defining the second boundary-layer turbomachine, the second plurality of ducts at least partially defined by a corresponding plurality of second duct walls that are frictionally engaged with the fluid and configured for drivable rotation about a longitudinal axis of the second boundary-layer turbomachine, the second plurality of duct walls configured to transfer energy to, or from, the fluid flowing in the second plurality of ducts to condense the fluid to generate the condensate for the heater.

[0046] In yet another aspect, the disclosure describes a system for generating power, comprising: a heater for transferring heat to condensate to generate fluid that is at least partially vaporized; a first boundary-layer turbine including a first plurality of ducts configured to receive the fluid from the heater and at least partially defined by corresponding first duct walls that are configured for drivable rotation about a longitudinal axis of the first boundary-layer turbine by the fluid frictionally dragging the first duct walls at least partially azimuthally around the longitudinal axis of the first boundary-layer turbine, the first duct walls configured to transfer energy from the fluid flowing in the first plurality of ducts; and a second boundary-layer turbomachine spaced apart from and coupled to the first boundary-layer turbine to receive the fluid from the first boundary-layer turbine into a second plurality of ducts at least partially

defining the second boundary-layer turbomachine, the second plurality of ducts at least partially defined by corresponding second duct walls that are frictionally engaged with the fluid and configured for drivable rotation about a longitudinal axis of the second boundary-layer turbomachine, the second duct walls configured to transfer energy to, or from, the fluid flowing in the second plurality of ducts to condense the fluid to generate the condensate for the heater.

[0047] In a further aspect, the disclosure describes a turbomachine, comprising: a first body elongated along a longitudinal axis and rotatable around the longitudinal axis; a second body elongated at least partially concentrically with the first body along the longitudinal axis and coupled for common rotation with the first body, the second body arranged at least partially within the first body to define a duct extending longitudinally in-between the first body and the second body; a flow inlet configured to receive fluid at least partially azimuthally around the longitudinal axis in accordance with the common rotation of the first body and the second body, the fluid being frictionally engaged with the first body and the second body to transfer mechanical energy to, or from, the fluid; and one or more protrusions on the first body extending longitudinally at least partially along the duct and radially towards the second body in the duct to define a channel in the duct, the channel configured to receive and draw the fluid from the flow inlet into the duct.

[0048] In some instances, only a limited amount of energy may be extracted from low-grade heat sources. Low-grade heat sources include sea water. Achieving efficient energy extraction from low-grade heat sources may lead to clean, cheap, and abundant energy. For example, combustion of fossil fuels may be avoided.

[0049] It is found that a challenge in extracting energy from low-grade heat sources is that any fluid suited to receive energy from such heat sources would likely be ill-suited to provide energy (or having energy extract from them), particularly by use of expanders and other turbomachines.

[0050] This challenge may be overcome by using two-fluids: a first fluid for receiving energy from low-grade heat sources and a second fluid for providing energy (i.e. for energy extraction). The first fluid and second fluid may be fluidly isolated from one another but may be otherwise be put in energy communication via one or more heat exchangers allowing heat communication between the first fluid and second fluid.

[0051] It is found that ammonia is particularly advantageous for receiving energy (or being heated by) low-grade heat sources. Ammonia has a relatively low boiling point and may therefore be operated as part of a cryogenic cycle, which may be appropriate for extracting energy from low-grade heat sources, such as ambient or room temperature fluids. Furthermore, ammonia is suited for gaining a relatively large amount of enthalpy for relatively small changes in temperature and/or pressure. The resulting large enthalpy capacity per unit mass allows for smaller masses (and, hence, volumes) of ammonia to be used to receive energy. Pumping requirements, and associated costs, may thereby decrease. In some cases, significant efficiency gains may be realized with respect to recuperating or recovering heat from low-grade heat sources by using ammonia compared to other fluids, such as carbon dioxide or ethane.

[0052] However, extracting energy from ammonia after it has absorbed energy from low-grade heat sources may be difficult. Ammonia is ill-suited or infeasible as a working fluid in an expander due to the properties of ammonia described above that gave it advantages as a recuperating fluid. Excessively large equipment may be required to efficiently and effectively extract energy from ammonia.

[0053] A separate fluid more suited to energy extraction therefrom may be used to absorb the energy in ammonia at an intermediate stage before being used as a working fluid in an expander.

[0054] Carbon dioxide as a working fluid may allow efficient and effective extraction of energy therefrom via turbomachinery. For example,

carbon dioxide has a 1:1 greenhouse effect unlike fluids such as methane, it is not combustible or flammable, and provides effective operation at low temperatures and pressures due its low temperature phase change. Cryogenic or near-cryogenic cycles may use carbon dioxide, at least partially, as a working fluid.

[0055] Thus, it is found that using two separate and isolated fluids may allow effective absorption of low-grade heat and efficient operation of expanders such as boundary-layer turbines. The pair of ammonia and carbon dioxide was found to be particularly advantageous. Ammonia may be used to absorb heat from a low-grade heat source and then may be passed through a heat exchanger to transfer heat to carbon dioxide, which then may be supplied to an expander.

[0056] In one aspect, there is disclosed a system for generating power using a first fluid and a second fluid fluidly isolated from each other, the system comprising: a heater configured to transfer heat to the first fluid to at least partially vaporize the first fluid; a first heat exchanger fluidly connected to the heater to receive the first fluid from the heater, the first heat exchanger configured to transfer heat from the first fluid to the second fluid to at least partially vaporize the second fluid; an expander fluidly connected to the first heat exchanger to receive the second fluid from the first heat exchanger and configured to rotatably drive a rotor of the expander using the second fluid; and a second heat exchanger fluidly connected to the expander to receive the second fluid from the expander and fluidly connected to the first heat exchanger to receive the first fluid from the first heat exchanger, the second heat exchanger configured to generate condensate of the second fluid by transferring heat from the second fluid to the first fluid.

[0057] In yet other further aspects, there is disclosed a method for generating power using a first fluid and a second fluid fluidly isolated from each other, the method comprising: (a) heating the first fluid to at least partially vaporize the first fluid; (b) transferring heat, in a first heat exchanger, from the

first fluid to the second fluid to at least partially vaporize the second fluid; (c) rotatably driving a rotor using the second fluid to generate power; and (d) transferring heat, in a second heat exchanger, from the second fluid to the first fluid to generate condensate of the second fluid.

[0058] Advantages of boundary-layer turbomachines may include the ability to operate with multiphase fluids. For example, working fluids may operate close to their boiling points and hence may change phase within a boundary-layer turbomachine. In some cases, it may be desired to extract a liquid phase of the working fluid from the boundary-layer turbomachine, including extracting the liquid phase as it forms within ducts of the boundary-layer turbomachine. Such extraction may reduce structural loading and fatigue on the boundary-layer turbomachine, as well improve efficiencies, e.g. work may be extracted with a lower fraction of liquid phase, and energy expended towards liquefying a multiphase working fluid may be reduced.

[0059] It is found that the liquid phase may be extracted from a boundary-layer turbomachine by exploiting a centrifugal effect associated with (common) rotation of the ducts of the boundary-layer turbomachine. Centrifugal separation may be achieved by supplying slots in duct walls for bleeding the liquid phase (or other heavier phase).

[0060] In some cases, separation of the liquid from gas phase components of the working fluid may be achieved by allowing the liquid to exit at a point or multiple points down the length of the boundary-layer turbomachine, similar to a centrifugal separator/liquid knock-out.

[0061] As the liquid phase and the gas phase travel together in the boundary-layer turbomachine, separating liquid and gas phases may allow vanes, protrusions, ribs, blades, wings and other features to be configured or adapted based on the phases present in the working fluid, and their characteristics. For example, a part of a rib or protrusion and duct walls may be textured to extract more work from the liquid phase, while another part of

the duct may remain smooth to enhance adhesion to remove more work from the gas phase of the working fluid.

[0062] In one aspect, there is disclosed a turbomachine, comprising: a first body elongated along a longitudinal axis and rotatable around the longitudinal axis; a second body elongated at least partially concentrically with the first body along the longitudinal axis and coupled for common rotation with the first body, the second body arranged at least partially within the first body to define a duct extending longitudinally in-between the first body and the second body; a flow inlet configured to receive fluid at least partially azimuthally around the longitudinal axis in accordance with the common rotation of the first body and the second body, the fluid being frictionally engaged with the first body and the second body to transfer mechanical energy to, or from, the fluid; a slot opening into the duct and radially spaced apart from the first body to receive a first portion of the fluid to draw the first portion of the fluid out of the duct while allowing a second portion of the fluid to remain in the duct, the first portion of the fluid being separated from the second portion of the fluid by being drawn centrifugally towards the slot relative to the second portion of the fluid; and an outlet port configured to receive the second portion of the fluid from the duct to discharge the second portion of the fluid out of the turbomachine.

[0063] In yet further aspects, there is disclosed a method of operating a turbomachine, comprising: receiving fluid at least partially azimuthally around a longitudinal axis in a duct defined between a first duct wall and a second duct wall via an inlet end of the turbomachine; frictionally engaging the fluid with the first duct wall and the second duct wall; rotating, in common, the first duct wall and the second duct wall, in accordance with the fluid; and discharging the fluid via an outlet end of the turbomachine.

[0064] Various embodiments can include combinations of the above described features.

[0065] Further details of these and other aspects of the subject matter of this application will be apparent from the detailed description included below and the drawings.

DESCRIPTION OF THE DRAWINGS

[0066] Reference is now made to the accompanying drawings, in which:

[0067] **FIG. 1A** is a rear elevation view of an exemplary boundary-layer turbomachine;

[0068] **FIG. 1B** is a front elevation view of the boundary-layer turbomachine;

[0069] **FIG. 1C** is a perspective view of the boundary-layer turbomachine;

[0070] **FIG. 2** is a cross-sectional view of the boundary-layer turbomachine along the reference line **2-2** in **FIG. 1B**;

[0071] **FIG. 3A** is an exploded perspective view of a plurality of rotors of the boundary-layer turbomachine defined at least partially by a plurality of tubes;

[0072] **FIG. 3B** is a front elevation view of the plurality of rotors;

[0073] **FIG. 4** is a schematic exploded perspective view of an axial turbine stage and the plurality of tubes coupled to a header block of the boundary-layer turbomachine;

[0074] **FIG. 5A** is a top elevation view of the plurality of tubes coupled to the header block, showing schematic flow directions;

[0075] **FIG. 5B** is an enlarged view of areas **5B-1** and **5B-2** in **FIG. 5A**;

[0076] **FIG. 5C** is an enlarged view of area **5C** in **FIG. 5A**;

[0077] **FIG. 6A** is an enlarged view of area **6A** in **FIG. 2**, showing schematic flow directions;

[0078] **FIG. 6B** is an enlarged view of area **6B** in **FIG. 2**, showing schematic flow directions;

[0079] **FIG. 6C** is an enlarged view of area **6C** in **FIG. 2**, showing schematic flow directions;

[0080] **FIG. 7** is a perspective view of velocity contours and streamlines in exemplary ducts of the plurality of ducts of an exemplary boundary-layer turbomachine;

[0081] **FIG. 8** is a perspective view of pressure contours in the exemplary ducts;

[0082] **FIG. 9** is a perspective view of temperature contours in the exemplary ducts;

[0083] **FIG. 10A** is an enlarged perspective view of velocity contours and streamlines in one of the exemplary ducts;

[0084] **FIG. 10B** is an enlarged perspective view of pressure contours in the exemplary duct;

[0085] **FIG. 10C** is an enlarged perspective view of temperature contours in the exemplary duct;

[0086] **FIG. 11** is a perspective view of velocity streamlines outside an exemplary nozzle of the boundary-layer turbomachine;

[0087] **FIG. 12** is a schematic block diagram of a system for generating power, in accordance with an embodiment;

[0088] **FIG. 13** is a schematic block diagram of a system for generating power, in accordance with another embodiment;

[0089] **FIG. 14** is a schematic block diagram of a system for generating power, in accordance with yet another embodiment;

[0090] **FIG. 15A** is a perspective view of the system of **FIG. 14**, in accordance with an embodiment;

[0091] **FIG. 15B** is a partial enlarged cross-sectional view of the system of **FIG. 15A**;

[0092] **FIG. 16A** is a perspective view of the system of **FIG. 14**, in accordance with an embodiment;

[0093] **FIG. 16B** is a cross-sectional view of the system of **FIG. 16A**;

[0094] **FIG. 16C** is a partial enlarged cross-sectional view of the system of **FIG. 16A**;

[0095] **FIG. 16D** is an internal perspective view of the boundary-layer turbine, with an outer housing removed to show a duct wall of a tube, a header section including a header block and a header plate, in accordance with an embodiment;

[0096] **FIG. 16E** is an internal side elevation view of the boundary-layer turbine of **FIG. 16D**, in accordance with an embodiment;

[0097] **FIG. 16F** is an enlarged view of the internal side elevation view of the boundary-layer turbine as shown in **FIG. 16E**, showing a clearance between the header block and a tube, in accordance with an embodiment;

[0098] **FIG. 16G** is an enlarged perspective view of the header block and an adjacent tube of the boundary-layer turbine of **FIG. 16D**, in accordance with an embodiment;

[0099] **FIG. 16H** is an internal perspective view of the header block and the adjacent tube of the boundary-layer turbine of **FIG. 16D**, wherein an outer housing of the header block is omitted to shown internal channels formed in the header block, in accordance with an embodiment;

[00100] **FIG. 16I** is an internal side elevation view of the header block and the adjacent tube of the boundary-layer turbine of **FIG. 16H**, in accordance with an embodiment;

[00101] **FIG. 17A** is a schematic cross-section of a duct parallel to a longitudinal axis, in accordance with an embodiment;

[00102] **FIG. 17B** is a schematic radial cross-section of the duct of **FIG. 17A** at a first longitudinal position, in accordance with an embodiment;

[00103] **FIG. 17C** is a schematic radial cross-section of the duct of **FIG. 17A** at a second longitudinal position, in accordance with an embodiment; and

[00104] **FIG. 18** is a flowchart of an exemplary method of generating power using a working fluid configured to change phase for generating power;

[00105] **FIG. 19** is a schematic block diagram of a system for generating power, in accordance with an embodiment;

[00106] **FIG. 20A** is a perspective view of the system, in accordance with an embodiment;

[00107] **FIG. 20B** is a cross-sectional view of the system of **FIG. 20A**, in accordance with an embodiment;

[00108] **FIG. 21A** is an enlarged view of region **21A** in **FIG. 20B**;

[00109] **FIG. 21B** is an enlarged view of region **21B** in **FIG. 20B**;

[00110] **FIG. 22A** is a perspective view of a boundary-layer pump-turbine, in accordance with an embodiment;

[00111] **FIG. 22B** is a cross-sectional view of the boundary-layer pump-turbine normal to a longitudinal axis thereof, in accordance with an embodiment;

[00112] **FIG. 22C** is an enlarged view of region **22C** in **FIG. 22B**;

[00113] **FIG. 23** is a side elevation view of the boundary-layer pump-turbine of **FIGS. 22A-22C** with a housing **2212** thereof not shown;

[00114] **FIG. 24** is an exploded view of bodies of a boundary-layer pump-turbine, in accordance with an embodiment;

[00115] **FIG. 25A** is a perspective view of a body of the boundary-layer pump turbine of **FIG. 24**;

[00116] **FIG. 25B** is a side elevation view of the body in **FIG. 25A**;

[00117] **FIG. 26** is a side elevation view of a body, in accordance with another embodiment;

[00118] **FIG. 27** is a side elevation view of a body, in accordance with yet another embodiment;

[00119] **FIG. 28** is a side elevation view of a body, in accordance with yet another embodiment;

[00120] **FIG. 29** is a flowchart of an exemplary method of generating power using a working fluid configured to change phase, at least partially, for generating power;

[00121] **FIG. 30** is a schematic block diagram of a system for generating power using a first fluid and a second fluid fluidly isolated from each other;

[00122] **FIG. 31** is a perspective view of a system using boundary-layer turbomachines, in accordance with an embodiment;

[00123] **FIG. 32A** is a cross-sectional view of the system of **FIG. 31**, in accordance with an embodiment;

[00124] **FIG. 32B** is an enlarged view of region **32B** in **FIG. 32A**, in accordance with an embodiment;

[00125] **FIG. 33** is a cross-sectional view of a boundary-layer turbomachine having slots, in accordance with an embodiment;

[00126] **FIG. 34** is a flowchart of an exemplary method for generating power using a first fluid and a second fluid fluidly isolated from each other; and

[00127] **FIG. 35** is a flowchart of an exemplary method a method of operating a turbomachine.

DETAILED DESCRIPTION

[00128] The following disclosure relates to turbomachines, and in particular boundary-layer turbomachines. In some embodiments, the assemblies and methods disclosed herein can facilitate more efficient generation of shaft power compared to existing turbines.

[00129] Boundary-layer turbomachines operate based on a boundary-layer effect, wherein a layer of fluid closest to a moving surface is constrained to move with the surface (due to the no-slip condition). Establishing fluid flow relative to a surface imparts force on the surface. Boundary-layer turbomachines may be more efficient than other types of turbomachines. In various embodiments, boundary-layer turbomachines may be over 20% or over 40% more efficient. Additionally, boundary-layer turbomachines may comprise fewer parts or fewer “moving parts”, and therefore may be easier and cheaper to construct, repair, and maintain.

[00130] In some cases, exemplary boundary-layer turbines may be especially useful for achieving desired efficiencies from systems based on a Rankine cycle, e.g. an Organic Rankine Cycle (ORC), or thermodynamic cycles wherein (high density) supercritical fluids are used. In various embodiments, the working fluid of the turbine may be a hydrofluorocarbon (HFC), perfluorocarbon (PFC), or a hydrocarbon such as isobutane, pentane, propane, or supercritical (superheated) CO₂.

[00131] In an exemplary boundary-layer turbomachine, a drum or tube may be made to rotate about its long axis by having fluid flow past its outer surface azimuthally around the long axis. A boundary-layer forms over the drum's surface, acting as a momentum sink and causing transfer of energy from the fluid to the drum in the form of rotational energy, e.g. as may be desired from a turbine operating by extracting energy from working fluid. Such fluid flow over the drum may generally have a radial extent, wherein the radially-inner end of the flow transmits energy to the drum. It is desirable to extract energy from other (more radially distanced) portions of the fluid flow.

[00132] Additional energy may be extracted from the fluid flow by ensconcing the original drum within and in axial alignment with a larger drum having an inner surface in contact with the fluid flow. In this case, momentum may also be extracted at a radially-outer end of the fluid flow. In such a manner, a plurality of drums may be ensconced within and in alignment with each other

to define a plurality of fluid channels (ducts or at least partially closed conduits) for (azimuthally) injecting fluid therein to drive the drums. The drums may be constrained in common rotation, e.g. by being cross-coupled using an end plate **232** or rotating head. In various embodiments, exit fluid flow from the channels may yet comprise an azimuthally component or a significant azimuthal component. In various embodiments, an opposite end of the drums from the end plate **232** may be supported by fluid bearings built into the boundary-layer turbomachine to allow rotation and prevent contact between the drums and other components, e.g. the fluid bearings may be open ended cavities retaining pressurized working fluid and thus may not require additional components.

[00133] In various embodiments, it is found that increasing the number, length, and/or average radii of the channels may increase energy extraction from the fluid flow. In some embodiments, it is found that arbitrarily increasing the number, length, and/or average radii of the channels may not commensurately increase energy extraction from the fluid flow. In some embodiments, energy extraction may be decreased beyond a certain point. For example, it is found that energy extracted via some channels may be used to drive other channels as pumps.

[00134] Energy extracted from the fluid flow may be increased by placing additional turbine stages that are compatible with the boundary-layer turbomachine. For example, in some embodiments, a plurality of blades oriented to receive azimuthally oriented fluid flow are placed downstream of adhesion surfaces of the boundary-layer turbine. The plurality of blades may be integrally formed with the adhesion surfaces (e.g. in unitary construction therewith) for common rotation, thereby reducing the number of moving parts and retaining advantages of the boundary-layer turbine. In some embodiments, the plurality of blades are manufactured by additively “growing” structures on to downstream end portions of the adhesion surfaces, and disposed inside the channels, at downstream ends thereof. In some embodiments, additional turbine stages may be placed further downstream.

For example, an axial impulse or reaction turbine stage may be placed downstream of the plurality of blades. The axial turbine stage may be compatible with the fluid flow coming off the plurality of blades. The blades of the axial turbine may be oriented to receive axially oriented flow from the plurality of blades.

[00135] In some embodiments, the additional efficiency may facilitate achieving desired power output from the boundary-layer turbine at less mechanically taxing (or more mild) conditions, such as at lower rotational frequencies, temperatures, and/or pressures. Thus, exemplary boundary-layer turbines may be easier and cheaper to construct, repair, and maintain. In some cases, lower rotational frequencies may be compatible with use of contact bearings, e.g. ceramic ball bearings, for supporting shafts (power shafts) of the boundary-layer turbine. In some embodiments, the boundary-layer turbine may be operable without (isolated or closed) pressurized hydraulic bearings, e.g. those configured for high-RPM applications. In some embodiments, material warping may be reduced.

[00136] In various embodiments, exemplary boundary-layer turbomachines may operate between 20,000 RPM and 100,000 RPM, or between 2,000 RPM and 20,000 RPM. In some embodiments, the boundary-layer turbine may operate at a lower overall temperature, e.g. between 75°C and 1000°C, such as due to the lower rotational frequency. In some embodiments, pressurized (working) fluid may enter the boundary-layer turbomachine at temperatures between 50°C and 1000°C and pressures between 50 psi and 10,000 psi. In some embodiments, the (working) fluid may leave the boundary-layer turbomachine at between temperatures between 1°C and 500°C and pressures between 0 psi and 2000 psi.

[00137] In some embodiments, the boundary-layer turbomachine may be used to extract energy from relatively lower temperature fluids. In some embodiments, the boundary-layer turbomachine may receive working fluid at less than 50°C and issue working fluid at less than 50°C. For example, the

working fluid may be around room temperature when received into the boundary-layer turbomachine and may be (further) subcooled when issued therefrom.

[00138] In some embodiments, the working fluid may remain in a single phase (liquid or gas), e.g. in some embodiments of hydraulic pumps and motors. In various embodiments, the working fluid may be configured to undergo an at least partial (or total, in some cases) change of phase from the inlet to the outlet of the boundary-layer turbomachine, which may result in greater energy transfer. In some embodiments, the working fluid at the inlet may be liquid or (relatively higher density) supercritical and may be gaseous or (relatively lower density) supercritical at the outlet.

[00139] Exemplary boundary-layer turbines are discussed herein, e.g. as referenced above. It is understood that boundary-layer turbomachines may include turbines as well as pumps, compressors, and other turbomachines wherein power is transferred between (to or from) a fluid and a shaft. For example, in some embodiments, a pump may involve an opposite direction of rotation (compared to a turbine) and/or a change in the configuration of blades and axial-flow stages.

[00140] Aspects of various embodiments are now described by reference to the figures.

[00141] **FIG. 1A-1C** are various views of an exemplary boundary-layer turbomachine **100**. The boundary-layer turbomachine **100** may be coupled to a shaft **110** for transmitting power between a fluid **112** and the shaft **110**.

[00142] **FIG. 1A** is a rear elevation view of the boundary-layer turbomachine **100**. **FIG. 1B** is a front elevation view. **FIG. 1C** is a perspective view.

[00143] For example, the boundary-layer turbomachine **100** may be a boundary-layer turbine wherein the fluid **112** is a working fluid, wherefrom energy is extracted to rotatably drive the shaft **110** around a longitudinal axis

102. The boundary-layer turbine transfers power from the working fluid to the shaft **110** to generate shaft power. In some embodiments, the shaft may have a diameter approximately 1". In some embodiments, the shaft diameter may range between 0.25" to 8" to 10", depending on structural requirements and power transmitted by the shaft **110**.

[00144] The fluid may generally flow longitudinally (in a longitudinal direction **106**), along the longitudinal axis **102**, and azimuthally, in an azimuthal direction **104** oriented laterally around the longitudinal axis **102**, through the boundary-layer turbomachine **100**. It is conceived that in some embodiments, the boundary-layer turbomachine **100** may be a boundary-layer compressor or pump.

[00145] The fluid may be received into the boundary-layer turbomachine **100** via inlet ports **114** situated at an upstream end of the boundary-layer turbomachine **100** to be subsequently expelled out via outlet ports **116** situated at a downstream end of the boundary-layer turbomachine **100**.

[00146] In various embodiments of boundary-layer turbines, the fluid at the inlet ports **114** may be at a high pressure and/or temperature than fluid at the outlet ports **116**. In some embodiments, the fluid may undergo a phase transition across the boundary-layer turbomachine **100** to enhance transfer of energy between the fluid and the boundary-layer turbomachine **100**. In some embodiments, the fluid at the inlet ports **114** is pressurized and is in a higher density supercritical state or a liquid state, while the fluid at the outlet ports **116** is in a, relatively lower pressure or depressurized, low density gaseous phase. In some embodiments, the fluid at the inlet ports **114** or the outlet ports **116** may be multiphase, e.g. due to condensing conditions wherein the fluid may be gaseous with a liquid phase dispersed therein.

[00147] In various embodiments, without being held to a particular theory of operation, it is understood that boundary-layer turbomachines may transfer energy or transmit power between the shaft **110** and the working fluid via a

boundary-layer effect or an adhesion principle at least partially or in a relatively major proportion.

[00148] For example, the exemplary boundary-layer turbomachine **100** may be a hybrid boundary-layer turbine comprising bladeless boundary-layer turbine section(s) and bladed rotor turbine section(s), such as the bladed (axial-flow) rotor **228**, which may be a bladed rotor of an axial turbine stage. In some embodiments, the hybrid boundary-layer turbomachine may comprise an assembly of multiple turbine stages operably integrated as a single unit, including having a common housing for the various stages.

[00149] The longitudinal axis **102** of the boundary-layer turbomachine **100** may generally reference a sequential arrangement of rotors and stator sections of the boundary-layer turbomachine **100** and an overall flow of the fluid therethrough. For example, the longitudinal axis **102** may be a rotational axis of rotors of the boundary-layer turbomachine **100**, and/or define an axis of (continuous or discrete) symmetry of stators of the boundary-layer turbomachine **100**. In some embodiments, the shaft's rotational axis may also coincide with the longitudinal axis **102**. It is conceived that the flow of fluid may change orientation in particular sections of the boundary-layer turbomachine **100** or may be turbulent.

[00150] The azimuthal direction **104** may be generally laterally oriented around the longitudinal axis **102**. For example, a point on a rotor may azimuthally trace a path around the longitudinal axis **102** when in rotation. A radial direction **108** may be oriented bi-laterally to both the longitudinal axis **102** and the azimuthal direction **104**.

[00151] In various embodiments, the boundary-layer turbomachine **100** may extend radially between 10" to 12". In various embodiments, an outer diameter may vary between 2" or less to 48" or greater.

[00152] **FIG. 2** is a section **200** (cross-sectional view) of the boundary-layer turbomachine **100** along the reference line **2-2** in **FIG. 1B**.

[00153] In generally sequential order, the boundary-layer turbomachine **100** may comprise a (stationary) header section **206**, one or more flow inlets **212**, a plurality of ducts **214**, a plurality of blade assemblies, an axial stage **224** which may be an axial turbine stage, and one or more structures, including a supporting structure **230** and a housing portion.

[00154] The header section **206** may include a header plate **208** and a header block **210**, which may be integrated together, e.g. via fasteners, or in unitary construction. In various embodiments, the header section **206** may remain stationary during operation, e.g. during rotation of the shaft **110**.

[00155] The boundary-layer turbomachine **100** receives the fluid via an inlet end **202** of the boundary-layer turbomachine **100** and discharges the fluid from the outlet ports **116** via an outlet end **204** of the boundary-layer turbomachine **100**. The inlet ports **114** of the boundary-layer turbomachine **100** may be formed at least partially in the header plate **208** and may be configured to channel fluid toward the inlet end **202**, via the header section **206**.

[00156] The one or more flow inlets **212** are disposed at the inlet end **202**. In some embodiments, the one or more flow inlets **212** may be substantially disposed at or extend into upstream ends **216** of the plurality of ducts **214**. The one or more flow inlets **212** are configured to draw the fluid into the plurality of ducts **214** at least partially azimuthally around the longitudinal axis **102** towards the outlet end **204**. Flows having azimuthal flow orientation may (mutually exert) drag on the duct walls **220** to transfer energy between the flow and the (rotating) duct wall. For example, in a boundary-layer turbine, such an azimuthal flow orientation imparts rotation to the duct walls **220** to rotatably drive the shaft **110**. In a boundary-layer pump or compressor, rotation of the duct walls **220** (via the shaft **110**) draws fluid into a corresponding duct towards the outlet end **204**. In some embodiments, one or more flow inlets **212** may direct the fluid at a partially radial angle to cause jet impingement on duct walls and/or create a fluid bearing seal or sealing between adjacent ducts of the plurality of ducts **214** based on pressurization of ducts.

[00157] In some embodiments, the one or more flow inlets **212** include at least two flow inlets positioned antipodally to balance a force on the duct walls **220**. In some embodiments, every flow inlet of the one or more flow inlets **212** include an opposing flow inlet positioned antipodally to improve a balance of the boundary-layer turbomachine **100**.

[00158] The plurality of ducts **214** may be positioned downstream of the header block **210** and connected thereto or in immediate proximity thereof. For example, in some embodiments the plurality of ducts **214** may include between two and five radially-spaced apart ducts. In some embodiments, the plurality of ducts **214** are three ducts. For larger diameter turbomachines, the plurality of ducts **214** may include more than five ducts. For example, a boundary-layer turbomachine **100** with outer diameter approximately 48" or greater may have up to 24 ducts.

[00159] In various embodiments, the header section **206** may be a multipressure or multiflow header section. In some embodiments, the header section **206** may supply each duct with fluid separately, e.g. the thermodynamic condition of the fluid entering each duct of the plurality of ducts **214** may be different or adjustable. For example, in some embodiments, the fluid entering a radially-outer duct may have a higher or lower pressure than the fluid entering a (relatively) radially-inner duct.

[00160] The plurality of ducts **214** are concentrically arranged or nested around the longitudinal axis **102** between the inlet end **202** and the outlet end **204** to thereby convey the fluid therebetween, from the inlet end **202** towards the outlet end **204**. The plurality of ducts **214** may be closed conduits elongated from an upstream end **216** to a downstream end **218** (which may refer to one or more upstream and downstream ends, respectively), and configured to rotate around the longitudinal axis **102**. Additional components, including channels and conduits, may be disposed between the inlet end **202** and the upstream end **216**, and the outlet end **204** and the downstream end.

[00161] The plurality of ducts **214** are at least partially defined by corresponding duct walls **220**, i.e. a plurality of radially-spaced apart duct walls **220**. For example, each duct may be defined by two duct walls extending longitudinally, i.e. along the longitudinal axis **102**, and defining a duct in a radial clearance (radially extending gap) therebetween.

[00162] The duct walls **220** of the plurality of ducts **214** define a plurality of rotors configured to rotate about the longitudinal axis **102**. Thus, the plurality of ducts **214** may be said to rotate about the longitudinal axis **102**. The plurality of rotors are drivably coupled to the shaft **110** to transfer energy between the shaft **110** and the fluid flowing in the plurality of ducts **214**.

[00163] A plurality of blades **222** may be drivably coupled to the shaft **110**. The plurality of blades **222** may define blade assemblies of the plurality of blade assemblies drivably coupled to the shaft **110**, and may be coupled to the shaft **110** each individually or as blade assemblies integrated with a central hub.

[00164] In some embodiments, each blade assembly may be disposed in a corresponding duct downstream of the one or more flow inlets **212**. In some embodiments, each duct may have a blade assembly therein such that a plurality of ducts **214** define therein the plurality of blade assemblies.

[00165] The plurality of blades **222** may be rotatably disposed around the longitudinal axis **102** at a downstream end of a corresponding duct. In various embodiments, the plurality of blades **222** may extend longitudinally from the downstream end, towards or away from the upstream end **216**. In some embodiments, the plurality of blades **222** may be arranged in a single row, e.g. a single row of blades in each duct of the plurality of ducts **214**. A row of blades may be substantially arranging along a common longitudinal position. A single row of blades may include blades circumferentially adjacent or non-overlapping.

[00166] The plurality of bladed assemblies and plurality of ducts **214** with duct walls **220** may be integrally formed as part of a hybrid boundary-layer

turbine, wherein the plurality of ducts **214** form a fluid adhesion (or boundary-layer) portion and the plurality of blades **222** form a bladed turbine portion.

[00167] In some embodiments, an axial stage **224** may be disposed downstream of the plurality of blades **222**. The axial stage **224** may be drivably coupled to the shaft **110**. For example, in some embodiments of boundary-layer turbines, the axial stage **224** may include one or more axial-flow stators and axial-flow rotors, which together may form the axial stage **224**. An axial-flow stator **226** may be disposed between the plurality of blades **222** and an axial-flow rotor **228**. Such an axial-flow stator **226** may form nozzle-like passages and/or may include flow straightening vanes. In various embodiments, the axial-flow rotor **228** may longitudinally extend approximately 0.8" or more. The axial stage **224** may be configured to achieve desired efficiency targets and energy extraction from the fluid, depending on characteristics such as velocity, pressure, and shaft/vane rotational speeds. In various embodiments, axial stages may have adapted vane sizes, vane shapes, and vane angles (such as angle of attack).

[00168] In various embodiments, additional turbine stages, such as additional axial-flow stages, may be disposed downstream of the axial stage **224** to extract more energy from the fluid or achieve greater efficiencies. The length, shape, and other configuration of stages and blades formed therein may be adjusted to achieve desired power generation and preventing stalling.

[00169] The shaft **110** may be disposed coaxially with the plurality of ducts **214**. In some embodiments, the shaft **110** may be disposed concentrically and radially inwardly of the plurality of ducts **214** such that it is circumferentially surrounded by the plurality of ducts **214**. In various embodiments, such an arrangement may lead to a compact turbine, with fewer components. In some embodiments, the shaft **110** is disposed coaxially with the plurality of rotors (defined by the ducts walls) to substantially co-rotate with the plurality of rotors, at a substantially similar rotational frequency to one or more of the plurality of rotors.

[00170] For example, the shaft **110** may be disposed coaxially inside an inner cavity **240** at least partially defining a radially-innermost duct wall or duct of the plurality of ducts **214**. The inner cavity **240** may be defined by a tube disposed radially-inwardly of the plurality of ducts **214** and defining a radially-inner wall of the radially-innermost duct.

[00171] The one or more structures may be generally disposed around the plurality of ducts **214** and upstream and downstream thereof, and may be used to support and cooperate with various parts of the boundary-layer turbomachine **100**. In some embodiments, a (supporting or not) structure of the one or more structures at least partially houses the plurality of ducts **214** (rotors).

[00172] A supporting structure **230** may be supported by the shaft **110** via bearings disposed therebetween to allow rotation of the shaft **110** relative to the supporting structure **230**. The structure may transmit certain vibrations and may prevent rotation with the plurality of rotors. In some embodiments, the supporting structure **230** may sealingly enclose the plurality of ducts **214** at upstream ends **216** thereof.

[00173] In some embodiments, the header block **210** may form part of the supporting structure **230**, and may also route flow therethrough from the inlet ports **114**.

[00174] An end plate **232** may be disposed downstream of the plurality of blade assemblies. The end plate **232** may simultaneously couple to the plurality of the duct walls **220**, e.g. via threadable fasteners defining substantially fixed joints, to lock the plurality of duct walls **220** (the plurality of rotors) in common rotation. The end plate **232** may also be coupled additionally to the shaft **110** to engage the plurality of rotors (the plurality of duct walls **220**) and the shaft **110** in common rotation. Thus, the plurality of rotors may substantially rotate in the same direction and may be constrained to rotate at a substantially similar rotational frequency, which may be similar to a rotational frequency of the shaft **110**.

[00175] The axial-flow stator **226** may be disposed immediately downstream of the plurality of blade assemblies and upstream of the axial-flow stator **226**. In some embodiments, the axial-flow rotor **228** may be coupled to the shaft **110** via the end plate **232**. The axial-flow stator **226** may be coupled or fastened to the (stationary) supporting structure **230** and may be separated from the shaft **110** via a clearance spacing to maintain a stationary position during rotation of the shaft **110** (and the plurality of rotors). For example, for an annulus-shaped axial-flow stator **226**, the axial-flow rotor **228** disposed downstream of the axial-flow stator **226** may protrude across the axial-flow stator **226** to couple (e.g. threadably fasten) directly to the shaft **110** via a shaft flange extending radially outwardly from the center of the shaft **110**. The axial-flow rotor **228** may thus engage with the shaft **110** and the plurality of rotors in common rotation, it may have a substantially similar rotational frequency thereto.

[00176] In some embodiments, the structure may be configured to rotatably support the shaft **110** in-place relative to the structure using bearings **234**. In some embodiments, the rotational frequency of the shaft **110** may be sufficiently low to facilitate support of the shaft **110** by the structure via cost-effective bearings coupled to the shaft **110** and disposed between the structure and the shaft **110**. For example, such bearings may include rotary contact (friction) bearings, e.g. ceramic ball bearings or silicon nitride ball bearings. In some embodiments, hydraulic, magnetic, or foil-air bearings may be used. In some embodiments, SKF™ S7004 CD/P4A contact bearings may be used.

[00177] In some embodiments of the boundary-layer turbine **100**, the plurality of rotors may be configured to generate 50-100 kW of shaft power transmitted directly to the shaft at no more than 43,000 RPM or between 15,000 RPM and 30,000 RPM. In some embodiments, a smaller boundary-layer turbomachine **100** may be configured for higher rotational frequencies while a larger boundary-layer turbomachine **100** may be configured for lower rotational frequencies. For example, in some embodiments, a smaller boundary-layer turbomachines **100** may output no more than 2 kW. For such

RPM ranges, an example range of torque generated by an exemplary boundary-layer turbine may be between 5 ft-lb and 50 ft-lbs. Such relatively large torques may be achievable at low RPM by higher efficiencies facilitated by aspects of the present disclosure. For example, in some embodiments, efficiencies may be 5% to 50% greater compared to baseline turbomachines comprising radial and axial turbines only. In some embodiments, overall total energy efficiencies may exceed 50%. In some cases, energy efficiencies may reach up to 75%.

[00178] In some embodiments of the boundary-layer turbine **100**, the fluid received through inlet ports **114** may be supercritical CO₂ at temperatures between 100 °C to 150 °C at pressures between 2500 psi to 5000 psi, or between 1500 to 6000 psi and the fluid passed through the outlet ports **116** may be at 80 °C or lower and pressures between 600-800 psi.

[00179] Outlet pressures and temperatures may depend on conditions downstream of the boundary-layer turbine **100** since otherwise positive-flow through the boundary-layer turbomachine **100** may not be established. In some embodiments, CO₂ may undergo at least partial (or complete) phase change. In some embodiments, the fluid may be a refrigerant and may flash in the boundary-layer turbine **100**.

[00180] Fluid properties at various positions in an exemplary turbine embodiment of a boundary-layer turbomachine **100** is shown in Table 1. Position A may be upstream of position B, which may be at or adjacent to the inlet end **202** or the inlet ports **114**. Position B may be downstream of the position C, which may be at or adjacent to the outlet end **204** or the outlet ports **116**.

TABLE 1

	Position	Quality	Phase
A	Upstream of inlet	-	Supercritical
B	Inlet	-	Supercritical
C	Outlet	Subcooled	Liquid

D	Downstream of outlet	Subcooled	Liquid
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[00181] Additional CO₂ fluid properties in the exemplary turbine embodiment discussed in Table 1, including coefficient of pressure (recovery) C_p , are tabulated in Table 2. The specific volume associated at these positions may computed as the inverse of the density.

TABLE 2

	Temperature (°F)	Pressure (PSI-G)	Density (lbm/ft ³)	Specific internal energy (BTU/lbm)	C_p
A	119.15	2500	47.292	120	0.61942
B	250	2500	20.884	187.15	0.44293
C	79.603	950	42.869	116.88	1.9239
D	78.427	950	44.109	115	1.5306

[00182] In a supercritical or multiphase state, the fluid may have properties of both liquid and vapor or may have liquid and vapor properties. Liquid and vapor properties in the exemplary turbine embodiment discussed in Table 1 are shown in Table 3.

TABLE 3

	Component	Density (lbm/ft ³)	Specific internal energy (BTU/lbm)	C_p
A	Liquid	-	-	-
	Vapor	47.292	120	0.61942
B	Liquid	-	-	-
	Vapor	20.884	187.15	0.44293
C	Liquid	42.869	116.88	1.9239
	Vapor	Subcooled	Subcooled	Subcooled
D	Liquid	44.109	115	1.5306

Vapor	Subcooled	Subcooled	Subcooled
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[00183] Lower rotational frequencies may benefit from milder operating conditions, e.g. more cost-effective bearings may be used. In some embodiments, rotational frequencies may exceed 100,000 RPM. For example, in some embodiments, boundary-layer turbomachines **100** with outer diameters that are smaller may have corresponding higher rotational frequencies.

[00184] In various embodiments, the upstream end **216** and the downstream end **218** may refer to the corresponding ends of an adhesion portion of the boundary-layer turbomachine **100**, e.g. a contiguously formed adhesion portion, which may be in unitary construction. The inlet end **202** and the outlet end **204** refer to ends of the boundary-layer turbomachine **100** defining an adhesion portion and a bladed portion, e.g. an adhesion portion and a bladed portion that may be in unitary construction, as may be the case in a hybrid turbine.

[00185] In various embodiments, an internal volume of the boundary-layer turbomachine **100** extending from the inner cavity **240** to the radially-outermost duct of the plurality of ducts **214** may be submerged or inundated with fluid, e.g. the working fluid, which may be pressurized fluid. Such an inundated volume may, in part, provide lubrication and support for components of the boundary-layer turbomachine **100**.

[00186] **FIG. 3A** is an exploded perspective view of the plurality of rotors **300** defined at least partially by a plurality of tubes **302**. The plurality of rotors **300** are shown exploded along the longitudinal axis **102**.

[00187] **FIG. 3B** is a front elevation view of the plurality of rotors **300**.

[00188] Directions of rotation of the plurality of rotors are indicated by double-headed arrows. The plurality of tubes **302** may be configured to be

drivably coupled to the shaft **110** to cause such rotation or to thereby cause rotation in the shaft **110** to generate shaft power.

[00189] In some embodiments, the plurality of tubes **302** may be circular tubes having a substantially circular cross-section lateral to the longitudinal axis **102**. In some embodiments, plurality of tubes **302** may include shaped surfaces or longitudinal sloped configurations. For example, in some embodiments, each tube of the plurality of tubes **302** may be diverging or converging, i.e. have a cross-section lateral to the longitudinal axis **102** that is, respectively, increasing or decreasing along the longitudinal axis **102** towards the outlet end **204**. In various embodiments, energy or power extraction may be enhanced by shaping or sloping one or more of the plurality of tubes **302**, or embedding a pattern in the surface(s) of one or more of the plurality of tubes **302** to increase and/or decrease the gap across the length of the tube as the fluids move towards blades (e.g. plurality of blades **222**).

[00190] Each tube (**310**, **302A**, **302B**, or **302C**) of the plurality of tubes **302** may be generally longitudinally elongated and may have tapered or pinched longitudinal ends (upstream end portion **304A**, **304B**, **304C** and downstream end portion **306A**, **306B**, **306C**), e.g. with generally smaller cross-sectional areas. Each tube may define a corresponding radially-inner space (**312A**, **312B**, **312C**, **312D**) lateral to the elongation direction. For example, wall thicknesses of the plurality of tubes **302** may vary from 0.3" near the longitudinal centers to 0.1" at one or more pinched longitudinal ends.

[00191] The radially-inner spaces may define progressively larger cross-sectional areas lateral to the longitudinal axis **102**. Each radially-inner space may be adapted to accommodate a relatively smaller tube of the plurality of tubes **302** to form a sequence or hierarchy of tubes fitting within each other. The plurality of tubes **302** may thus be nested concentrically around the longitudinal axis **102**. Portions of the radially-inner spaces may define the plurality of ducts **214**. For example, each of the radially-inner spaces **312D**, **312A**, **312B**, may define a corresponding duct bounded at a radially-inner end

by the respective duct wall **220A**, **220B**, **220C** of the corresponding tube **302A**, **302B**, **302C**.

[00192] In various embodiments, the radially-inner spaces **312A**, **312B**, **312C**, **312D** may be cylindrical spaces having respective diameters of approximately 5.2", 4.4", 3.6", and 6". In various embodiments, each of the plurality of tubes **302** may longitudinally extend between 7" and 8".

[00193] The plurality of tubes **302** may be generally concentrically spaced apart from each other, in the radial direction **108**. Each duct of the plurality of ducts **214** may be formed in the resulting clearance between a pair of concentrically adjacent tubes of the plurality of tubes **302**. In some embodiments, each pair of concentrically adjacent tubes forms therebetween a corresponding duct of the plurality of ducts **214**. Thus, each duct of the plurality of ducts **214** is at least partially defined by a corresponding duct wall **220A** (or **220B**, **220C**) commonly shared with a corresponding concentrically adjacent duct.

[00194] One or more of the plurality of ducts **214** may have an annular-shaped cross-section lateral to the longitudinal axis **102** (e.g. circular annular shapes), to form a sequence of concentric annuli having coincident edges. The resulting plurality of ducts **214** may be thereby rendered relatively compact, which may thereby reduce cost of manufacturing and improve performance. For example, a first duct formed in the radially-inner space **312D** may share the duct wall **220A** with a second duct formed in the radially-inner space **312A**, and the second duct in turn may share the duct wall **220B** with a third duct formed in the radially-inner space **312B**.

[00195] Each tube **302A**, **302B**, **302C**, **302D** of the plurality of tubes **302** is generally longitudinally elongated from a corresponding (respective) free end of the free ends **314A**, **314B**, **314C**, **314D**, and a corresponding and opposed joint end **316A**, **316B**, **316C**, **316D**, to define a plurality of free ends of the plurality of tubes **302** opposing a plurality of joint ends of the plurality of tubes **302**.

[00196] The radially-innermost tube **302C** of the plurality of tubes **302** may at least partially define a radially-innermost duct of the plurality of ducts **214** and the inner cavity **240**, wherein the shaft **110** may be coaxially disposed for corotation with the plurality of tubes **302**. Similarly, a radially-outermost tube **310** may at least partially define a radially- outermost duct of the plurality of ducts **214**. Thus, the plurality of ducts **214** are disposed between the radially-outermost tube **310** and the radially-innermost tube **302C**. The radial separation between the radially-outermost and radially-innermost duct partially defines a flow-through region for the fluid. The (common) housing, forming a housing portion of the supporting structure **230**, circumferentially surrounds the radially-outermost tube **310** to surround the plurality of tubes **302**.

[00197] In some embodiments, a flow path may be established to prevent or reduce energy lost via leakage from the boundary-layer turbomachine. For example, the fluid may leak or escape from the radially inside the radially-outermost tube **310** to outside within the housing portion of the support structure **230** in a cavity formed between the radially-outermost tube **310** and the housing portion. The fluid may flow down the cavity to come into contact with the axial-flow stator **226** and be redirected across the axial-flow rotor **228** to extract power from such leaked fluid escaping from gaps proximal to the inlet end **202**.

[00198] Each blade assembly may include a corresponding plurality of blades **222A** (or **222B**, **222C**) rotatably disposed around the longitudinal axis **102**. As referred to herein, plurality of blades **222** may refer to one or more of the corresponding plurality of blades **222A** (or **222B**, **222C**). In various embodiments, the plurality of tubes **302** may include at least or at most four tubes. In some embodiments, at least or at most three tubes may have blade assemblies associated therewith, e.g. three tubes may have blades additively grown thereon. In some embodiments, all but one of the plurality of tubes **302** may have blades grown thereon.

[00199] The plurality of blades **222** associated with the plurality of blade assemblies are disposed in the plurality of ducts **214**, e.g. at downstream ends thereof. The plurality of blades **222** extend radially relative to the longitudinal axis **102** from their corresponding duct walls **220** (**220A**, **220B**, and/or **220C**). In some embodiments, each duct may have blades extending from only one of its duct walls, e.g. a radially-outer duct wall or a radially-inner duct wall. In some embodiments, blades may extend from both walls, e.g. alternately. Thus, in some embodiments, the radially-outermost duct wall may not have blades extending therefrom, while in some embodiments, the radially-innermost tubes may not have blades extending therefrom.

[00200] The plurality of blades **222** may be integrally formed with the duct wall for co-rotation with the duct wall, e.g. using fasteners and/or slotted connectors. In some embodiments, the plurality of blades **222** may be in unitary construction with the associated duct walls **220** (i.e. each duct wall is in unitary construction with a blade it is associated with). For example, the plurality of blades **222** may be additively manufactured on the plurality of tubes **302**. Thus, the plurality of blades **222** may necessarily be constrained to rotate together with the plurality of tubes **302** or duct walls **220** (co-rotation or common rotation). In some embodiments, each duct may have at least one blade assembly disposed therein.

[00201] The plurality of tubes **302** may be considered combined or hybrid rotors of a hybrid boundary-layer turbomachine.

[00202] For example, a tube may be viewed as a hybrid boundary-layer turbomachine rotor, wherein a section of an adhesion or friction surface of a boundary-layer turbine is equipped with blades to form a hybrid rotor with increased efficiency, wherein a concentrically adjacent tube is relied upon for forming a shroud circumferentially around the blades. Thus, the blades may form obstructions in the ducts defining radially extending (and circumferentially discrete) flow passages, e.g. the flow passages **308**.

[00203] For example, the tube may be viewed as a bladed rotor of a turbomachine having a longitudinally elongated (and radially enlarged) hub configured to form an adhesion surface to increase efficiency and to serve as a shroud of a concentrically adjacent tube.

[00204] The plurality of blades **222** may be configured to extract additional energy from the fluid after energy is extracted therefrom in the adhesion section.

[00205] **FIG. 4** is a schematic exploded perspective view of the axial stage **224** and the plurality of tubes **302** coupled to the header block **210**. A path of the fluid **112** through the various components is shown schematically, as well as the rotation direction of the plurality of tubes **302** and the axial-flow rotor **228** (with double-headed arrows). Stationary components are indicated using twin lines. The shaft **110**, not shown for clarity, is disposed coaxially with the longitudinal axis **102** within central openings in the components of **FIG. 6**.

[00206] The fluid **112** enters an adhesion or rotor portion of the boundary-layer turbomachine **100** via one or more flow inlets **212**, e.g. three flow inlets **212A**, **212B**, **212C**. As referred to herein, flow inlets may extend from an outer location (e.g. inlet ports **114**) to the adhesion or rotor portion. In various embodiments a flow inlet **212A** (and/or **212B**, **212C**) may have a nozzle end for injecting jets of the fluid **112** oriented normal or lateral to the longitudinal direction **106** to force rotation of the plurality of rotors **300**. Each duct, i.e. each tube of the plurality of tubes **302**, may be exposed to such azimuthally oriented jets of the fluid.

[00207] As mentioned previously, the axial stage **224** is disposed downstream the adhesion portion and may be an axial turbine stage, including the axial-flow stator **226** and the axial-flow rotor **228**. The axial stage **224** may be adapted to receive the fluid oriented generally parallel to the longitudinal axis **102** (in the longitudinal direction **106**), and discharge the fluid oriented generally parallel to the longitudinal axis **102**. In various embodiments, the axial stage **224** may be an impulse turbine or reaction turbine, depending on

the configuration of the axial-flow stator **226** and axial-flow rotor **228**. The axial-flow turbine may be adapted extract residual energy from the fluid.

[00208] In various embodiments, blades and vanes may be configured/altered to best suit fluid type and associated thermodynamic conditions (such as pressures, temperatures, velocities, and densities), e.g. supercritical CO₂ may be treated differently than R134A.

[00209] The axial-flow stator **226** may be a vaned stator, comprising guide vanes, axially aligned with the plurality of rotors **300** along the longitudinal axis **102**. The vaned stator may be annular-shaped to define a core **410** through which the axial-flow stator **226** may couple to the plurality of rotors via the shaft **110**. The vaned stator may comprise plurality of guide vanes having leading edges (the edges closest to the oncoming flow and/or the plurality of blades **222**) oriented substantially in an axial direction. In various embodiments, the axial-flow rotor **228** may be a bladed rotor axially aligned with the vaned stator and disposed downstream of the vaned stator to receive flow off the plurality of guide vanes. The blades of the bladed rotor may have trailing edges oriented substantially in an axial direction.

[00210] In some embodiments, vaned stators and/or rotors may extend radially across more than one duct of the plurality of ducts **214**. In some embodiments, these may extend to the shaft for structural support.

[00211] **FIG. 5A** is a top elevation view of the plurality of tubes **302** coupled to the header block **210**, showing schematic flow directions.

[00212] **FIG. 5B** is an enlarged view of areas **5B-1** and **5B-2** in **FIG. 5A**.

[00213] **FIG. 5C** is an enlarged view of area **5C** in **FIG. 5A**.

[00214] A plurality of nozzles **510** including a nozzle **510A** and a nozzle **510B** may be integrated into the supporting structure **230**. In various embodiments, the plurality of nozzles **510** distributed circumferential thereabout to convey the fluid through the plurality of ducts **214** to the outlet end **204**. In some embodiments, the plurality of nozzles **510** may include six

nozzles uniformly distributed around the longitudinal axis **102**, i.e. forming an azimuthal angle of 60 degrees between adjacent nozzles. In some embodiments, the nozzle **510A** may be approximately 0.3".

[00215] In some embodiments, the boundary-layer turbomachine **100** may have a diameter greater than 48" and may comprise 40 nozzles per tube. In some embodiments, the boundary-layer turbomachine **100** may have a diameter less than 2" and may have only a single nozzle per tube.

[00216] The plurality of nozzles **510** may form part of the one or more flow inlets **212** disposed at the inlet end **202**. For example, the nozzles **510A**, **510B** may be integrated with the respective flow inlets **212A**, **212B**. The one or more flow inlets **212** may be configured to draw the fluid into the plurality of ducts **214**, via the plurality of nozzles (or one or more plurality of nozzles).

[00217] The plurality of nozzles may be circumferentially distributed about an upstream end **216** of a duct to issue fluid jets into the duct. In some embodiments, such may be the case for all ducts of the plurality of ducts **214**, i.e. each may have a corresponding plurality of nozzles (which altogether may also be referred to as a plurality of nozzles). The plurality of nozzles may be circumferentially spaced apart and oriented to reduce flow interaction between the fluid jets. As mentioned above, in various embodiments, the plurality of nozzles may be circumferentially equi-spaced. For example, in some embodiments, six nozzles (or eight nozzles) may be distributed circumferentially around a longitudinal end of a tube, corresponding to an upstream end **216** of a duct, such that an angle around the longitudinal axis **102** between adjacent nozzles is substantially 60 degrees (or 45 degrees, respectively). In some embodiments, such a distribution may mitigate turbulence, which may particularly arise due to cross-impingement of jets upon each other.

[00218] The plurality of nozzles may be adapted to issue fluid jets generally, or at least partially, azimuthally around the longitudinal axis **102** towards the outlet end **204**. In various embodiments, a nozzle may include a

structure adapted for issuance of fluid jet therefrom. For example, the nozzle **510** may include a port for allowing fluid therethrough. In some embodiments, the nozzle **510** may include rectangular slot.

[00219] The plurality of nozzles may include a variety of opening sizes to control velocity and flow of fluids, and may be specific to each tube of the plurality of tubes **302**. For example, in some embodiments, to ensure inlet fluid velocity is matched to surface velocities of the plurality of tubes **302** and to synchronize rotational speeds of tubes of the plurality of tubes **302**, relatively larger outer diameter tubes may be provided with more nozzles having smaller openings to increase fluid velocity and mass flow rate while smaller outer diameter tubes (i.e. tubes having smaller outer diameter) may be provided with fewer nozzles with larger openings. Thus up to 100 or more tubes may be synchronized so that each tube contributes torque at a given common shaft rotational frequency. For example, since surface speeds of tubes is approximately equal to the product of angular velocity and radius, an outer 8" diameter (radius of 1/3') tube rotating at 20,000 RPM (approximately 666.66π rad/s or 2100 rad/s) has an associated surface speed of approximately 700 ft/sec, while a 4" diameter tube (radius of 1/3') then has an associated surface speed of approximately 350 ft/sec. With increasing number of tubes and/or difference in diameter between inner and outer tubes increases, such a disparity between surface speeds increase significantly, e.g. a surface speed of a 48" tube (rotating at 20,000 RPM) is approximately 4200 ft/sec. A configuration of a plurality of adjustable/adapted nozzles enables synchronization of tubes.

[00220] The outlet face of each nozzle may form a corresponding exit angle **520** with the azimuthal direction **104**. In various embodiments, this corresponding exit angle **520** may be substantially 0 degrees, or vary between 0 and 5 degrees, 0 and 10 degrees, or 0 and 20 degrees. For example, in some embodiments, the plurality of nozzles are aligned within 30 degrees, 10 degrees or 5 degrees of the azimuthal direction **104**, i.e. the exit angle **520**

may be less than 10 degrees or 5 degrees, respectively. In some embodiments, exit angle **520** may exceed 20 degrees.

[00221] As the fluid **112** flows from the inlet end **202** to the outlet end **204**, the fluid **112** changes direction, aligning more with the longitudinal direction **106**. In various embodiments, the angle **540** may be between 0° and 10° of the longitudinal direction **106**. In some embodiments, the fluid **112** spirals around the plurality of ducts **214** until it reaches the plurality of blades **222**, (e.g. following a generally helical flow path around the longitudinal axis **102**).

[00222] The exit angle **520** may at least partially determine energy extraction. A larger exit angle **520** may lead to lower residence time (in an adhesion portion), shorter flow path, and/or larger pitch of an approximately spiraling flow path through the plurality of ducts **214**. Total energy drop in the fluid may be diminished.

[00223] In various embodiments, the exit angle **520** may be adapted such that the fluid reaches the plurality of blades **222** before its energy drops below a threshold magnitude, e.g. kinetic energy of the fluid proximal to the plurality of blades **222** may be maintained at a sufficiently high level to maintain energy extraction from the fluid or to prevent energy consumption by the corresponding tube due to pumping of fluid.

[00224] The fluid **112** at the downstream end **218** may be relatively more aligned with the longitudinal axis **102** compared to the fluid **112** at the inlet end **202**. In some embodiments, an azimuthal deviation **530** at the downstream end **218** may be less than 20 degrees more than the exit angle **520**. In some embodiments, the azimuthal deviation **530** may be between 10 and 30 degrees.

[00225] In various embodiments, the fluid may be supercritical and/or multiphase prior to exit from the nozzle and may cease to be so, i.e. either or both supercritical and multiphase, after exit from the nozzle. In some embodiments, the fluid may be supercritical and/or multiphase after exit from the nozzle and may cease to be so, i.e. either or both supercritical and

multiphase, at the plurality of blades **222** or downstream thereof, e.g. at the axial-flow stator **226**. Such change in phase may depend on a flow length and/or longitudinal length(s) of the plurality of ducts **214**.

[00226] Longitudinal lengths (length along the longitudinal axis **102**) of the plurality of ducts **214** may be substantially similar. In some embodiments, longitudinal lengths of the plurality of ducts **214** may be different. For example, in some embodiments, successive ducts moving radially outwardly may have increasing longitudinal length, and in some embodiments, decreasing longitudinal length.

[00227] In various embodiments, such longitudinal lengths of the plurality of ducts **214** may be adapted to limit the azimuthal deviation of the fluid, e.g. to at most 10 or 20 degrees, control the level of turbulence in the flow received by the plurality of blades **222**, maintain sufficient fluid velocity immediately upstream of the plurality of blades **222** (to prevent pumping behavior), support rotor synchrony, encourage positive torque generation, and/or prevent stall conditions (such as due to flow stagnation or reversal). In some embodiments, the azimuthal deviation of the fluid may be limited to at most 10 or 20 degrees. For example, the level of turbulence may be desirably lower rather than higher. In some embodiments, rotational frequencies of the boundary-layer turbomachine **100** are at least partially determined by turbulence characteristics upstream, within, and downstream of the plurality of ducts **214**.

[00228] The plurality of blades **222** of each blade assembly may be adapted to receive the fluid oriented at least partially azimuthally around the longitudinal axis **102**. Each blade may have a blade profile **550**, which may generally vary from root to tip and which defines a leading edge **552A** and a trailing edge **552B**. For example, the leading edges of the plurality of blades **222** may be adapted to or aligned with the azimuthal deviation **530** of the fluid **112** along the duct to receive the fluid **112** in substantial alignment therewith. The fluid **112** may thereby impart rotation to the plurality of blades **222** about the longitudinal axis **102** to rotatably drive the shaft **110**.

[00229] The plurality of blades **222** redirect the fluid **112** generally parallel to the longitudinal axis **102** at a downstream end thereof, i.e. at the outlet end **204**. For example, the trailing edges may be generally aligned with the longitudinal axis **102**.

[00230] For example, in various embodiments, azimuthal gaps **580**, **582** may be approximately 0.35", or less or more.

[00231] **FIG. 6A** is an enlarged view of area **6A** in **FIG. 2**, showing schematic flow directions.

[00232] **FIG. 6B** is an enlarged view of area **6B** in **FIG. 2**, showing schematic flow directions.

[00233] **FIG. 6C** is an enlarged view of area **6C** in **FIG. 2**, showing schematic flow directions.

[00234] As before, the fluid **112** is indicated by means of arrows. Reference numerals are left out for clarity.

[00235] In various embodiments, the plurality of ducts **214** may include intermediate portions **614** disposed between upstream portions **610** and downstream portions **612**, e.g. each duct may thus have corresponding portions: one of an upstream portion **610A**, **610B**, or **610C**, a downstream portion **612A**, **612B**, or **612C**, and an intermediate portion **614A**, **614B**, or **614C**. The intermediate portions **614A**, **614B**, or **614C** may have corresponding radial widths **658A**, **658B**, or **658C**.

[00236] In some embodiments, the plurality of tubes **302** may be substantially free or supported hydraulically at their free ends **314A**, **314B**, **314C**, **314D**, e.g. the free ends **314A**, **314B**, **314C** may be supported via pressurized fluid circulating in open cavities formed in a separate structure (supporting structure **230**) for retaining the free ends **314A**, **314B**, **314C**. In some embodiments, the plurality of tubes **302** may be fastened or jointed at the joint ends **316A**, **316B**, **316C**, **316D** with the end plate **232**, e.g. to be locked in for common rotation. In some embodiments, the plurality of tubes **302**

may be fastened to each other via fasteners passing through the plurality of tubes **302**.

[00237] The upstream portions **610** and downstream portions **612** each may be generally cross-sectionally tapering, from respective larger cross-sections such as respective cross-sections **650A** and **652A** in the corresponding upstream portion **610A** and downstream portion **612A**, towards the intermediate portions **614** to define relatively narrow cross-sections (**658A**, **658B**, **658C**) of the intermediate portions **614**, e.g. for enhancing imparting of rotation to the intermediate portion **614A**, **614B**, or **614C**.

[00238] In various embodiments, the cross-sections defined by the radial widths **658A**, **658B**, **658C** may each radially extend 0.1" or greater than 0.05". In some embodiments, the cross-sections defined by the radial widths **658A**, **658B**, **658C** may each radially extend greater than 1" or more. Radial widths of the plurality of ducts **214** may not be all the same, and may vary depending on the number of nozzles, number of the plurality of tubes **302**, the inner diameter of the radially-innermost tube and the outer diameter of the radially-outermost tube. For example, in turbine embodiments, radial widths may be varied to ensure the rotors are synchronized, and that the torque generated from each tube of the plurality of tubes **302** remains positive, i.e. there is no fluid pump by the boundary-layer turbomachine **100** (for turbine embodiments). Radial widths may vary along the longitudinal lengths of the ducts, e.g. the ducts may thereby be shaped in intermediate portions to achieve desired fluid dynamical behavior.

[00239] In some embodiments, the upstream portions **610** may have larger cross-sections, e.g. larger cross-section **650A**, to accommodate the one or more flow inlets **212**. The upstream portions **610** may be cross-sectionally adapted to receive the fluid jets, via nozzles, at the upstream end **216** of each of the plurality of ducts **214**. In some embodiments, the cross-section **650A** may radially extend 0.3". In various embodiments, the upstream portions **610** itself may extend longitudinally approximately 0.5".

[00240] A cross-sectional size of the one or more flow inlets **212** (lateral to the out flow direction) may be limited to a minimum size due to manufacturability or cost considerations. In various embodiments, radial widths of each of the plurality of ducts **214** that yield more efficient driving of the plurality of rotors **300** may be smaller than a maximum radial width indicative of the size of the one or more flow inlets **212**. For example, in certain flow regimes, ratios of boundary-layer thickness to channel radial width inside the plurality of ducts **214** may be larger for more efficient driving. In various embodiments, a tapering **654A** of the radial width from the cross-sections **650A** towards lower radial widths, oriented towards the outlet end **204** or the downstream end **218**, may increase efficiency of driving of the plurality of rotors **300** while accommodating larger sizes of the one or more flow inlets **212**. The tapering **654A** may also accelerate and/or compress the fluid flow (the fluid **112**), which may increase efficiency of driving of the plurality of rotors **300**. In various embodiments, the tapering **654A** may be gradual or relatively smooth (as shown) to prevent formation of undesirable flow conditions or to encourage appropriate conditions for increasing efficiency of driving the plurality of rotors **300**. In various embodiments, the tapering **654A** may be axi-symmetric about the longitudinal axis **102**, as suggested in **FIG. 3A**.

[00241] Similarly, the downstream portions **612** may have larger cross-sections, e.g. larger cross-section **652A**, to accommodate the plurality of blades **222**. The downstream portions **612** may be cross-sectionally partially complementary to the flow passages **308** defined by the plurality of blades **222** at the downstream ends **218** of the plurality of ducts **214**. In some embodiments, the cross-section **652A** may radially extend 0.230". In various embodiments, the downstream portion **612** itself may extend longitudinally between 1" and 1.5".

[00242] In various embodiments, radial widths of the plurality of blades **222** may be large relative to efficient radial widths of the plurality of ducts **214**, discussed above. The larger radial widths of the plurality of blades **222** may confer efficiency or other advantages to the plurality of blades **222** for driving

of the plurality of rotors **300**. In various embodiments, a tapering **656A** of the radial width from the cross-sections **652A** towards lower radial widths, oriented towards the inlet end **202** or the upstream end **216**, may increase efficiency of driving of the plurality of rotors **300** while accommodating larger sizes of plurality of blades **222**. The tapering **656A** may also decelerate, diffuse, expand, or pressurize the fluid flow (the fluid **112**), which may increase efficiency of driving of the plurality of rotors **300** and the plurality of blades **222**. In various embodiments, the tapering **656A** may be gradual or relatively smooth (as shown) to prevent formation of undesirable flow conditions or to encourage appropriate conditions for increasing efficiency of driving the plurality of rotors **300**. For example, it is known that a sudden expansion may lead to flow detachment and formation of a separation bubble. In various embodiments, the tapering **656A** may be axi-symmetric about the longitudinal axis **102**, as suggested in **FIG. 3A**.

[00243] The intermediate portions **614** may be defined between the upstream portions **610** and the downstream portions **612**.

[00244] The supporting structure **230** may include one or more or a plurality of slots **620A**, **620B**, **620C** configured to receive a corresponding free end **314A**, **314B**, **314C** of the plurality of the tubes **302**. In various embodiments, the plurality of slots **620A**, **620B**, **620C** may have a longitudinal depth of 0.580" and may be configured to receive tongues of the plurality of tubes **302** having radial thickness of approximately 0.10". The slots **620A**, **620B**, **620C** may be in fluid communication with the fluid **112**. Similarly, an opposed end of the plurality of tubes **302** may be substantially cantilevered from joint ends **316A**, **316B**, **316C**, **316D** of the plurality of tubes **302**. The longitudinal depth and the radial thickness of the plurality of slots **620A**, **620B**, **620C** may depend on material stiffness of tubes and may be configured to prevent metal-to-metal (or material-to-material) contact.

[00245] The supporting structure **230** may include one or more inlet channels, e.g. winding through the header block **210**, to feed the fluid **112** to the plurality of nozzles and the plurality of slots **620A**, **620B**, **620C**.

[00246] In various embodiments, the plurality of ducts **214** may be in fluid communication with each other via the plurality of slots **620A**, **620B**, **620C**. The inner cavity **240** may be in fluid communication with the plurality of ducts **214**. In some embodiments, the slot opens to at least one of the inner cavity **240** or a duct of the plurality of ducts **214** to establish fluid communication with the fluid.

[00247] The slots **620A**, **620B**, **620C** may be dimensioned to maintain clearance from the plurality of free ends, e.g. by maintaining a clearance **630** between the free end **314A** and the slot **620A** when the free end **314A** is received therein. Thus, by maintaining a clearance such as the clearance **630**, the slots **620A**, **620B**, **620C** may be adapted to allow rotation of the plurality of tubes **302** relative to the slots **620A**, **620B**, **620C**. For example, in various embodiments, the slots **620A**, **620B**, **620C** may each maintain a clearance of approximately 0.02" on each radial end of the respective slot of the slots **620A**, **620B**, **620C**. In various embodiments, each of the **620A**, **620B**, **620C** may have a radial width of 0.140", or between 0.001" to 0.250". In some embodiments, excessively large radial depths may cause redirection of fluid away from ducts to (circulating) flow in or near the slot, thereby leading to leakages and loss of efficiency. In some embodiments, excessively small radial depths may encourage or cause physical contact between the slot (walls) and one or more tubes of the plurality of tubes **302**. It is noted that, in some embodiments, longitudinal and radial depths may vary from one slot to another.

[00248] A lubricating film of the fluid **112** may be maintained between the free ends **314A**, **314B**, **314C** of each corresponding (respective) tube **302A**, **302B**, **302C**, and its corresponding slot **620A**, **620B**, **620C**, e.g. in a clearance such as the clearance **630**. The lubricating film may at least partially (rotatably) support the free end **314A**, **314B**, **314C** of each tube **302A**, **302B**, **302C** in its

corresponding slot **620A**, **620B**, **620C** and substantially prevent sliding friction (contact) therebetween. In some embodiments, clearances in the plurality of slots **620A**, **620B**, **620C** may be adapted to generate relatively low pressure zones inside the plurality of slots **620A**, **620B**, **620C** when the plurality of tubes **302** are rotating to draw the fluid **112**, via the plurality of ducts **214**, into the plurality of slots **620A**, **620B**, **620C** to maintain lubrication between the free ends **314A**, **314B**, **314C** of tubes **302A**, **302B**, **302C** and their corresponding slots **620A**, **620B**, **620C**. In some embodiments, the fluid-filled slots may provide a fluid bearing-like behaviour.

[00249] In various embodiments, the slots **620A**, **620B**, **620C** are substantially annular slots configured to sleeve over longitudinal cylindrical (annular) edges of the tubes **302A**, **302B**, **302C**. In various embodiments, the slots **620A**, **620B**, **620C** may be formed in a monoblock.

[00250] The end plate **232** may be coupled to a tube **302A**, **302B**, **302C**, or **310**, of the plurality of tubes **302** at a corresponding joint end of the joint ends **316A**, **316B**, **316C**, or **316D**, of the tube to, e.g. substantially freely, cantilever the tube **302A**, **302B**, **302C**, or **310**, from the joint end **316A**, **316B**, **316C**, or **316D**. The end plate **232** may be a monoblock. In various embodiments, cantilevering refers to having one end fixed while the other may be substantially non-fixed to permit a cantilevering effect.

[00251] In various embodiments, the end plate **232** is coupled to the tube **302A**, **302B**, **302C**, or **310** by threadably engaging along the longitudinal axis **102** with the respective joint end of the joint ends **316A**, **316B**, **316C**, or **316D**.

[00252] For example, a joint end **316A**, **316B**, **316C**, or **316D** may be threaded or tapped to threadably engage with a complementary fastener. The joint end **316A**, **316B**, **316C**, or **316D** may have one or more discrete fastening portions, such as tapped grooves or threaded extensions, which may be distributed about the circumference of the tube at the joint end **316A**, **316B**, **316C**, or **316D**.

[00253] In some embodiments, the joint have a fastening portion extending circumferentially around the joint end **316A**, **316B**, **316C**, or **316D** of the tube **302A**, **302B**, **302C**, or **310**, e.g. the tube **302A**, **302B**, **302C**, or **310** may be threaded at the joint end **316A**, **316B**, **316C**, or **316D** or may be (internally) tapped such that the joint end **316A**, **316B**, **316C**, or **316D** threadably engages as a whole to couple the tube **302A**, **302B**, **302C**, or **310** with the end plate **232**.

[00254] In some embodiments, the joint end **316A**, **316B**, **316C**, or **316D** may have an internally threaded annular groove extending circumferentially that may be configured to receive a complementary threaded fastening portion extending from the end plate **232**. In various embodiments, this complementary threaded fastening portion may be integrally formed or in unitary construction with the end plate **232**, or may be a separate coupling component for simultaneously engaging with the end plate **232** and the tube **302A**, **302B**, **302C**, or **310**.

[00255] For example, the separate coupling component may be a threaded fastener configured to engage with the tube **302A**, **302B**, **302C**, or **310** via the end plate **232**. An example of such coupling components are cap screws joining the end plate **232** and the tube **302A**, **302B**, **302C**, or **310** by passing through a clearance hole in the end plate **232** to screw into a tapped hole, axially aligned with and adjacent to the clearance hole, at the joint end of the tube. In various embodiments, each tube **302A**, **302B**, **302C**, or **310** of the plurality of tubes **302** may be so (e.g. independently or separately) coupled to the end plate **232**.

[00256] In some embodiments, the plurality of tubes **302** may be a press fit into the end plate **232** rotating head, e.g. manufactured by heat expansion of one component to allow fitting of another component therein. In some embodiments, such a configuration may be less expensive and more robust but may not be disassembled easily. In some embodiments, the plurality of tubes **302** may have longitudinal edges configured to threadably engage with

the end plate **232**. For example, a longitudinal edge may be threaded or comprise a circumferentially extending slot that is tapped.

[00257] While the discussion above focused on the tube **302A** and the duct formed therein, it is understood that similar discussions may extend to other tubes and ducts formed therein.

[00258] It is found that for certain distributions of radial widths of the plurality of ducts **214**, the radially outer ducts may generate power consumed by radially inner ducts for pumping fluid thereacross. In some embodiments, a radially-innermost duct wall **660A** defined by the plurality of duct walls **220** is radially dimensioned relative to the radially-outermost duct wall **660B** defined by the plurality of duct walls **220**. Such dimensioning is configured to prevent pumping of the fluid **112** through one or more ducts of the plurality of ducts **214** using shaft power generated by the plurality of rotors **300**.

[00259] In various embodiments, the radially-innermost duct **660A** is greater than a first predetermined radius, and/or the radially-outermost duct **660B** is less than a second predetermined radius greater than the first predetermined radius. In various embodiments, the (individual) radial widths **658A**, **658B**, or **658C** of the intermediate portions **614A**, **614B**, or **614C** may each be different, and possibly varying. For example, for turbine embodiments of the boundary-layer turbomachine **100**, the radial widths **658A**, **658B**, or **658C** may be configured to prevent or mitigate pumping in one or all of the plurality of ducts **214**.

[00260] In various embodiments, a housing portion **670** of the supporting structure **230** circumferentially surrounds the plurality of tubes **302**. In some embodiments, the housing portion **670** is configured to maintain pressurization of the fluid in the plurality of ducts **214**. In various embodiments, the housing portion may comprise an opening for a regulator valve for regulating pressure.

[00261] **FIG. 7** through **FIG. 11** show computational fluid dynamics results.

[00262] FIG. 7 is a perspective view of velocity contours and streamlines, computed using computational fluid dynamics, in exemplary ducts of the plurality of ducts **214** of an exemplary boundary-layer turbomachine **100**.

[00263] FIG. 8 is a perspective view of pressure contours, computed using computational fluid dynamics, in the exemplary ducts.

[00264] FIG. 9 is a perspective view of temperature contours, computed using computational fluid dynamics, in the exemplary ducts.

[00265] The ducts are formed above a radially-outermost tube **700A**, a radially-innermost tube **700C**, and a radially-intermediate tube **700B**.

[00266] The flow spirals around the tubes as it flows towards the plurality of blades, and reduces in temperature and pressure along the way. Radially-inner tubes may be generally at higher pressures, slower speeds, and/or lower temperatures than radially-outer tubes.

[00267] FIG. 10A is an enlarged perspective view of velocity contours and streamlines, computed using computational fluid dynamics, in one of the exemplary ducts.

[00268] FIG. 10B is an enlarged perspective view of pressure contours, computed using computational fluid dynamics, in the exemplary duct.

[00269] FIG. 10C is an enlarged perspective view of temperature contours, computed using computational fluid dynamics, in the exemplary duct.

[00270] The exemplary duct is formed over a tube **1000** of the plurality of the tubes **302**. The enlarged view shows flow conditions around the plurality of blades. In particular, the plurality of blades are adapted to receive the streamlines.

[00271] FIG. 11 is a perspective view of velocity streamlines, computed using computational fluid dynamics, outside an exemplary nozzle **1100** of a boundary-layer turbomachine **100**. The fluid jet exiting from the nozzle may be azimuthally aligned.

[00272] FIG. 12 is a schematic block diagram of a system 1200 for generating power, in accordance with an embodiment.

[00273] In FIG. 12, thick hollow arrows may indicate general transfer of energy, solid arrows may indicate fluid flows (which may generally involve transport of energy as well), and dashed lines may represent flows and components that may be absent in some embodiments.

[00274] In some embodiments, the system 1200 may be similar to or based on a Rankine power cycle and/or a Brayton power cycle.

[00275] The system 1200 may include a boundary-layer energy extraction subsystem 1204 for extracting energy from working fluid and a regeneration subsystem 1202 for regenerating the working fluid to allow subsequent energy extraction in the boundary-layer energy extraction subsystem 1204.

[00276] In some embodiments, a secondary subsystem 1203 may be coupled to the regeneration subsystem 1202 to provide staged heat transfer in the system 1200, e.g. the secondary subsystem 1203 may utilize a different working fluid than the regeneration subsystem 1202 and the boundary-layer energy extraction subsystem 1204.

[00277] The secondary subsystem 1203 may provide heat to, and receive heat from, the regeneration subsystem 1202 using, respectively, a secondary heat input 1211 and a secondary heat output 1209. The secondary heat input 1211 and the secondary heat output 1209 may each be a separate, or a same, intermediate energy storage medium (fluid or solid).

[00278] The boundary-layer energy extraction subsystem 1204 and the regeneration subsystem 1202 may be coupled to each other for feedback. In various embodiments, the secondary subsystem 1203 may be coupled to the regeneration subsystem 1202.

[00279] Fluid may enter the boundary-layer energy extraction subsystem 1204 at position A-12 as a higher temperature, pressure, and/or volume fluid

(or higher energy fluid) from the regeneration subsystem **1202** and enter the regeneration subsystem **1202** as a lower temperature, pressure, and/or volume fluid (or lower energy fluid) from the boundary-layer energy extraction subsystem **1204**.

[00280] In some embodiments, the working fluid at A-12 and B-12 may be a second fluid, which may be heated in the secondary subsystem **1203** using a first fluid, e.g. using a heat exchanger that isolates the first fluid from the second fluid (and vice versa). The second fluid may enter the regeneration subsystem **1202** at position C-12 as a higher temperature, pressure, and/or volume fluid (or higher energy fluid) from the secondary subsystem **1203** and enter the secondary subsystem **1203** at position D-12 as a lower temperature, pressure, and/or volume fluid (or lower energy fluid) from the regeneration subsystem **1203**.

[00281] In various embodiments, the (second) working fluid at position A-12 may be vapor or multiphase. In some embodiments, the working fluid at position A-12 may be superheated vapor.

[00282] The energy extracted in the boundary-layer energy extraction subsystem **1204** may be supplied as power output **1260**. In some embodiments, the power output **1260** may be shaft power.

[00283] In some embodiments the power output **1260** may be used in an electric generator **1270** to drive the electric generator **1270** to produce electricity output **1280**.

[00284] In various embodiments, the electric generator **1270** may produce waste heat, which may be considerable in some cases. For example, an alternating current (AC) generator may generate waste heat (or heat losses) due to internal resistance, hysteresis loss, mechanical losses due to friction and drag. In some embodiments, the waste heat generated may substantially represent efficiency loss in the generator. For example, if the electric generator **1270** operates at 50% efficiency, substantially 40-50% of energy input to the electric generator **1270** may be lost as waste heat.

[00285] In some embodiments, working fluid may be supplied to the electric generator **1270** to cool the electric generator **1270** and/or preheat the working fluid, including by using the waste heat to improve overall system efficiency and improve performance of the electric generator **1270**.

[00286] The boundary-layer energy extraction subsystem **1204** may include one or more boundary layer turbines **1230** for extracting energy from the working fluid. The boundary-layer turbines **1230** may include one or more embodiments of the boundary-layer turbomachine **100**. In some embodiments, the boundary-layer energy extraction subsystem **1204** may include one or more bladed turbine(s) **1234**, and/or stators **1236**. For example, the axial stage **224** may be included in the boundary-layer energy extraction subsystem **1204**.

[00287] In some embodiments, boundary-layer energy extraction subsystem **1204** may condense the working fluid or at least partially condense the working fluid by extracting energy therefrom. For example, the working fluid at position B-12 may be a liquid and/or multiphase. In some embodiments, the boundary-layer energy extraction subsystem **1204** may receive a multiphase working fluid and may generate multiphase working fluid with higher mass fraction in liquid phase. In some embodiments, the vapor quality of the working fluid at position A-12 may be higher than the vapor quality of the working fluid at position B-12.

[00288] The regeneration subsystem **1202** may include a heat exchanger **1220**, a compressor **1222**, a liquid pump **1224**, and/or a condenser **1226**.

[00289] The regeneration subsystem **1202** may receive heat input **1210**. In various embodiments, the heat input **1210** may be heat generated by combustion and/or oxidation. In some embodiments, the heat input **1210** may be waste heat from industrial processes.

[00290] In some embodiments, the heat input **1210** may be used to heat the working fluid via the heat exchanger **1220**. In some embodiments, the heat exchanger **1220** may include a shell-and-tube heat exchanger. In some embodiments, the heat exchanger **1220** may include a furnace. Heating the

working fluid may increase its temperature and/or pressure. For example, in some embodiments, the working fluid may be liquid or multiphase fluid that is vaporized upon heating. Vaporization may allow greater energy absorption due to the heat of vaporization.

[00291] In some embodiments, the working fluid may be compressed in a compressor **1222** prior to being supplied to the heat exchanger **1220**. The compressor **1222** may include one or more axial, mixed flow and/or centrifugal compressor(s). For example, the working fluid may be a vapor prior to compression such that compression liquefies the working fluid.

[00292] In some embodiments, the (liquid) working fluid may be pumped using a liquid pump **1224**, e.g. a positive-displacement pump.

[00293] The working fluid may be liquified in the condenser **1226** prior to pumping, which may lead to a heat output **1208**. Condensing the working fluid may be advantageous to leverage the heat of vaporization for energy from a heat source supplying the heat input **1210**. In some embodiments, the heat output **1208** may be lost to the environment as waste heat.

[00294] In various embodiments, the compressor **1222** and/or liquid pump **1224** may be powered by the power output **1260**. The compressor **1222** and/or the liquid pump **1224** may provide motive force for circulating the working fluid through the power generation cycle to generate power.

[00295] In some embodiments, the working fluid may be liquid or substantially liquid at position B-12 due to condensation in the boundary-layer turbine(s) **1230** caused by energy extraction from the working fluid.

[00296] In some embodiments, the heat may be supplied to the regeneration subsystem **1202** via the secondary subsystem **1203**. The first fluid in the secondary subsystem **1203** may absorb the heat input **1210** and transfer it to the second fluid to supply the regeneration subsystem **1202** with energy.

[00297] In some embodiments, heat lost from the regeneration subsystem **1202** may be absorbed by the secondary subsystem **1203**. The secondary subsystem **1203** may output energy as heat output **1208**.

[00298] In some embodiments, the secondary subsystem **1203** may include components for driving the first fluid into and out of the regeneration subsystem **1202**. In some embodiments, the secondary subsystem **1203** may include a compressor.

[00299] **FIG. 13** is a schematic block diagram of a system **1300** for generating power, in accordance with an embodiment.

[00300] The system may include a heater **1205** for injecting energy into the system **1200** by heating the working fluid of the system **1200**. In some embodiments, the heater **1205** may include a heat input **1210** source supplying energy to a heat exchanger **1220**.

[00301] In some embodiments, the working fluid may include at least some condensate prior to heating in the heater **1205**. For example, the working fluid may be liquid, substantially liquid, and/or multi-phase (liquid and vapor). Such condensate may arise from compression and/or cooling in other components of the system **1200**.

[00302] The heater **1205** may heat the working fluid to then generate working fluid (or fluid) that is at least partially vaporized. For example, the heated working fluid may be vapor, substantially vapor, and/or multi-phase (liquid and vapor). When the working fluid is multiphase before and after heating, heating may increase the vapor pressure or mass-fraction of vapor relative to liquid.

[00303] The heated working fluid may be supplied to a (first) boundary-layer turbine **1230A**, which may be an embodiment of the boundary-layer turbomachine **100**, to extract energy from the working fluid.

[00304] After energy extraction from the working fluid in the boundary-layer turbine **1230A**, the working fluid may be supplied to an axial stage **224**.

The axial stage **224** may be coupled to the boundary-layer turbine **1230A** to receive the working fluid from the boundary-layer turbine **1230A** to extract energy from the working fluid. The axial stage **224** may include an axial-flow rotor, such as an axial turbine, and/or an axial stator.

[00305] In some embodiments, the axial stage **224** may be configured to rotatably drive a shaft. In various embodiments, the axial stage **224** may be directly coupled to one, or both, of the boundary-layer turbines **1230A**, **1230B** without an intervening shaft. The axial stage **224** and the boundary-layer turbines **1230A**, **1230B** may be coupled, with or without a distinct shaft, to transmit generated power.

[00306] The energy of the working fluid may be reduced in the axial stage **224**. For example, in some cases, the pressure and/or temperature of the working fluid may be reduced.

[00307] After energy extraction from the working fluid in the axial stage **224**, the working fluid may be supplied to a second boundary-layer turbine **1230B**.

[00308] The boundary-layer turbines **1230A**, **1230B** may have respective duct walls to supply energy to the respective boundary-layer turbines **1230A**, **1230B** to generate power, e.g. shaft power, from the working fluid.

[00309] The boundary-layer turbines **1230A**, **1230B** may be configured for drivable rotation about corresponding longitudinal axes of the respective boundary-layer turbomachine by the working fluid frictionally dragging the aforementioned respective duct walls at least partially azimuthally around respective longitudinal axes of the boundary-layer turbines **1230A**, **1230B**.

[00310] In some embodiments, the cooled and condensed working fluid may be supplied to the electric generator **1270** for cooling of the electric generator **1270**, i.e. preheating of working fluid condensate. The working fluid is then returned to the heater **1205** in the form of at least partial condensate. It

is found advantageous to configure the system **1200** to generate substantially liquid working fluid for supplying to the heater **1205**.

[00311] The thermodynamic properties of the working fluid at positions A-13, B-13, C-13, and D-13 are listed in Table 4, for an exemplary embodiment.

TABLE 4

Position	Temperature (°F)	Pressure (psig)	Density (lbm/ft ³)	Vapor quality (lbm/lbm)
A-13	300.0	1000	10.0	1.00
B-13	64.2	100	1.9	0.55
C-13	62.9	100	31.5	0.0
D-13	70.8	1000	32.0	0.0

Note: the vapor quality is defined as the ratio of the mass of the vapor fraction of the working fluid to the total mass of the working fluid, and a vapor quality of 0.0 in Table 4 above indicates subcooled liquid.

[00312] Multi-phase properties of the working fluid are listed in Table 5, for an exemplary embodiment.

TABLE 5

Position	Density (lbm/ft ³)		Enthalpy (BTU/lbm)	
	Liquid	Vapor	Liquid	Vapor
A-13	-	10.0	-	314.4
B-13	31.4	1.1	105.8	255.5
C-13	31.5	-	105.0	-
D-13	32.0	-	110.9	-

In various embodiments, the working fluid may be propane and the efficiency of such a system may be about 60%, e.g. to generate approximately 700-800 hp, or about 700-740 hp (about 530-550 kW).

[00313] In some embodiments, the heat input may be about 895 kW and the heat output **1208** may be about 368 kW.

[00314] In various embodiments, the liquid pump **1224** may be configured for a volumetric flow rate about 8 ft³/min.

[00315] In various embodiments of systems for generating power, a plurality of boundary-layer turbomachines **100** may be coupled together, e.g. three or four boundary-layer turbomachines **100** may be staged. Each boundary-layer turbomachine **100** may have configured differently, e.g. the number of duct walls, the radius, the number of inlet vanes, and other parameters may vary from one boundary-layer turbomachine **100** to another.

[00316] **FIG. 14** is a schematic block diagram of a system **1400** for generating power, in accordance with an embodiment.

[00317] In system **1400**, the second boundary-layer turbine **1230B** may be configured to generate condensate by extracting energy from the working fluid. The condensate generated in the second boundary-layer turbine **1230B** may decrease the vapor quality of the working fluid to a level suitable for reheating (and vaporization) in the heater **1205**.

[00318] Advantageously, a separate condenser may not be used. Energy (heat) lost due to condensing working fluid in a separate condenser may be avoided. Such energy, or some portion thereof, may be converted into mechanical energy. In some embodiments, improved efficiencies may be achieved.

[00319] In various embodiments, a (vapor) compressor **1222** may be disposed downstream of the heater **1205** to compress the working fluid after vaporization. Compression and/or pressurization may establish a suitable pressure gradient in the system **1400** to draw through the working fluid.

[00320] The thermodynamic properties of the working fluid (which may be propane) at positions A-13, B-13, and C-13 are listed in Table 6, for an exemplary embodiment.

TABLE 6

Position	Temperature (°F)	Pressure (psig)	Density (lbm/ft ³)	Vapor quality (lbm/lbm)
A-14	256.6	150	1.02	1.00
B-14	-31.5	5	0.20	0.95
C-14	70.0	5	0.16	1.00

[00321] Multi-phase properties of the working fluid are listed in Table 7, for an exemplary embodiment.

TABLE 7

Position	Density (lbm/ft ³)		Enthalpy (BTU/lbm)	
	Liquid	Vapor	Liquid	Vapor
A-14	-	1.02	-	345.5
B-14	35.76	0.20	49.9	229.8
C-14	-	0.16	-	267.9

[00322] **FIG. 15A** is a perspective view of the system **1300**, in accordance with an embodiment.

[00323] **FIG. 15B** is a partial enlarged cross-sectional view of the system **1300** of **FIG. 15A**.

[00324] In reference to **FIGS. 15A-15B**, material flows in ducts of the system **1300** are indicated, where appropriate, using large (outlined) arrows.

[00325] In reference to **FIGS. 15A-15B**, a longitudinal axis **102** of the system **1200** may define a common rotational axis for duct walls of the boundary-layer turbine **1230A**, **1230B**, rotors of the axial stage **224**, and the electric generator **1270**. In some embodiments, one or more of these components may have distinct rotational axes. Having a common rotational axis may simplify construction and allow direct coupling of components.

[00326] Hot working fluid is supplied to the plurality of ducts of the boundary-layer turbine **1230A** via an inlet duct **1510**.

[00327] The plurality of ducts of the boundary-layer turbine **1230** may be at least partially defined by corresponding duct walls. These duct walls may be configured for drivable rotation about the longitudinal axis **1560** by the working fluid to generate shaft power.

[00328] The axial stage **224** may be sandwiched in-between the boundary-layer turbine **1230A** and the boundary-layer turbine **1230B**.

[00329] The boundary-layer turbine **1230B** may receive the working fluid, with reduced energy, from the axial stage **224** into a plurality of ducts at least partially defining the boundary-layer turbine **1230B**. The plurality of ducts may be at least partially defined by corresponding second duct walls that are frictionally engaged with the working fluid and configured for drivable rotation about the longitudinal axis **1560** by the working fluid. In various embodiments, the duct walls of the boundary-layer turbine **1230B** may be configured to transfer energy from the working fluid flowing in the plurality of ducts of the boundary-layer turbine **1230B** in order to at least partially condense or cool the working fluid.

[00330] The axial stage **224** may be coupled to the two boundary-layer turbomachines at opposite ends of the axial stage **224** to axially space apart the boundary-layer turbine **1230A** and the boundary-layer turbine **1230B**.

[00331] In various embodiments, the boundary-layer turbine **1230A**, the axial stage **224**, and the boundary-layer turbine **1230B** (and, in some

embodiments, the electric generator **1270**) may be integrally formed for common rotation. For example, in some embodiments, the components may be attached or integrally coupled to one another via threadable connections without intermediate shaft bodies or gearing. For example, a “shaft” may be formed after integrating separate components together.

[00332] The electric generator **1270** is coupled to the axial stage **224** and the boundary-layer turbines **1230A**, **1230B** to generate electricity, which is output from the electric generator **1270** via electrical cables **1550**.

[00333] In various embodiments, the electric generator **1270** may be an induction generator or a permanent magnet generator/motor. The electric generator **1270** may generate heat which may lead to the degradation of the service life and/or performance of the electric generator **1270**. The generated heat may also represent a loss of energy from the system **1300** if not reclaimed.

[00334] After cooling in the boundary-layer turbine **1230B**, cool working fluid is drawn into and/or around the electric generator **1270** via a generator inlet **1520**. In some embodiments, the cold working fluid may be supplied to a heat exchanger surrounding hot parts of the electric generator **1270**. For example, the cold working fluid may be supplied to helical ducting **1570** around the longitudinal axis **102** configured for heat exchange.

[00335] After cooling the electric generator **1270**, the working fluid is drawn out via an outlet duct **1530** back to the heater **1205** via the condenser **1226** and the liquid pump **1224**.

[00336] A valve **1540** may be provided to control the flow of working fluid. The valve **1540** may be a controllable valve. In some embodiments, the valve **1540** may be controllable to vary a flow rate through the valve **1540**. In various embodiments, the valve **1540** may electrically (e.g. via a solenoid), hydraulically, and/or pneumatically actuatable.

[00337] In various embodiments, the boundary-layer turbine **1230A**, and/or ducts thereof, may have substantially similar inner and outer diameters to, respectively the boundary-layer turbine **1230B**, and/or ducts thereof. In some embodiments, the number of ducts of the boundary-layer turbine **1230A** and the boundary-layer turbine **1230B** may be substantially similar.

[00338] In various embodiments, bearings **1580** may be provided to support components around coupling locations about the longitudinal axis **102**. In some embodiments, boundary-layer turbomachinery may facilitate operation at relatively low rotational frequencies to allow use of cost-effective bearings such as ceramic bearings.

[00339] In various embodiments, the respective sets of duct walls of the boundary-layer turbines **1230A**, **1230B** may be integrally formed via fasteners **1582** coupling the duct walls of a particular boundary-layer turbine together to prevent differential rotation between the duct walls. For example, annular tubes defining the duct walls of a particular boundary-layer turbine may all rotate at a similar or the same angular velocity.

[00340] In various embodiments, one or more rotors and/or stators of the axial stage **224** may be diverging in a longitudinally downstream direction.

[00341] **FIG. 16A** is a perspective view of the system **1400**, in accordance with an embodiment.

[00342] **FIG. 16B** is a cross-sectional view of the system **1400** of **FIG. 16A**.

[00343] **FIG. 16C** is a partial enlarged cross-sectional view of the system **1400** of **FIG. 16A**.

[00344] In reference to **FIGS. 16A-16C** (and also **FIGS. 16D-16I** discussed later), material flows in ducts of the system **1400** are indicated, where appropriate, using large (outlined) arrows.

[00345] Heat input **1210** may be provided to the heat exchanger **1220** via hot fluid entering the heat exchanger through an inlet **1602** and exiting through

an outlet **1604**. In some embodiments, the heat exchanger **1220** may be a shell-and-tube heat exchanger.

[00346] The compressor **1222** may be a bladed compressor. For example, the compressor **1222** may be an axial, centrifugal, and/or mixed flow compressor. In some embodiments, the compressor **1222** may be a type of impeller. The compressor **1222** may be configured to receive a substantially single-phase fluid. The compressor **1222** may be configured for substantially single-phase operation.

[00347] The energy (enthalpy) of the working fluid may decrease from an inlet of the first boundary-layer turbine **1230A** to the output of the second boundary-layer turbine **1230B**. The energy drawn from the working fluid may be converted to mechanical work. The second boundary-layer turbine **1230B** may cool the fluid sufficiently to increase condensate in the working fluid. In some embodiments, condensate formed may be similar in quantity to a condenser.

[00348] In various embodiments, the length of the second boundary-layer turbine **1230B** may be varied to achieve a desired fraction of condensate forming and/or to achieve a desired amount of power generation (or energy extraction from the working fluid). In various embodiments, the plurality of ducts of the boundary-layer turbine **1230A** may be substantially axially shorter than the plurality of ducts of the boundary-layer turbine **1230B**. In some cases, it is found that the boundary-layer turbine **1230A**, and/or ducts thereof, may be advantageously between one-third and one-half an axial length of, respectively, the boundary-layer turbine **1230B**, and/or ducts thereof.

[00349] In some embodiments, the cooled and condensed working fluid from the boundary-layer turbine **1230B** may be supplied to the electric generator **1270** for cooling of the electric generator **1270**, i.e. preheating of the condensate. The working fluid is then returned to the heater **1205** in the form of at least partial condensate.

[00350] It is found advantageous to configure the system **1400** to generate substantially liquid working fluid for supplying to the heater **1205**.

[00351] Advantageously, heat generated by the electric generator **1270** may be absorbed by the working fluid to simultaneously mitigate heat-associated degradation (e.g. via heat buildup) in the electric generator **1270** and to preheat the working fluid to reduce heat loss from the system **1400**.

[00352] A plenum **1606** around the electric generator **1270** may receive cold working fluid for cooling the electric generator **1270** and for preheating the working fluid. The plenum **1606** may fluidly connect an outlet of the boundary-layer turbine **1230B** to a duct fluidly connected to the heat exchanger **1220**.

[00353] In some embodiments, the system **1400** may be substantially closed to heat escape. For example, heat may only enter the system **1400** via the heat exchanger **1220** and may not otherwise exit the system, except via leakage, due to imperfect insulation and other conductive losses, noise, and/or vibration. Heat supplied to the system **1400** may be converted to mechanical energy, e.g. shaft energy. Parasitic loading on the system **1400** may also be present, e.g. parasitic loading due to the compressor **1222**.

[00354] As referred to herein, "shaft energy" refers to mechanical energy in the form of rotary motion of a massive object, i.e. an object having a moment of inertia. For example, shaft energy may be generated even in the absence of a distinct unitary (or unitarily constructed) shaft.

[00355] **FIG. 16D** is an internal perspective view of the boundary-layer turbine **1230A**, with an outer housing removed to show a duct wall of a tube **302**, the header section **206** including header block **210** and header plate **208**, in accordance with an embodiment.

[00356] **FIG. 16E** is an internal side elevation view of the boundary-layer turbine **1230A** of **FIG. 16D**, in accordance with an embodiment.

[00357] **FIG. 16F** is an enlarged view of the internal side elevation view of the boundary-layer turbine **1230A** as shown in **FIG. 16E**, showing a

clearance **1608** between the header block **210** and a tube **302**, in accordance with an embodiment.

[00358] Working fluid may exit the header block **210**, part of the supporting structure **230**, via flow inlets **212** into ducts.

[00359] The header block **210** may be adjacent to a free end of the tube **302**. The free end of the tube **302** may be unattached to other components and may be free to rotate about the longitudinal axis **102**.

[00360] The header block **210** may be adapted to maintain the clearance **1608** between the free end of the tube **302** and the header block **210** to allow rotation of the tube **302** relative to the header block **210**. In various embodiments, the clearance may vary between 3 and 8 thousandths of an inch (3-8 thou).

[00361] As shown in **FIG. 16F**, in some embodiments, the respective faces of the header block **210** and the tube **302** defining (opposing ends of) the clearance may be substantially parallel to each other. In some embodiments, these faces substantially normal to the longitudinal axis. For example, simplified construction and advantageous fluid dynamical behaviour may thereby be achieved.

[00362] As discussed previously, in some embodiments, the faces of the clearance may be substantially parallel to the longitudinal axis in some embodiments and may comprise a face of a tongue and a face of a slot receiving the tongue.

[00363] In various embodiments, the clearance **1608** may be adapted to maintain a lubricating film of the fluid between the tube **302** and the header block **210**.

[00364] In various embodiments, the flow inlets **212** may be formed in the header block **210** at an end thereof adjacent to the free end of the tube **302**.

[00365] A plurality of the flow inlets **212** may be azimuthally inclined to inject fluid across the clearance **1608** into a duct defined by the plurality of tubes.

[00366] Injection of fluid into ducts across the clearance may mitigate or reduce transfer of fluid between concentrically adjacent ducts. For example, the formation of a fluid dynamical layer (such as a shear layer) may sustain an adverse pressure gradient that reduces cross-flow between ducts of the plurality of ducts via the clearance **1608**.

[00367] In various embodiments, the fasteners **1582** may be fastened through the plurality of ducts through vanes defined therein. The vanes, as seen in **FIGS. 16D-16E**, may have varying inclination along the tube. For example, vanes relatively proximal to the flow inlets may be oriented more in an azimuthal direction compared to vanes relatively distal therefrom.

[00368] The plurality of blades **222** may be formed on an end of the tube **302** opposite the free end. The end of the tube **302** may form a ridge **1610** or lip extending radially outwardly from the tube **302**. In some embodiments, the end of the tube **302** may incline radially inwardly away from the flow inlets **212**. In various embodiments, the radial inclination may be between 12°-18° or about 16°.

[00369] **FIG. 16G** is an enlarged perspective view of the header block **210** and the adjacent tube **302** of the boundary-layer turbine **1230A** of **FIG. 16D**, in accordance with an embodiment.

[00370] **FIG. 16H** is an internal perspective view of the header block **210** and the adjacent tube **302** of the boundary-layer turbine **1230A** of **FIG. 16D**, wherein an outer housing of the header block **210** is omitted to shown internal channels formed in the header block **210**, in accordance with an embodiment.

[00371] **FIG. 16I** is an internal side elevation view of the header block **210** and the adjacent tube **302** of the boundary-layer turbine **1230A** of **FIG. 16H**, in accordance with an embodiment.

[00372] The flow inlets **212** may be rectangular ports (or slots) that may be defined at ends of channels formed in the header block **210**. The channels may at least partially be defined by a housing thereof surrounding the header block **210**.

[00373] The channels may receive working fluid substantially parallel to the longitudinal axis and may reorient the fluid in an azimuthal direction. In some embodiments, the channels may be formed in-between elements rising out of the header block **210**. For example, such elements may be fitted on to the tube **302** or may be additively formed thereon. In some embodiments, the channels may be arcuately shaped in a flow direction (to achieve relatively smooth or gradual azimuthal reorientation of the fluid) and may be converging towards the outlet end (proximal to the flow inlets **212**) to form (partially) azimuthally inclined jets providing impulse to the tube **302** to cause rotation thereof to generate power.

[00374] In some embodiments, the flow inlets **212** into the ducts may be equi-spaced around the longitudinal axis. In some embodiments, the flow inlets **212** may be spaced apart along a circumference of the tube **302** to prevent interference or substantial cross-flow between jets issuing from adjacent flow inlets. In some embodiments, the flow inlets **212** may be spaced apart no more than such a distance. In various embodiments, the number, size, and flow characteristics associated with the flow inlets **212** may be varied to achieve a desired power output and torque generated by the boundary-layer turbine **1230A**.

[00375] In some embodiments, the flow inlets **212** may be formed in pairs. The total number of flow inlets **212** may be even. Each flow inlet may have an opposing flow inlet associated therewith formed antipodally across the tube **302** to improve a force balance in the boundary-layer turbine **1230**.

[00376] Embodiments of the header block **210**, as described above in references to **FIGS. 16A-16I**, may be part of various embodiments of the boundary-layer turbomachine **100**.

[00377] FIG. 17A is a schematic cross-section of a duct 1700 parallel to the longitudinal axis 102, in accordance with an embodiment.

[00378] The duct walls 220 may have a decreasing cross-sectional area in the longitudinal direction.

[00379] In some embodiments, the duct walls 220 may be converging longitudinally. In some embodiments, a radial separation 1702A between the duct walls 220 at a first longitudinal position 1704A may be different than a radial separation 1702B between the duct walls 220 at a second longitudinal position 1704B.

[00380] The first longitudinal position 1704A may be proximal to the inlet end 202 and distal from the outlet end 204 compared to, or relative to, the second longitudinal position 1704B.

[00381] FIG. 17B is a schematic radial cross-section of the duct 1700 at the first longitudinal position 1704A, in accordance with an embodiment.

[00382] FIG. 17C is a schematic radial cross-section of the duct 1700 at the second longitudinal position 1704B, in accordance with an embodiment.

[00383] A first radial cross-section 1706A of the duct 1700 is larger than a second radial cross-section 1706B of the duct 1700. The first radial cross-section 1706A is proximal to the inlet end 202 relative to the second radial cross-section 1706B.

[00384] FIG. 18 is a flowchart of an exemplary method 1800 of generating power using a working fluid configured to change phase for generating power.

[00385] Step 1802 of the method 1800 may include imparting heat to condensate to cause at least partial vaporization of the condensate to generate the working fluid.

[00386] Step 1804 of the method 1800 may include receiving the working fluid flowing at least partially azimuthally into a duct extending longitudinally between radially-separated duct walls.

[00387] **Step 1806** of the method **1800** may include driving rotatably a duct wall of the radially-separated duct walls via frictionally engaging the duct wall with the working fluid in the duct to exchange energy with the working fluid to cause condensation of the working fluid to generate the condensate.

[00388] Some embodiments of the method **1800** include receiving the working fluid on blades of a turbine rotor to drivably rotate the turbine rotor to generate shaft power, and wherein receiving the working fluid flowing at least partially azimuthally into a duct extending longitudinally between radially-separated duct walls includes receiving the working fluid flowing at least partially azimuthally from the turbine rotor.

[00389] Some embodiments of the method **1800** include driving an electric generator by rotatably driving the duct wall of the radially-separated duct walls; and cooling the electric generator using the condensate and/or the working fluid to preheat, respectively, the condensate and or the working fluid. For example, the working fluid may be multiphase.

[00390] In some embodiments of the method **1800**, imparting heat to the condensate to cause at least partial vaporization of the condensate to generate the working fluid includes using a heater configured to receive the condensate. Some embodiments of the method **1800** include driving an electric generator by rotatably driving the duct wall of the radially-separated duct walls; preheating the condensate in a heat exchanger using heat from the electric generator; and receiving the condensate into the heater via the heat exchanger.

[00391] In some embodiments of the method **1800**, the working fluid is imparted energy via compression to cause condensation to generate the condensate.

[00392] In some embodiments of the method **1800**, receiving the working fluid flowing at least partially azimuthally into a duct extending longitudinally between radially-separated duct walls includes receiving the working fluid flowing at an upstream end of the duct; and a first radial cross-section defined

between the radially-separated duct walls is larger than a second radial cross-section defined between the radially-separated duct walls, the first radial cross-section being proximal to the upstream end relative to the second radial cross-section.

[00393] In some embodiments of the method **1800**, a first radial separation between the radially-separated duct walls is larger than a second radial separation between the radially-separated duct walls, the first radial separation being proximal to the upstream end relative to the second radial separation.

[00394] **FIG. 19** is a schematic block diagram of a system **1900** for generating power, in accordance with an embodiment.

[00395] In various embodiments, the system **1900** may be similar to system **1300** in some respects. For example, the boundary-layer energy extraction subsystem **1204** includes a boundary-layer **1230** and an axial stage **224**.

[00396] In some embodiments, after the axial stage **224**, the working fluid may be drawn into a boundary-layer pump-turbine **1950** coupled to the axial stage **224**, which may be an embodiment of the boundary-layer turbomachine **100**. As referred to herein, a boundary-layer pump-turbine **1950** may be act as a boundary-layer compressor-turbine **1950**.

[00397] The boundary-layer pump-turbine **1950** may be configured to change a thermodynamic state of the working fluid. In particular, the boundary-layer pump-turbine **1950** may be configured to liquefy the working fluid, at least partially. Such liquefaction may be advantageous to leverage the heat of vaporization for energy from a heat source supplying the heat input **1210**. For example, extraction of heat from low-grade heat sources may be enabled. Advantageously, use of heat sink(s) such as condensers, which cause net loss of energy from the system **1900**, may be avoided.

[00398] The boundary-layer pump-turbine **1950** may include a plurality of duct walls defining ducts configured to receive the working fluid. The plurality of duct walls of the boundary-layer pump-turbine **1950** may be frictionally engaged with the working fluid and configured for drivable rotation about a longitudinal axis of the boundary-layer turbine **1950**. The plurality of duct walls may be configured to transfer energy (transmit power) to and/or from the working fluid flowing therein. As a result, the working fluid may be condensate to generate the condensate for the heater **1205**.

[00399] In some embodiments, the boundary-layer pump-turbine **1950** may act substantially as a pump to ensure appropriate pumping of fluid through the system **1900**. In some embodiments, the boundary-layer pump-turbine **1950** may compress the working fluid to cause phase change from vapor to liquid. For example, the boundary-layer pump-turbine **1950** may receive multi-phase (vapor and liquid) working fluid and may compress this working fluid to condense at least some of the vapor in the working fluid to generate condensate. In some cases, boundary-layer pump-turbine **1950** may substantially generate fully liquid working fluid.

[00400] In some embodiments, the boundary-layer turbine **1230** and the axial stage **224** may be part of, or may form, the boundary-layer energy extraction subsystem **1204**. Additional turbine stages may be provided, e.g. in the regeneration subsystem **1202**. In some embodiments, the axial stage **224** may be absent from the regeneration subsystem **1202**. In some embodiments, only boundary-layer turbomachines may be provided in the regeneration subsystem **1202**.

[00401] In some embodiments, the boundary-layer pump-turbine **1950** may act as a turbine to extract energy from the working fluid to further reduce the energy of the working fluid to generate condensate therefrom for re-use.

[00402] In some embodiments, the boundary-layer pump-turbine **1950** may be configured to operate flexibly as either a pump or turbine to generate the condensate.

[00403] In some embodiments, the cooled and condensed working fluid from the boundary-layer pump-turbine **1950** may be supplied to the electric generator **1270** for cooling of the electric generator **1270**, i.e. preheating of the condensate. The working fluid is then returned to the heater **1205** in the form of at least partial condensate. It is found advantageous to configure the system **1900** to generate substantially liquid working fluid for supplying to the heater **1205**.

[00404] The thermodynamic properties of the working fluid at positions A-19, B-19, and C-19 are listed below for an exemplary embodiment. In some embodiments, the working fluid may be ethane. In some embodiments, the working fluid may be carbon dioxide, propane, or propyne.

Position	Temperature (°F)	Pressure (psig)	Density (lbm/ft ³)	Vapor quality (lbm/lbm)
A-19	65.00	250	1.58	1.00
B-19	-23.71	150	1.23	0.94
C-19	12.17	250	1.95	1.00

Note: the quality is defined as the ratio of the mass of the vapor fraction of the working fluid to the total mass of the working fluid.

Multi-phase properties of the working fluid are listed below for an exemplary embodiment.

Position	Density (lbm/ft ³)		Enthalpy (BTU/lbm)	
	Liquid	Vapor	Liquid	Vapor
A-19	-	1.58	-	266.13
B-19	28.82	1.16	65.10	233.29
C-19	-	1.95	-	238.68

[00405] FIG. 20A is a perspective view of the system, in accordance with an embodiment.

[00406] FIG. 20B is a cross-sectional view of the system of FIG. 20A, in accordance with an embodiment.

[00407] FIG. 21A is an enlarged view of region 21A in FIG. 20B.

[00408] FIG. 21B is an enlarged view of region 21B in FIG. 20B.

[00409] The plurality of ducts of the boundary-layer turbine 1230 may be at least partially defined by corresponding duct walls. These duct walls may be configured for drivable rotation about the longitudinal axis 102 by the working fluid frictionally dragging them at least partially azimuthally around the longitudinal axis 102 to transfer energy from the working fluid flowing in the plurality of ducts.

[00410] The axial stage 224 may be sandwiched in-between the boundary-layer turbine 1230 and the boundary-layer pump-turbine 1950.

[00411] The boundary-layer pump-turbine 1950 may receive the working fluid, with reduced energy, from the axial stage 224 into a plurality of ducts at least partially defining the boundary-layer pump-turbine 1950. The plurality of ducts may be at least partially defined by corresponding second duct walls that are frictionally engaged with the working fluid and configured for drivable rotation about the longitudinal axis 102.

[00412] In various embodiments, the duct walls of the boundary-layer pump-turbine 1950 may be configured to transfer energy to, or from, the working fluid flowing in the plurality of ducts of the boundary-layer pump-turbine 1950 in order to at least partially condense the working fluid.

[00413] The axial stage 224 may be coupled to the two boundary-layer turbomachines at opposite ends of the axial stage 224 to axially space apart the boundary-layer turbine 1230 and the boundary-layer pump-turbine 1950.

[00414] In various embodiments, the boundary-layer turbine 1230, the axial stage 224, and the boundary-layer pump-turbine 1950 (and, in some

embodiments, the electric generator **1270**) may be integrally formed for common rotation. For example, in some embodiments, the components may be attached or integrally coupled to one another via threadable connections without intermediate shaft bodies or gearing and, thus, a “shaft” may be formed only after integrating the separate components together.

[00415] The electric generator **1270** may be coupled to the axial stage **224** and the boundary-layer turbine **1230** via coupling with the boundary-layer pump-turbine **1950** to generate electricity, which is output from the electric generator **1270** via electrical cables **1550**.

[00416] After forming condensate in the boundary-layer pump-turbine **1950**, cold working fluid is drawn into and/or around the electric generator **1270** via a generator inlet **1520**.

[00417] Advantageously, heat generated by the electric generator **1270** may be absorbed by the working fluid to simultaneously mitigate heat-associated degradation (e.g. via heat buildup) in the electric generator **1270** and to preheat the working fluid to reduce heat loss from the system **1200**.

[00418] After preheating by receiving heat from the electric generator **1270**, the working fluid is drawn out via an outlet duct **1530** back to the heat exchanger **1220** of the heater **1205**.

[00419] In various embodiments, the boundary-layer turbine **1230**, and/or ducts thereof, may have substantially similar inner and outer diameters to, respectively the boundary-layer pump-turbine **1950**, and/or ducts thereof. In some embodiments, the number of ducts of the boundary-layer turbine **1230** and the boundary-layer pump-turbine **1950** may be substantially similar.

[00420] In various embodiments, the plurality of ducts of the boundary-layer turbine **1230** may be substantially axially shorter than the plurality of boundary-layer pump-turbine **1950**.

[00421] In various embodiments, the boundary-layer pump-turbine **1950** may comprise ducts with protrusions or features extending therein to guide the fluid helically around an outlet end of the ducts.

[00422] In reference to **FIG. 21B**, a duct of the boundary-layer pump-turbine **1950** may comprise duct walls **220A**, **220B**, **220C**, **220D**, **220E**, **220F** that may be elongated along the longitudinal axis **102** and that may be circumferentially surrounding the longitudinal axis. In some embodiments, these may be cylindrically-shaped around the longitudinal axis **102**.

[00423] In various embodiments, protrusions **2110** from the duct walls **220A**, **220C**, **220E** may radially extend to respective opposed duct walls **220B**, **220D**, **220F**. In some embodiments, the protrusions **2110** may spirally extend at least partially along the longitudinal axis **102** to draw the working fluid along the respective ducts. For example, the protrusions **2110** may be additively manufactured.

[00424] The axial stage **224** may be diverging along the longitudinal axis **102**.

[00425] **FIG. 22A** is a perspective view of a boundary-layer pump-turbine **1950**, in accordance with an embodiment.

[00426] **FIG. 22B** is a cross-sectional view of the boundary-layer pump-turbine **1950** normal to the longitudinal axis **102**, in accordance with an embodiment.

[00427] **FIG. 22C** is an enlarged view of region **22C** in **FIG. 22B**.

[00428] In some cases, the boundary-layer pump-turbine **1950** may be an embodiment of the boundary-layer turbomachine **100**.

[00429] Several bodies **2210** (a plurality thereof) of the boundary-layer pump-turbine **1950** may be elongated along the longitudinal axis **102** and may be rotatable thereabout.

[00430] The bodies **2210** may be arranged at least partially concentrically with each other around the longitudinal axis **102**. The bodies **2210** may be

elongated at least partially concentrically with each other along the longitudinal axis **102**. The bodies **2210** may be coupled for common rotation with each other. A body **2210** may be arranged at least partially within another body **2210** to define a duct **214** extending longitudinally therebetween.

[00431] The bodies **2210** may be substantially hollow to allow a co-axial arrangement thereof. In various embodiments, the bodies **2210** may be axis-symmetric or substantially axis-symmetric about the longitudinal axis **102**. For example, the bodies **2210** may be continuously symmetric about the longitudinal axis **102**, such as if the bodies were bodies of revolution, or may define a discrete n-fold symmetry about the longitudinal axis **102**. In some embodiments, the bodies **2210** may be cylindrically-shaped or frusto-conically shaped (or otherwise radially tapered along the longitudinal axis **102**). In some embodiments, the bodies **2210** may be substantially similar to the tubes **302**.

[00432] In some embodiments, working fluid flowing through the boundary-layer pump-turbine **1950** may change density, e.g. the working fluid may change phase, partially or completely. In various embodiments, the shape(s) of the bodies **2210** may be adapted to accommodate the changing density of the working fluid, such as by varying a cross-sectional area of ducts **214** along the longitudinal axis **102**. For example, a frusto-conical shape may be adapted to facilitate efficient operation when the working fluid changes phase from vapor to liquid, partially or completely. In particular, a reduction in cross-sectional area may mitigate formation of empty pockets and facilitate adhesion contact between the working fluid and duct walls to allow rotational driving via rotation of the bodies **2210**. In some embodiments, the shape(s) of the bodies **2210** may be adapted to promote compression and/or pumping of working fluid.

[00433] One or more protrusions on a body **2210** may extend longitudinally at least partially along the duct and radially towards another body **2210** in the duct **214** to define at least one channel in the duct.

[00434] In some embodiments, the one or more protrusions **2110** on the body **2210** may extend to the body **2210** in the duct **214**.

[00435] In some embodiments, the protrusions **2110** may spirally extend along and around the longitudinal axis **102** in the duct **214** to draw working fluid along the duct **214** and/or induct fluid into the duct **214**. In some embodiments, the protrusions **2110** may be configured similar to inducer blades.

[00436] In some embodiments, the channel may be a spiral channel (or spiralling channels), such as spiral channels **2312A**, **2312B**, **2312C**. The channel may be configured to receive and draw the fluid from a flow inlet **212** into the duct **214**.

[00437] The flow inlet **212** may be configured to receive working fluid at least partially azimuthally around the longitudinal axis **102** into the duct **214** in accordance with the common rotation of the bodies **2210**. For example, the azimuthal component of the velocity of the fluid in the duct **214** may be generally in alignment with an azimuthal component of the velocity of a surface of wall of the bodies **2210**.

[00438] The working fluid in the duct **214** may be frictionally engaged with the bodies **2210** to transfer mechanical energy to, or from, the fluid.

[00439] In some embodiments, the flow inlet **212** may be configured to supply working fluid into the duct **214** to frictionally drive the bodies **2210** to achieve common rotation thereof. This common rotation may be in alignment with the azimuthal component of the velocity of the walls of the duct **214** defined by the bodies with the azimuthal component of the velocity of the fluid therein.

[00440] In some embodiments, the flow inlet **212** may be configured to draw working fluid into the duct **214** via frictional engagement with rotating bodies **2210** by imparting an azimuthal component of velocity. This velocity may be in alignment with the azimuthal component of the velocity of the walls

of the duct **214** defined by the bodies with the azimuthal component of the velocity of the fluid therein.

[00441] In some embodiments, the flow inlet **212** may be an (at least partially azimuthally inclined) nozzle or slot.

[00442] The bodies **2210** may be circumferentially surrounded by a housing **2212** that is coupled to the bodies **2210** for common rotation with the bodies **2210** around the longitudinal axis. The housing **2212** may be constructed substantially similarly to a body **2210**. The housing **2212** may be elongated along the longitudinal axis **102** and may circumferentially surround the longitudinal axis **102**.

[00443] The one or more protrusions **2110** may extend fully from one body **2210** to the next concentric body **2210** (or the housing **2212**). For example, tip clearances between the protrusion **2110** and a body **2210** may be substantially zero to prevent any flow from passing across the protrusion **2110**.

[00444] **FIG. 23** is a side elevation view of the boundary-layer pump-turbine **1950** of **FIGS. 22A-22C** with the housing **2212** not shown, in accordance with an embodiment.

[00445] The view shows a body **2210** with protrusions **2110** extending therefrom. The protrusions **2110** may extend radially from the body **2210** to another surrounding body to define a duct **214** therebetween. In various embodiments, the protrusions **2110** may fill a radial extent between two concentrically arranged adjacent bodies **2210** to mitigate or completely stop flow normal to the protrusion, at the protrusion itself, along the body **2210**.

[00446] The body **2210** has a first portion **2310A**, a second portion **2310B**, and a third portion **2310C**. Each portion may have a different type of protrusion extending therefrom.

[00447] In the first portion **2310A** and the second portion **2310C**, the body **2210** may have protrusions **2110** that may spirally extend at least partially

along and around the longitudinal axis **102** to induct working fluid into the duct **214** and/or draw working fluid along the duct **214**.

[00448] In some embodiments, the protrusions **2110** may define the spiral channels **2312A**, **2312B**, **2312C** (or spiralling channels) along the longitudinal axis **102** in the duct **214**. The protrusions **2110** may define walls of the spiral channels **2312A**, **2312B**, **2312C**. For example, three substantially continuous helical protrusions adjacent to each other helically extend along the longitudinal axis **102** to define three adjacent helical channels. Inlets of the spiral channel **2312A**, **2312B**, **2312C** may be azimuthally oriented to receive the fluid supplied by flow inlets **212**.

[00449] In some embodiments, the spiral channels **2312A**, **2312B**, **2312C** may have fixed pitch and/or variable pitch.

[00450] In the second portion **2310B**, the body **2210** may have a plurality of blades **222**, which may also be referred to herein as protrusions. The plurality of blades **222** may be disposed in the duct **214** downstream of the protrusions **2110** of the first portion **2310A**. The plurality of blades **222** may be configured to reorient flow received between the plurality of blades **222** from a first direction **2315** having a first azimuthal component **2314** to a second direction **2317** having a second azimuthal component **2316**. The first azimuthal component **2314** may be opposed to the second azimuthal component **2316**.

[00451] In some embodiments, the plurality of blades **222** may facilitate energy extraction from the working fluid.

[00452] In various embodiments, reorientation of the working fluid to reverse the azimuthal component of the working fluid may cause or facilitate pumping or compression of the fluid in the third portion **2310C**.

[00453] In the third portion **2310C**, the body **2210** may include spiralling protrusions **2110**. The protrusions **2110** may define spiral channels, e.g. helical channels, as in the first portion **2310A**. In some embodiments, the pitch of the protrusion **2110** in the third portion **2310C** may be different than the pitch of

the protrusion **2110** in the first portion **2310A**. In some embodiments, the pitch may be larger in the third portion **2310C** than in the first portion **2310A**.

[00454] In some embodiments, the chirality (or handedness) of a helix or spiral defined by the protrusions **2110** may vary from the first portion **2310A** to the third portion **2310C**. In some embodiments, reorientation of the flow from the first direction **2315** to the second direction **2317** in the second portion **2310B** may be configured to adapt a direction of the working fluid to an angle or chirality of the helix or spiral (or a channel defined thereby) in the third portion **2310C**. In some embodiments, the protrusions **2110** in the third portion **2310C** may be adapted to the direction **2317** to allow receiving of the working fluid therefrom.

[00455] In various embodiments, the first portion **2310A** may be configured draw energy from the working fluid. The third portion **2310C** may be configured to compress or pump the working fluid, including by inducing fluid along the duct **214** via the protrusions **2110**. In both the first portion **2310A** and the third portion **2310C**, duct walls of the duct **214** may be in common rotation to achieve frictional engagement with the working fluid (via frictional drag) to transfer energy to, and/or from, the working fluid. Advantageously, allow common rotation of duct walls may facilitate energy transfer to and/or from the fluid via frictional drag.

[00456] In various embodiments, a turbomachine hub of unitary construction (the body **2210**) may be used to achieve energy extraction and energy injection in sequence.

[00457] **FIG. 24** is an exploded view of bodies **2210** of a boundary-layer pump-turbine **1950**, in accordance with an embodiment.

[00458] The bodies **2210** may be concentrically arranged inside or within each other along the longitudinal axis **102** to define ducts **214** therebetween. In some embodiments, the bodies **2210** may be generally cylindrical with protrusions **2110** extending therefrom. In some embodiments, the protrusions **2110** on the bodies **2210** may be substantially the same. The housing **2212**

may envelope the plurality the bodies **2210**. In various embodiments, the housing **2212** and the bodies **2210** may be fastened together for rotation about the longitudinal axis **102**.

[00459] FIG. **25A** is a perspective view of a body **2210** of the boundary-layer pump turbine **1950** of FIG. **24**.

[00460] FIG. **25B** is a side elevation view of the body **2210** in FIG. **25A**.

[00461] Large white arrows in FIG. **25B** schematically represent flow through the boundary-layer pump-turbine **1950**.

[00462] In reference to FIGS. **25A-25B**, the body **2210** comprises two portions (see braces in FIG. **25B**). In some embodiments, a first portion may be configured to extract energy from the fluid and a second fluid may be configured to inject energy into the fluid to pump or compress the fluid.

[00463] In some embodiments, an azimuthal direction of the fluid around the longitudinal axis **102** may reverse from the first portion to the second portion.

[00464] Each portion has a spiralling or helical protrusion extending radially outwardly. Each spiral may have a pitch **2502** defined by a longitudinal distance between consecutive peaks of the spiral or helix, a radial depth **2504** defined by the radial extension of the protrusion **2110**, and an angle **2506** defined by the slant of the spiral relative to the longitudinal axis **102**. In various embodiments, the pitch **2502** may be configured to draw the fluid at least partially through the duct **214**.

[00465] In various embodiments, the pitch **2502** may be adapted to or may be configured to control a dwell time or flow-through distance of the fluid in the duct **214**. For example, reducing the pitch **2502** may increase the flow-through distance of the fluid in the duct **214** to thereby increase (a duration or length of) frictional contact of the working fluid with one or both walls of the duct, as may be defined by the bodies **2210** and/or the housing **2212**.

Increasing frictional contact may allow higher or more efficient energy extraction from the fluid.

[00466] In some embodiments, the pitch **2502** may be adapted to prevent reverse flow in the longitudinal direction (longitudinal flow reversal). For example, excessive flow resistance (such as via an adverse pressure gradient) may result if the pitch **2502** is excessively small and/or the protrusion **2110** concerned is configured to induce reorientation of a (azimuthal) direction of the fluid. In various embodiments, the pitch **2502** may be widened to reduce flow resistance.

[00467] In some embodiments, the pitch **2502** may be adapted to mitigate an adverse pressure gradient preventing the fluid from being drawn out of the duct **214** via the outlet end **204**.

[00468] In some embodiments, the pitch **2502** may vary from the first portion to the second portion. The pitch **2502** in the first portion may be relatively smaller than the pitch **2502** in the second portion, e.g. for one or more reasons described above.

[00469] In some embodiments, the protrusion **2110**, or a direction of elongation thereof, may be relatively more aligned with the azimuthal direction around the longitudinal axis **102** and/or have a relatively smaller pitch **2502** at an upstream position in the duct **214** compared to a downstream position therein. At downstream positions, a direction of elongation of the protrusion **2110** may be more misaligned with the azimuthal direction and/or the pitch **2502** may be larger. For example, in some cases, such a configuration may prevent stalling of a turbine and pumping of the fluid in the duct **214**.

[00470] In some embodiments, the pitch **2502** may be decreased and the protrusion more aligned (or completely) aligned with the azimuthal direction to achieve pumping of fluid in the duct **214**.

[00471] The radial depth **2504** may be adapted to a height of a duct **214** to prevent flow across the protrusion **2110**, e.g. over the protrusion **2110**.

Avoiding formation of gaps between the protrusion **2110** and an outer body or housing may prevent formation of small gaps which may lead to structural failure and/or fatigue. For example, rapid acceleration in a narrow gap can cause phase change, and in some cases, generation of high-speed high-density fluid which may ballistically impact surfaces of turbomachinery components.

[00472] In some embodiments, the radial depth **2504** may vary along the longitudinal axis **102**, e.g. to account for changes in duct height due to changes in density of the working fluid. In some embodiments a radial depth **2504** may be larger or smaller than a duct height to account for temperature expansion and/or to allow frictional engagement between bodies **2210** via the protrusions **2110**.

[00473] The angle **2506** may vary from the first portion to the second portion. In some embodiments, the angle **2506** may be between 4° and 4.5° in the first portion and may be between -5° and -5.5° in the second portion. The angle **2506** may be varied to achieve or induce a change in the azimuthal component of the flow direction or may be adapted to a predetermined azimuthal component of the flow direction.

[00474] In various embodiments, the protrusions **2110** may protrude from a surface of the duct wall in a shape having a triangular cross-section (normal to the longitudinal axis **102**) in the first portion (see region A in **FIG. 25B**) and a rectangular cross-section (normal to the longitudinal axis **102**) in the second portion (see region B in **FIG. 25B**). In some embodiments, profiles of the protrusions **2110** may be based on turbomachinery blades, such as inducer blades.

[00475] In various embodiments, the bodies **2210** and the housing **2212** may be coupled for common rotation via one or more fasteners **1582**.

[00476] As shown in **FIG. 25B**, the fasteners **1582** may be adapted to the flow direction, e.g. substantially oriented along a general flow direction. For examples, the fasteners **1582** may be adapted to facilitate laminar flow and

reduce interference. In some embodiments, the protrusion **2110** or a width thereof may be adapted to allow fastening via the fastener **1582**. For example, in some embodiments, a width of the protrusion **2110** may be at least as large as an elongated fastener or a through hole configured to complementarily receive the elongated fastener. Such an elongated fastener may pass through all of, or a plurality, of the bodies **2210** (and/or housing **2212**) to couple the respective bodies **2210** (and/or housing **2212**) to each other for common rotation. In some embodiments, the fasteners **1582** may be threadable fasteners. In some embodiments, the fastener may be a bolt configured to couple to a nut. In various embodiments, the fastener **1582** may be integrally coupled to the bodies **2210** to act as a rigid body.

[00477] In some embodiments, the bodies **2210** may be in unitary construction or otherwise integrally formed. For example, the bodies **2210** may be additively manufactured. In some embodiments, the fasteners **1582** may be pillars or coupling structures for coupling a plurality of bodies **2210** to each other. For example, such pillars may be additively grown from one body **2210** to the another, solid-state welded to couple two or more bodies **2210** to each other, and/or formed by selectively machining (subtractively manufactured) out the duct **214** from a solid structure.

[00478] **FIG. 26** is a side elevation view of a body **2210**, in accordance with another embodiment.

[00479] The pitch **2502** of the protrusion **2110** in **FIG. 26** may vary along the longitudinal axis **102**. For example, the pitch **2502** may gradually or continuously decrease.

[00480] The protrusion **2110** may define a single channel **2312** continuously spiralling around the body **2210**.

[00481] In some embodiments, energy extraction may be decreased as the pitch **2502** is reduced and energy injection (pumping or compression) may correspondingly increase.

[00482] In some embodiments, the pitch **2502** may be varied to account for a change in density of the working fluid. Reducing the pitch **2502** may correspondingly reduce how much space a fluid has available to flow through by reducing a width of the channel **2312** in the longitudinal direction. This space may be adapted to the volume reduction in working fluids due to density change as they flow through the duct **214**. In some embodiments, considerable volume change may occur due to phase change.

[00483] In various embodiments, the surface of the duct walls may be varied to control the amount for frictional drag exerted on the fluid. Varying the frictional drag may vary the energy extracted from, or injected into, the fluid. For example, methods of drag reduction and/or drag enhancement may be employed.

[00484] In some embodiments, a boundary-layer adjacent to a duct wall may be tripped using a tripping device or features to modify turbulent characteristics of the flow to vary the frictional drag.

[00485] In some embodiments, surface roughness and/or chemistry may be varied to achieve desired drag and/or slippage, e.g. surface roughness and/or chemistry may be adapted based on a predetermined target friction.

[00486] In some embodiments, one surface may have a different surface roughness than an opposed surface in the same duct **214**, e.g. the surface roughness may be varied based on a density of working fluid near the surface wall. This density may vary radially from one surface to the next surface, including due to centrifugal forces drawing heavier fluid radially outward in the duct. In some embodiments, fluid near the radially outer surface of a duct **214** may have a larger mass fraction or proportion of liquid phase than fluid near the radially inner surface of a duct. In some embodiments, the surface roughness on the radially outward surface may be greater, or in some cases lesser, than surface roughness on a radially inner surface to extract more work from the heavier fluid.

[00487] In some embodiments, the surfaces of duct walls may be smoothened to reduce friction to reduce azimuthal flow, e.g. to allow greater compression (by restricting volume) and/or flow straightening by the vanes or the plurality of blades **222**.

[00488] In some embodiments, duct walls may be partially sheathed with a material, such as vulcanized rubber, with desired frictional and chemical properties to vary adhesion of the fluid to the surface. For example, a tubular section **2610** of material may be used. In some embodiments, coatings may be chemically bonded to duct walls. In some embodiments, such sheathing may be upstream or downstream of a plurality of blades **222**. In some embodiments, such sheathing may be provided on a body **2210** devoid of protrusions or devoid of protrusions other than the plurality of blades **222**.

[00489] **FIG. 27** is a side elevation view of a body **2210**, in accordance with yet another embodiment.

[00490] The body **2210** may comprise a helical protrusion **2110** radially extending from the body **2210** to form a protrusion defining a triangular cross-section. The helical protrusion **2110** may have a constant pitch **2502**.

[00491] In some embodiments, the protrusions **2110**, the duct walls **220**, and the housing **2212** in common rotation may allow admit advantages associated with bladed turbomachines and adhesion-based turbines. For example, in various embodiments, multiphase operation and efficient compression/pumping may be achieved.

[00492] Common rotation of the protrusions **2110**, the duct walls **220**, and the housing **2212** may establish at least partially azimuthal flow of the working fluid through ducts **214** defined between co-rotating frictional surfaces defined by the duct walls **220**. In some embodiments, a turbomachine may have only a single duct **214** defined between co-rotating frictional surfaces. Co-rotation of the frictional surfaces may allow contact of the protrusions **2110** with both frictional surfaces defining the duct without seizing of turbomachinery. Co-rotation of the frictional surfaces may allow frictionally dragging of the working

fluid by the frictional surfaces or the frictional surfaces by the working fluid, depending on the relative azimuthal or angular velocity between the frictional surfaces configured for common rotation and the working fluid, i.e. the difference between the azimuthal component of the working fluid and the azimuthal velocity of the frictional surfaces. Due to differences in radial distances from the longitudinal axis **102** of different (adjacent) duct walls **220**, the azimuthal velocities of adjacent frictional surfaces may be different. In various embodiments, the azimuthal velocities of adjacent frictional surfaces defined by duct walls **220** of a duct **214** may both be greater than the azimuthal component of the working fluid (such as for energy injection into the working fluid for pumping and/or compression), or less than the same (such as for energy extraction from the working fluid for power generation). In some embodiments, energy extraction and energy injection may be provided in a single duct by varying the geometry of the duct **214** using the duct walls **220** and the protrusions **2110** to achieve desired working fluid velocities.

[00493] Some embodiments of turbomachines may include concentrically arranged elongated inducer hubs having blades extending outwardly from the hubs and having a housing surrounding the hubs, wherein the blades of the inducer are in contact with the housing to prevent flow across the blades, and the hubs and the housing are coupled together for common rotation, e.g. by being fastened to each other.

[00494] **FIG. 28** is a side elevation view of the body **2210**, in accordance with a further embodiment.

[00495] The embodiment of **FIG. 28** includes protrusions **2110A**, **2110B**, **2110C**, **2110D** that are configured to extend longitudinally at least partially along the duct **214** and radially in the duct **214** to define channels **2313A**, **2313B**, **2313C** in the duct **214**.

[00496] The protrusion **2110A** may be separate from the protrusions **2110B**, **2110C** and the protrusion **2110B** may be separate from the protrusion **2110C**.

[00497] The channels **2313A**, **2313B**, **2313C** may be defined between, respectively, the protrusion **2110A** and the protrusion **2110B**, the protrusion **2110B** and the protrusion **2110C**, and the protrusion **2110C** and the protrusion **2110D**.

[00498] The channels **2313A**, **2313B**, **2313C** may be configured to receive and draw the fluid from the flow inlets **212** into the duct **214**.

[00499] The protrusions **2110A**, **2110B**, **2110C**, **2110D** may be at least partially azimuthally oriented to receive the fluid supplied by the one or more flow inlets **212** into the channels **2313A**, **2313B**, **2313C**.

[00500] In some embodiments, the protrusions **2110A**, **2110B**, **2110C**, **2110D** may extend radially from a first body **2210** and a second body **2210** defining the duct **214**.

[00501] The bodies **2210** defining the duct **214** may be drivably rotatable to draw the fluid through the turbomachine to achieve pumping of the fluid. The protrusions **2110A**, **2110B**, **2110C**, **2110D** may allow operation of boundary-layer turbomachines for at least partial pumping of fluids as they may prevent premature orientation of the fluid velocity parallel to the longitudinal axis. Flow reversal and stalling may be prevented.

[00502] **FIG. 29** is a flowchart of an exemplary method **2900** of generating power using a working fluid configured to change phase, at least partially, for generating power.

[00503] At step **2902**, the method **2900** may include imparting heat to condensate to cause at least partial vaporization of the condensate to generate the working fluid.

[00504] At step **2904**, the method **2900** may include receiving the working fluid on blades of a turbine rotor to drivably rotate the turbine rotor to generate shaft power.

[00505] At step **2906**, the method **2900** may include receiving the working fluid flowing at least partially azimuthally from the turbine rotor into a duct

defined between a first duct wall and a second duct wall. The first duct wall and second duct wall may circumferentially extend around the longitudinal axis and may be elongated along the longitudinal axis. The first duct wall may be radially-separated from the second duct wall.

[00506] At step **2908**, the method **2900** may include driving rotatably the first duct wall and the second duct wall via frictionally engaging the first duct wall and the second duct wall with the working fluid in the duct to exchange energy with the working fluid to cause condensation of the working fluid to generate the condensate.

[00507] Some embodiments of the method **2900** may further comprise using the shaft power to drive an electric generator, cooling the electric generator using the condensate to preheat the condensate, preheating the condensate in a heat exchanger using heat from the electric generator, and/or receiving the condensate into the heater via the heat exchanger.

[00508] In some embodiments of the method **2900**, a protrusion from the first duct wall may radially extend to the second duct wall and spirally extend at least partially along the longitudinal axis to draw the working fluid along the duct.

[00509] In some embodiments of the method **2900**, imparting heat to the condensate to cause at least partial vaporization of the condensate to generate the working fluid may include using a heater configured to receive the condensate.

[00510] In some embodiments of the method **2900**, the working fluid may be imparted energy via compression to cause condensation to generate the condensate.

[00511] **FIG. 30** is a schematic block diagram of a system **3000** for generating power using a first fluid and a second fluid fluidly isolated from each other.

[00512] The first fluid may flow through positions E-30 through H-30, while the second fluid may flow through positions A-30 through D-30.

[00513] In some embodiments, it is found particularly advantageous to use ammonia as the first fluid and carbon dioxide as the second fluid due to their specific properties.

[00514] A heater **1205** may be configured to transfer heat to the first fluid to at least partially vaporize the first fluid. The heater **1205** may be provided heat input **1210**, e.g. through combustion of renewable natural gas or from low-grade heat sources such as sea-water. The heat input **1210** may be transferred to the first fluid via a heat exchanger **1220A** of the heater **1205**.

[00515] A heat exchanger **1220C** may be fluidly connected (directly or indirectly) to the heater **1205** to receive the first fluid from the heater **1205**. The heat exchanger **1220C** may be configured to transfer heat from the first fluid to the second fluid to at least partially vaporize the second fluid.

[00516] An expander **3010** may be fluidly connected to the heat exchanger **1220C** to receive the second fluid from the heat exchanger **1220C**. The expander **3010** may be configured to rotatably drive a rotor of the expander **3010**, such as a rotor of the plurality of rotors **300**, using the second fluid. Thus, the expander **3010** may be configured to generate power. In various embodiments, the expander **3010** may be an axial turbine, a radial turbine, and/or other type of expander.

[00517] In some embodiments, the expander **3010** may be a boundary-layer turbine **1230**. The plurality of ducts **214** may be configured to receive the second fluid from the heater **1205**, which may frictionally drag the plurality of duct walls at least partially azimuthally around the longitudinal axis **102** of the boundary-layer turbine **1230**. The plurality of duct walls may be configured to transfer energy from the fluid flowing in the plurality of ducts **214**.

[00518] Another heat exchanger **1220B** may be fluidly connected to the expander **3010** to receive the second fluid therefrom. The heat exchanger

1220B may be fluidly connected to the heat exchanger **1220C** to receive the first fluid therefrom. The heat exchanger **1220B** may be configured to generate condensate of the second fluid by transferring heat from the second fluid to the first fluid. Preheating of the first fluid may be achieved via the heat exchanger **1220B**.

[00519] In various embodiments, the first fluid, which may be ammonia, is cooled in the heat exchanger **1220C** by between 200 °C and 250 °C, or between 300 °C and 400 °C, and heated in the second heat exchanger **1220B** by between 60 °C and 80 °C, or between 50 °C and 100 °C.

[00520] A liquid pump **1224** (or pump) may be fluidly connected to the heat exchangers **1220B**, **1220C**. The liquid pump **1224** may be configured to draw the condensate of the second fluid from the heat exchanger **1220C** into the heat exchanger **1220B** for vaporization of the second fluid.

[00521] The liquid pump **1224** may be configured to pump liquids. The heat exchanger **1220C** may ensure that the second fluid is substantially in liquid form for pumping in the liquid pump **1224**. At least a portion of the energy removed from the second fluid may be returned thereto via the heat exchanger **1220B**. The heat exchanger **1220B** may provide at least partial re-vaporization of the second fluid after pumping in the liquid pump **1224**.

[00522] The liquid pump **1224** may be drivably coupled to the expander **3010** for driving the liquid pump **1224**. The liquid pump **1224** may be mechanically coupled to a drive shaft of the expander **3010**.

[00523] A compressor **1222** may be fluidly connected to the heat exchangers **1220B**, **1220C**. The compressor **1222** may be configured to receive the first fluid from heat exchanger **1220C** and to draw the first fluid from the heat exchanger **1220B** to the second heat exchanger **1220C**.

[00524] The compressor **1222** may be drivably coupled to the expander **3010**. The compressor **1222** may be mechanically coupled to a drive shaft of the expander **3010**. In some embodiments, directly coupling the compressor

1222 to the expander **3010** may provide certain advantages, e.g. increased efficiency.

[00525] The heat exchangers **1220B**, **1220C** may be configured to prevent interaction of the first fluid with the second fluid. For example, the heat exchangers **1220B**, **1220C** may include counter-flow or co-flow heat exchangers, such as shell-and-tube heat exchangers.

[00526] The rotor may drive an electric generator **1270** to generate electricity. In some embodiments, a heat exchanger of the electric generator **1270** may be configured to receive the second fluid from the expander **3010** to draw heat away from the electric generator **1270**.

[00527] In some embodiments, the heat exchanger **1220B** may be configured to transfer heat from the first fluid to the second fluid to substantially completely vaporize the second fluid.

[00528] In some embodiments, the heat exchanger **1220A** of the heater **1205** may be configured to receive a third fluid to transfer heat from the third fluid to the first fluid. For example, in some embodiments, the third fluid may be water or steam. In some embodiments, the third fluid may be a waste gas stream, e.g. flue gases from industrial processes. In various embodiments, the third fluid may be a liquid, gas, supercritical fluid, or other type of fluid.

[00529] In some embodiments, heat input may be provided to the system **3000** by conductive heat transfer, radiative heat transfer, or other type of transfer. For example, solar energy may be provided to directly heat the first fluid and/or heat water to transfer heat to the first fluid.

[00530] In some embodiments, a valve **3012**, such as a pressure release valve or pressure control valve, may be disposed between the heat exchangers **1220B**, **1220C** to control a pressure of the first fluid flowing from the heat exchanger **1220B** to the heat exchanger **1220C**. For example, controlling the pressure of the first fluid may include depressurizing the fluid.

[00531] In some embodiments, the (pressure release or pressure control) valve **3012** may be configured to control the pressure of the first fluid to achieve substantially complete vaporization of the first fluid in the heat exchanger **1220C** to operate the compressor **1222** in a substantially single phase condition. For example, depressurizing the first fluid may prevent or mitigate liquefaction and/or maintaining the fluid in a liquified state.

[00532] In some embodiments, the compressor **1222** and the liquid pump **1224** are drivably connected to the expander **3010** via a common drive shaft.

[00533] In some embodiments, the electric generator **1270**, the expander **3010**, the liquid pump **1224**, and the compressor **1222** may be mechanically coupled to each other. In some embodiments, the mechanical coupling may be a common shaft. In some embodiments, one or more of the electric generator **1270**, the expander **3010**, the liquid pump **1224**, or the compressor **1222** may be supported on the common shaft by bearings.

[00534] For an exemplary embodiment, where the first fluid is ammonia and the second fluid is carbon dioxide, the thermodynamic properties of the second fluid at positions A-30, B-30, C-30, and D-30 are listed in Table 8 and the thermodynamic properties of the first fluid at positions E-30, F-30, G-30, and H-30 are listed in Table 9.

TABLE 8

Position	Temperature (°F)	Pressure (psig)	Density (lbm/ft ³)	Vapor quality (lbm/lbm)
A-30	370.00	1500	8.22	1.00
B-30	-14.12	95	0.93	(Superheated)
C-30	-60.73	95	72.43	(Subcooled)
D-30	-57.00	1500	73.27	(Subcooled)

[00535]

TABLE 9

Position	Temperature (°F)	Pressure (psig)	Density (lbm/ft ³)	Vapor quality (lbm/lbm)
E-30	378.75	27	0.05	(Superheated)
F-30	-10.00	27	41.77	(Subcooled)
G-30	-69.49	4	0.16	0.10
H-30	60.00	4	0.012	(Superheated)

[00536]

[00537] For an exemplary embodiment, where the first fluid is ammonia and the second fluid is carbon dioxide, multiphase properties of the second fluid at positions A-30, B-30, C-30, and D-30 are listed in Table 10 and the multiphase properties of the first fluid at positions E-30, F-30, G-30, and H-30 are listed in Table 11.

TABLE 10

Position	Density (lbm/ft ³)		Enthalpy (BTU/lbm)	
	Liquid	Vapor	Liquid	Vapor
A-30	-	8.22	-	265.26
B-30	-	0.93 (Superheated)	-	196.00 (Superheated)
C-30	72.43 (Subcooled)	-	38.70 (Subcooled)	-
D-30	73.27 (Subcooled)	-	41.56 (Subcooled)	-

TABLE 11

Position	Density		Enthalpy	
	(lbm/ft ³)		(BTU/lbm)	
	Liquid	Vapor	Liquid	Vapor
E-30	-	0.05 (Superheated)	-	890.75 (Superheated)
F-30	41.77 (Subcooled)	-	102.92 (Subcooled)	-
G-30	44.27	0.016	39.727	656.88
H-30	-	0.012 (Superheated)	-	721.43 (Superheated)

In various embodiments, such a system may generate approximately 500-600 kW. The mass flow rate of the fluid (the second fluid) entering the expander **3010** may be approximately 40,000 lbs/hr. In some embodiments, wherein the first fluid is ammonia, the mass flow rate of the fluid through the heat exchangers 1220B, 1220C may be substantially less, e.g. 11,000 lbs/hr or less. Low pressures and temperatures may allow more reliable operation and reduce capital costs and maintenance of structures of the system **3000**.

[00538] FIG. 31 is a perspective view of a system **3100** using boundary-layer turbomachines **100A**, **100B**, in accordance with an embodiment.

[00539] FIG. 32A is a cross-sectional view of the system **3100** of FIG. 31, in accordance with an embodiment.

[00540] FIG. 32B is an enlarged view of region **32B** in FIG. 32A, in accordance with an embodiment.

[00541] The boundary-layer turbomachines **100A**, **100B** may include a plurality of bodies **2210**, each of which is elongated along the longitudinal axis **102** and rotatable thereabout. The plurality of bodies **2210** may include bodies **2210A**, **2210B**, **2210C**, **2210D** which may all coupled for common rotation. A

plurality of bodies **2210** including bodies **2210B**, **2210C**, **2210D** may be elongated along the longitudinal axis **102** for receiving fluid therein.

[00542] The body **2210A** may be concentrically contained or arranged within the body **2210B**, which may be contained in the body **2210C**, which may be contained in the body **2210D**. Ducts **214A**, **214B**, **214C** may be defined between, respectively, body **2210A** and the body **2210B**, body **2210B** and body **2210C**, and body **2210C** and body **2210D**.

[00543] Slots **3202A**, **3202B**, **3202C** may open into respective ducts **214A**, **214B**, **214C**. The slots **3202A**, **3202B**, **3202C** may be radially spaced apart (relative to the longitudinal axis **102**) from the respective bodies **2210A**, **2210B**, **2210C**.

[00544] Each duct **214A**, **214B**, **214C** may have a corresponding first portion and second portion of the fluid. The first portions may be received into the respective slots **3202A**, **3202B**, **3202C**. The first portions of the fluid may be drawn out of the respective ducts **214A**, **214B**, **214C** while allowing respective second portions of the fluid to remain in the respective ducts **214A**, **214B**, **214C**.

[00545] An outlet port **116** may be configured to receive the second portions of the fluid from the respective ducts **214A**, **214B**, **214C**. In some embodiments, the outlet port **116** may be configured to discharge turbomachine the fluid out of the turbomachine. In some embodiments, the outlet port **116** may be disposed downstream of the slots **3202A**, **3202B**, **3202C** in the duct.

[00546] In some embodiments, each slot **3202A**, **3202B**, **3202C** extends radially through the respective body **2210B**, **2210C**, **2210D** to open radially into the respective duct **214A**, **214B**, **214C**.

[00547] In some embodiments, the slots **3202A**, **3202B**, **3202C** may be circular slots, longitudinally spaced apart by spacing **3206**. In some embodiments, adjacent circular slots may be longitudinally spaced apart by at

least a distance of two radii of one of the slots or by a sum of the radii of the adjacent slots.

[00548] The slots **3202A**, **3202B** may be longitudinally spaced apart from each other to allow a further portion of a portion of the fluid that passes through the respective slot **3202A**, **3202B** to be drawn into a respective additional slot **3202B**, **3202C**. The slot **3202A** may open, or may be adapted to or configured to open, into the duct to convey a portion of the fluid from the duct **214A** to the duct **214B**.

[00549] A discharge outlet **3204** may discharge fluid out of the boundary-layer turbomachine **100B**. The discharge outlet **3204** may include an annular space extending around the plurality of ducts **214** and the longitudinal axis **102**.

[00550] **FIG. 33** is a cross-sectional view of a boundary-layer turbomachine **100** having slots **3202A**, **3202B**, in accordance with an embodiment.

[00551] The bodies **2210A**, **2210B**, **2210C** may be coupled for common rotation as indicated by the direction **3302**. The fluid in the ducts **214A**, **214B** may be multiphase, including vapor and liquid phase.

[00552] First portions **3304A**, **3304B** of the fluid may be heavier than respective second portions **3306A**, **3306B** of the fluid. For example, the first portions **3304A**, **3304B** may include more liquid **3308** than the second portions **3306A**, **3306B**. In some embodiments, the first portions **3304A**, **3304B** may be substantially completely liquid and the second portions **3306A**, **3306B** may be substantially completely gas

[00553] The first portions **3304A**, **3304B** of the fluid may be separated from respective the second portions **3306A**, **3306B** of the fluid by being drawn centrifugally towards the respective slots **3202A**, **3202B** relative to the respective second portion **3306A**, **3306B**.

[00554] In some embodiments, the boundary-layer turbomachine **100** may be a boundary-layer turbine **1230** that generates power by extracting

energy from the fluid flowing therein via frictional engagement. Extraction of energy may cool the fluid and cause phase change or at least partial phase change in the boundary-layer turbine **1230**. For example, the working fluid may progressively change from full vapor phase (possibly), through multi-phase and to, possibly full liquid phase.

[00555] Temperature change with phase change involves a significant release of energy compared to temperature change without phase change. As such, once a portion of the working fluid becomes liquid, the amount of energy extracted therefrom becomes relatively less.

[00556] Removing liquid phase via the slots **3202A**, **3202B** from the working fluid in the plurality of ducts **214**, as described above, may improve efficiency by reducing pumping requirements and reduce structure loads on the turbomachine. In some cases, a cross-sectional area of the ducts may become smaller in the longitudinal direction, as shown in **FIGS. 22A-22C**, to accommodate removal of liquid phase.

[00557] **FIG. 34** is a flowchart of an exemplary method **3400** for generating power using a first fluid and a second fluid fluidly isolated from each other.

[00558] Step **3402** may include heating the first fluid to at least partially vaporize the first fluid.

[00559] Step **3404** may include transferring heat, in a first heat exchanger, from the first fluid to the second fluid to at least partially vaporize the second fluid.

[00560] Step **3406** may include rotatably driving a rotor using the second fluid to generate power.

[00561] Step **3408** may include transferring heat, in a second heat exchanger, from the second fluid to the first fluid to generate condensate of the second fluid.

[00562] Step **3410** may include using the power generated by driving the rotor to at least partially draw the condensate of the second fluid from the second heat exchanger into the first heat exchanger, and to draw the first fluid from the first heat exchanger into the second heat exchanger

[00563] Some embodiments of the method **3400** may include driving a pump using the rotor to draw the condensate of the second fluid from the second heat exchanger into the first heat exchanger for vaporization.

[00564] Some embodiments of the method **3400** may include driving a compressor using the rotor to draw the first fluid from the first heat exchanger to the second heat exchanger.

[00565] In some embodiments of the method **3400**, the rotor may be a rotor of an expander.

[00566] In some embodiments of the method **3400**, the expander may be a boundary-layer turbine.

[00567] Some embodiments of the method **3400** may include driving an electric generator using the rotor to generate electricity; and transferring heat from electric generator to the second fluid to cool the electric generator.

[00568] In some embodiments of the method **3400**, wherein the first fluid may be ammonia.

[00569] In some embodiments of the method **3400**, the first fluid may be cooled in the first heat exchanger from between 300 °F and 400 °F to -10 °F and -20 °F.

[00570] In some embodiments of the method **3400**, the second fluid may be carbon dioxide.

[00571] In some embodiments of the method **3400**, wherein the first fluid may be cooled in the first heat exchanger by between 200 °C and 400 °C and heated in the second heat exchanger by between 50 °C and 100 °C. Such a temperature range may allow low-grade energy absorption and may facilitate effective energy extraction from the second working fluid.

[00572] FIG. 35 is a flowchart of an exemplary method **3400** a method of operating a turbomachine.

[00573] Step **3502** includes receiving fluid at least partially azimuthally around a longitudinal axis in a duct defined between a first duct wall and a second duct wall via an inlet end of the turbomachine.

[00574] Step **3504** includes frictionally engaging the fluid with the first duct wall and the second duct wall.

[00575] Step **3506** includes rotating, in common, the first duct wall and the second duct wall, in accordance with the fluid.

[00576] Step **3508** includes discharging the fluid via an outlet end of the turbomachine.

[00577] Some embodiments of the method **3500** may include rotating a plurality of blades around the longitudinal axis in common with the first duct and the second duct wall, and receiving the fluid from the duct on to the plurality of blades at least partially azimuthally to redirect the fluid generally parallel to the longitudinal axis.

[00578] Some embodiments of the method **3500** may include supporting the first duct wall and the second duct wall at a longitudinal end to cantilever the first duct wall and the second duct wall along the longitudinal axis.

[00579] Some embodiments of the method **3500** may include comprising issuing jets of the fluid into the duct at least partially azimuthally to rotatably drive the first duct wall and the second duct wall.

[00580] In some embodiments of the method **3500**, receiving the fluid at least partially azimuthally around the longitudinal axis in the duct includes drawing the fluid through a channel in the duct that is defined by one or more protrusions extending radially from the first duct wall to the second duct wall.

[00581] In some embodiments of the method **3500**, the first duct wall is a radially-inner wall and the second duct wall is a radially-outer wall.

[00582] Some embodiments of the method **3500** include drawing the fluid in the duct azimuthally around the longitudinal axis to centrifugally push relatively dense portions of the fluid away from the longitudinal axis; and discharging the relatively dense portions of the fluid out of the duct via a port radially spaced apart from the radially-inner wall.

[00583] Some embodiments of the method **3500** may include comprising constricting the fluid in the duct as the fluid flows from the inlet end towards the outlet end.

[00584] The term "connected" or "coupled to" may include both direct coupling (in which two elements that are coupled to each other contact each other) and indirect coupling (in which at least one additional element is located between the two elements).

[00585] The embodiments described in this document provide non-limiting examples of possible implementations of the present technology. Upon review of the present disclosure, a person of ordinary skill in the art will recognize that changes may be made to the embodiments described herein without departing from the scope of the present technology. For example, configurations may be varied to account for thermal expansion and structural loading. Yet further modifications could be implemented by a person of ordinary skill in the art in view of the present disclosure, which modifications would be within the scope of the present technology.

WHAT IS CLAIMED IS:

1. A boundary-layer turbomachine configured to receive fluid via an inlet end and discharge the fluid via an outlet end, comprising:
 - a plurality of ducts concentrically arranged around a longitudinal axis of the boundary-layer turbomachine between the inlet end and the outlet end to convey the fluid from the inlet end towards the outlet end, the plurality of ducts at least partially defined by corresponding duct walls configured to rotate about the longitudinal axis; and
 - one or more flow inlets disposed at the inlet end and configured to receive the fluid into the plurality of ducts at least partially azimuthally around the longitudinal axis towards the outlet end in accordance with rotation of the duct walls of the plurality of ducts, the fluid being frictionally engaged with the duct walls to transfer mechanical energy to, or from, the fluid flowing in the plurality of ducts.
2. The boundary-layer turbomachine of claim 1, wherein the boundary-layer turbomachine is a boundary-layer turbine, and the one or more flow inlets are configured to draw the fluid into the plurality of ducts to impart rotation to the duct walls to generate power.
3. The boundary-layer turbomachine of claim 2, wherein the one or more flow inlets are one or more nozzles configured to inject the fluid into the plurality of ducts to convey the fluid to the outlet end at least partially azimuthally around the longitudinal axis.
4. The boundary-layer turbomachine of claim 2 or 3, further comprising a plurality of blades rotatably disposed around the longitudinal axis at a downstream end of a duct of the plurality of ducts, the plurality of blades adapted to receive the fluid oriented at least partially azimuthally around the

longitudinal axis and to redirect the fluid generally parallel to the longitudinal axis, the fluid thereby imparting rotation to the plurality of blades about the longitudinal axis to generate power.

5. The boundary-layer turbomachine of claim 4, further comprising an axial turbine stage downstream of the plurality of blades to receive the fluid oriented generally parallel to the longitudinal axis.
6. The boundary-layer turbomachine of claim 5, wherein the axial turbine stage includes a vaned stator axially aligned along the longitudinal axis and a bladed rotor axially aligned with the vaned stator, the bladed rotor disposed downstream of the vaned stator.
7. The boundary-layer turbomachine of claim 4, wherein the plurality of blades extend radially relative to the longitudinal axis from a duct wall of the duct.
8. The boundary-layer turbomachine of claim 4, wherein the plurality of blades extend radially relative to the longitudinal axis from a first duct wall of the duct to a second duct wall of the duct opposed the first duct wall.
9. The boundary-layer turbomachine of claim 7, wherein the plurality of blades are integrally formed with the duct wall for co-rotation with the duct wall.
10. The boundary-layer turbomachine of claim 9, wherein the plurality of blades are in unitary construction with the duct wall.
11. The boundary-layer turbomachine of claim 2 or 3, further comprising a plurality of blade assemblies configured to transmit power, each blade assembly of the plurality of blade assemblies disposed in a corresponding duct downstream of the one or more flow inlets and including a corresponding plurality of blades rotatably disposed around the longitudinal axis and adapted to receive the fluid oriented at least partially azimuthally around the longitudinal axis to redirect the fluid generally parallel to the

longitudinal axis, the fluid thereby imparting rotation to the corresponding plurality of blades about the longitudinal axis to generate power.

12. The boundary-layer turbomachine of claim 11, wherein the corresponding plurality of blades extend radially relative to the longitudinal axis from an associated duct wall of the corresponding duct and are integrally formed with the associated duct wall for co-rotation with the associated duct wall.
13. The boundary-layer turbomachine of claim 12, wherein the corresponding plurality of blades are in unitary construction with the associated duct wall and each duct has at least one blade assembly disposed therein.
14. The boundary-layer turbomachine of claim 1, further comprising: a shaft drivably coupled to the plurality of ducts, the shaft being coaxial with the plurality of ducts and circumferentially surrounded by the plurality of ducts.
15. The boundary-layer turbomachine of claim 14, further comprising:
 - a plurality of tubes nested concentrically around the longitudinal axis, generally spaced apart from each other, and having progressively larger cross-sectional areas lateral to the longitudinal axis,
 - wherein each of the plurality of ducts is formed between a pair of concentrically adjacent tubes of the plurality of tubes, and the shaft is disposed coaxially inside an inner cavity formed by a radially-innermost tube of the plurality of tubes at least partially defining a radially-innermost duct of the plurality of ducts.

16. The boundary-layer turbomachine of claim 15, wherein each pair of concentrically adjacent tubes forms therebetween a corresponding duct of the plurality of ducts.
17. The boundary-layer turbomachine of claim 1, wherein at least one of the plurality of ducts has an annular-shaped cross-section lateral to the longitudinal axis.
18. The boundary-layer turbomachine of claim 17, wherein the annular-shaped cross-section is a circular annulus.
19. The boundary-layer turbomachine of claim 1, further comprising:
a plurality of blades rotatably disposed around the longitudinal axis at a downstream end of a duct of the plurality of ducts to generate power;
and wherein:
the one or more flow inlets includes one or more nozzles configured to issue fluid jets at an upstream end of the duct and generally azimuthally around the longitudinal axis into the duct towards the outlet end, and
the duct of the plurality of ducts includes:
an upstream portion cross-sectionally adapted to receive the fluid jets at the upstream end of the duct;
a downstream portion cross-sectionally partially complementary to flow passages defined by the plurality of blades at the downstream end of the duct;
and
an intermediate portion defined between the upstream portion and the downstream portion, the upstream portion and downstream portion each generally

cross-sectionally tapering towards the intermediate portion to define a relatively narrow cross-section of the intermediate portion.

20. The boundary-layer turbomachine of claim 1, further comprising:
- a shaft drivably coupled to the plurality of ducts;
 - a structure at least partially housing the plurality of ducts and configured to remain substantially stationary relative to the shaft;
 - and
 - a contact bearing coupled to the shaft and disposed between the structure and the shaft to rotatably support the shaft, in-place relative to the structure,
- wherein the shaft is elongated along the longitudinal axis for rotation about the longitudinal axis.
21. The boundary-layer turbomachine of claim 20, wherein the plurality of ducts are configured to rotate at less than 43,000 revolutions per minute to generate shaft power transmitted to the shaft.
22. The boundary-layer turbomachine of claim 1 or 21, further comprising:
- a radially-outermost tube at least partially defining a radially-outermost duct of the plurality of ducts; and
 - a radially-innermost tube at least partially defining a radially-innermost duct of the plurality of ducts, the plurality of ducts being disposed between the radially-outermost tube and the radially-innermost tube,
- wherein each duct of the plurality of ducts is at least partially defined by a corresponding duct wall commonly shared with a corresponding concentrically adjacent duct.
23. The boundary-layer turbomachine of claim 1, further comprising:

a plurality of tubes nested concentrically around the longitudinal axis and generally longitudinally elongated; and

an end plate coupled to a tube of the plurality of tubes at a joint end of the tube to cantilever the tube from the joint end, the tube generally longitudinally elongated from the joint end,

wherein the plurality of tubes are concentrically spaced apart from each other such that each duct of the plurality of ducts is formed between a pair of concentrically adjacent tubes of the plurality of tubes, the plurality of tubes configured to generate power.

24. The boundary-layer turbomachine of claim 23, wherein the end plate is coupled to the tube of the plurality of tubes by threadably engaging along the longitudinal axis with the joint end.

25. The boundary-layer turbomachine of claim 1, further comprising:

a plurality of tubes nested concentrically around the longitudinal axis and generally longitudinally elongated; and

a supporting structure including a slot configured to receive a free end of a tube of the plurality of the tubes, the tube generally longitudinally elongated from the free end, the slot in fluid communication with the fluid and adapted to maintain a clearance between the free end and the slot to allow rotation of the tube relative to the slot,

wherein the plurality of tubes are concentrically spaced apart from each other such that each duct of the plurality of ducts is formed between a pair of concentrically adjacent tubes of the plurality of tubes, the plurality of tubes configured to generate power.

26. The boundary-layer turbomachine of claim 25, wherein the clearance is adapted to maintain a lubricating film of the fluid between the tube of the plurality of tubes and the slot to at least partially support the tube of the plurality of tubes in the slot and substantially prevent sliding friction between the slot and the tube of the plurality of tubes.
27. The boundary-layer turbomachine of claim 24 or 26, wherein the clearance is adapted to generate a relatively low pressure zone inside the slot when the tube of the plurality of tubes is rotating to draw the fluid into the slot to maintain lubrication between the tube of the plurality of tubes and the slot.
28. The boundary-layer turbomachine of claim 25, wherein the supporting structure is supported by a shaft via a bearing disposed between the supporting structure and the shaft, the shaft drivably coupled to the plurality of tubes.
29. The boundary-layer turbomachine of claim 25, wherein the plurality of tubes have progressively larger cross-sectional areas lateral to the longitudinal axis, and further comprising: a shaft drivably coupled to the plurality of tubes, the shaft disposed coaxially with the plurality of tubes inside an inner cavity formed by a radially-innermost tube of the plurality of tubes.
30. The boundary-layer turbomachine of claim 29, wherein the inner cavity is in fluid communication with the plurality of ducts and the slot opens to at least one of the inner cavity or a duct of the plurality of ducts.
31. The boundary-layer turbomachine of claim 1, further comprising:
a plurality of tubes nested concentrically around the longitudinal axis, each tube of the plurality of tubes generally longitudinally elongated from a corresponding free end to define a plurality of free ends of the plurality of tubes; and

a supporting structure including a plurality of slots configured to receive the plurality of free ends, the plurality of slots in fluid communication with the fluid and adapted to maintain clearance from the plurality of free ends to allow rotation of the plurality of tubes relative to the plurality of slots,

wherein the plurality of tubes are concentrically spaced apart from each other such that each duct of the plurality of ducts is formed between a pair of concentrically adjacent tubes of the plurality of tubes, the plurality of tubes configured to generate power.

32. The boundary-layer turbomachine of claim 31, wherein the plurality of ducts are in fluid communication with each other via the plurality of slots.
33. The boundary-layer turbomachine of claim 32, wherein the clearance is adapted to generate relatively low pressure zones inside the plurality of slots when the tube of the plurality of tubes is rotating to draw the fluid into the plurality of slots via the plurality of ducts to maintain lubrication films between the plurality of tubes and the plurality of slots, the lubrication films at least partially supporting the plurality of tubes in the plurality of slots and substantially preventing sliding friction between the plurality of slots and the plurality of tubes.
34. The boundary-layer turbomachine of claim 33, wherein a housing portion of the supporting structure circumferentially surrounds the plurality of tubes to maintain pressurization of the fluid in the plurality of ducts, the housing portion comprising a regulator valve for regulating pressure.
35. The boundary-layer turbomachine of claim 1, wherein the one or more flow inlets includes a plurality of nozzles circumferentially distributed at an upstream end of a duct of the plurality of ducts and configured to issue fluid jets generally azimuthally around the longitudinal axis into the duct towards the outlet end.

36. The boundary-layer turbomachine of claim 35, wherein the plurality of nozzles are aligned within 10 degrees of an azimuthal direction.
37. The boundary-layer turbomachine of claim 36, wherein the plurality of nozzles are circumferentially spaced apart and oriented to reduce flow interaction between the fluid jets.
38. The boundary-layer turbomachine of any one of claims 36-37 wherein the plurality of nozzles are circumferentially equi-spaced around an upstream end of the duct.
39. The boundary-layer turbomachine of claim 1 or 2, wherein the duct walls are coupled for common rotation.
40. The boundary-layer turbomachine of claim 4, wherein a flow inlet of the one or more flow inlets is configured to draw the fluid into an upstream end of a duct of the plurality of ducts generally azimuthally around the longitudinal axis, and a longitudinal length of the duct is adapted to limit an azimuthal deviation of the fluid to at most 10 degrees.
41. The boundary-layer turbomachine of claim 40, wherein leading edges of the plurality of blades are adapted to the azimuthal deviation of the fluid along the duct to receive the fluid in substantial alignment therewith.
42. The boundary-layer turbomachine of claim 40, wherein the flow inlet draws the fluid into the upstream end oriented within 10 degrees of an azimuthal direction around the longitudinal axis.
43. The boundary-layer turbomachine of claim 36, further comprising:
a shaft drivably coupled to the plurality of ducts; and
a supporting structure supported by the shaft via bearings disposed therebetween to allow rotation of the shaft relative to the supporting structure, the supporting structure sealingly enclosing the plurality of ducts at upstream ends thereof, the plurality of

nozzles integrated into the supporting structure, the support structure including one or more inlet channels feeding the fluid to the plurality of nozzles and a plurality of slots in fluid communication with the fluid and configured to receive a plurality of free ends of duct walls of the plurality of ducts,

wherein the plurality of slots are adapted to draw fluid therein to maintain lubrication films rotatably supporting the plurality of free ends substantially without contact.

44. The boundary-layer turbomachine of claim 1, wherein a first radial cross-section of the duct is larger than a second radial cross-section of the duct, the first radial cross-section proximal to the inlet end relative to the second radial cross-section.

45. The boundary-layer turbomachine of claim 1, further comprising:
a plurality of tubes nested concentrically around the longitudinal axis and generally longitudinally elongated; and
a supporting structure adjacent to a free end of a tube of the plurality of the tubes, the tube generally longitudinally elongated from the free end, the supporting structure adapted to maintain a clearance between the free end and the supporting structure to allow rotation of the tube relative to the supporting structure,
wherein the plurality of tubes are concentrically spaced apart from each other such that each duct of the plurality of ducts is formed between a pair of concentrically adjacent tubes of the plurality of tubes, the plurality of tubes configured to generate power.

46. The boundary-layer turbomachine of claim 45, further comprising an end plate coupled to the tube at a joint end of the tube opposed the free end

to cantilever the tube from the joint end, the tube longitudinally elongated from the joint end to the free end.

47. The boundary-layer turbomachine of claim 46, wherein the end plate is coupled to the tube of the plurality of tubes by threadably engaging along the longitudinal axis with the joint end.
48. The boundary-layer turbomachine of claim 45, wherein the clearance is adapted to maintain a lubricating film of the fluid between the tube of the plurality of tubes and the supporting structure.
49. The boundary-layer turbomachine of claim 45 or 48, wherein the one or more flow inlets are formed in the supporting structure at an end of the supporting structure adjacent to the free end, a plurality of the one or more flow inlets being azimuthally inclined to inject fluid across the clearance into a duct defined by the plurality of tubes.
50. The boundary-layer turbomachine of claim 1, wherein the one or more flow inlets include at least two flow inlets positioned antipodally around the longitudinal axis to balance a force on the duct walls.
51. The boundary-layer turbomachine of claim 1, further comprising:
- a slot opening into a duct of the plurality of ducts and radially spaced apart from a radially-inner wall of the duct to receive a first portion of the fluid to draw the first portion of the fluid out of the duct while allowing a second portion of the fluid to remain in the duct, the first portion of the fluid being separated from the second portion of the fluid by being drawn centrifugally towards the slot relative to the second portion of the fluid; and
 - a flow outlet configured to receive the second portion of the fluid from the duct to discharge the second portion of the fluid out of the boundary-layer turbomachine.

52. The boundary-layer turbomachine of claim 1, further comprising:
one or more protrusions extending longitudinally at least partially along
a duct of the plurality of ducts and radially in the duct to define a
channel in the duct, the channel configured to receive and draw
the fluid from the flow inlet into the duct.
53. The boundary-layer turbomachine of claim 52, wherein the one or
more protrusions includes a first protrusion and a second protrusion
separate from the first protrusion, the channel being defined between the
first protrusion and the second protrusion, the first protrusion and second
protrusion being at least partially azimuthally oriented to receive the fluid
supplied by the one or more flow inlets into the channel.
54. The boundary-layer turbomachine of claim 52, wherein the one or
more protrusions includes a protrusion extending radially in the duct and
spirally extending along and around the longitudinal axis in the duct to draw
the fluid along the duct.
55. The boundary-layer turbomachine of claim 54, wherein the channel is
a spiral channel and the protrusion defines walls of the spiral channel
defined around the longitudinal axis in the duct, an inlet of the spiral channel
azimuthally oriented to receive the fluid supplied by the one or more flow
inlets.
56. The boundary-layer turbomachine of claim 52, wherein the channel is
a spiral channel and the protrusion defines walls of the spiral channel
defined around the longitudinal axis in the duct, a pitch of the spiral channel
decreasing from the one or more flow inlets.
57. The boundary-layer turbomachine of claim 52, wherein the channel is
a spiral channel and the protrusion defines walls of the spiral channel
defined around the longitudinal axis in the duct, a pitch of the spiral channel
configured to draw the fluid at least partially through the duct.

58. The boundary-layer turbomachine of claim 57, wherein the pitch of the spiral channel is adapted to mitigate an adverse pressure gradient preventing the fluid from being drawn out of the duct via the outlet end.
59. A method of generating power using a working fluid configured to at least partially change phase for generating power, comprising:
- imparting heat to condensate to cause at least partial vaporization of the condensate to generate the working fluid;
 - receiving the working fluid flowing at least partially azimuthally into a duct extending longitudinally between radially-separated duct walls; and
 - driving rotatably a duct wall of the radially-separated duct walls via frictionally engaging the duct wall with the working fluid in the duct to exchange energy with the working fluid to cause condensation of the working fluid to generate the condensate.
60. The method of claim 59, further comprising:
- receiving the working fluid on blades of a turbine rotor to drivably rotate the turbine rotor to generate shaft power,
 - and wherein receiving the working fluid flowing at least partially azimuthally into a duct extending longitudinally between radially-separated duct walls includes receiving the working fluid flowing at least partially azimuthally from the turbine rotor.
61. The method of claim 59, further comprising:
- driving an electric generator by rotatably driving the duct wall of the radially-separated duct walls; and
 - cooling the electric generator using the condensate to preheat the condensate.
62. The method of claim 59, further comprising:

driving an electric generator by rotatably driving the duct wall of the radially-separated duct walls; and

cooling the electric generator using the working fluid to preheat the working fluid.

63. The method of claim 59, wherein imparting heat to the condensate to cause at least partial vaporization of the condensate to generate the working fluid includes using a heater configured to receive the condensate, the method further comprising:

driving an electric generator by rotatably driving the duct wall of the radially-separated duct walls;

preheating the condensate in a heat exchanger using heat from the electric generator; and

receiving the condensate into the heater via the heat exchanger.

64. The method of claim 59, wherein the working fluid is imparted energy via compression to cause condensation to generate the condensate.

65. The method of claim 59, wherein:

receiving the working fluid flowing at least partially azimuthally into a duct extending longitudinally between radially-separated duct walls includes receiving the working fluid flowing at an upstream end of the duct; and

a first radial cross-section defined between the radially-separated duct walls is larger than a second radial cross-section defined between the radially-separated duct walls, the first radial cross-section being proximal to the upstream end relative to the second radial cross-section.

66. The method of claim 65, wherein a first radial separation between the radially-separated duct walls is larger than a second radial separation

between the radially-separated duct walls, the first radial separation being proximal to the upstream end relative to the second radial separation.

67. A system for generating power, comprising:
- a heater for transferring heat to condensate to generate fluid that is at least partially vaporized;
 - a first boundary-layer turbine including a first plurality of ducts configured to receive the fluid from the heater and at least partially defined by corresponding first duct walls that are configured for drivable rotation about a longitudinal axis of the first boundary-layer turbine by the fluid frictionally dragging the first duct walls at least partially azimuthally around the longitudinal axis of the first boundary-layer turbine, the first duct walls configured to transfer energy from the fluid flowing in the first plurality of ducts;
 - an axial turbine coupled to the first boundary-layer turbine to receive the fluid from the first boundary-layer turbine to extract energy from the fluid; and
 - a second boundary-layer turbine coupled to the axial turbine to receive the fluid from the axial turbine into a second plurality of ducts at least partially defining the second boundary-layer turbine, the second plurality of ducts at least partially defined by corresponding second duct walls that are configured for drivable rotation about a longitudinal axis of the second boundary-layer turbine by the fluid frictionally dragging the second duct walls at least partially azimuthally around the longitudinal axis of the second boundary-layer turbine, the second duct walls configured to transfer energy from the fluid flowing in the second plurality of ducts to condense the fluid to generate the condensate for the heater.

68. A system for generating power, comprising:
- a heater for transferring heat to condensate to generate fluid that is at least partially vaporized;
 - a first boundary-layer turbine including a first plurality of ducts configured to receive the fluid from the heater and at least partially defined by corresponding first duct walls that are configured for drivable rotation about a longitudinal axis of the first boundary-layer turbine by the fluid frictionally dragging the first duct walls at least partially azimuthally around the longitudinal axis of the first boundary-layer turbine, the first duct walls configured to transfer energy from the fluid flowing in the first plurality of ducts; and
 - a second boundary-layer turbine spaced apart from and coupled to the first boundary-layer turbine to receive the fluid from the first boundary-layer turbine into a second plurality of ducts at least partially defining the second boundary-layer turbine, the second plurality of ducts at least partially defined by corresponding second duct walls that are configured for drivable rotation about a longitudinal axis of the second boundary-layer turbine by the fluid frictionally dragging the second duct walls at least partially azimuthally around the longitudinal axis of the second boundary-layer turbine, the second duct walls configured to transfer energy from the fluid flowing in the second plurality of ducts to condense the fluid to generate the condensate for the heater.
69. A method of generating power using a working fluid configured to change phase for generating power, comprising:
- imparting heat to condensate to cause at least partial vaporization of the condensate to generate the working fluid;

receiving the working fluid on blades of a turbine rotor to drivably rotate the turbine rotor to generate shaft power;

receiving the working fluid flowing at least partially azimuthally from the turbine rotor into a duct defined between a first duct wall and a second duct wall, the first duct wall and second duct wall circumferentially extending around a longitudinal axis and elongated along the longitudinal axis, the first duct wall being radially-separated from the second duct wall; and

driving rotatably the first duct wall and the second duct wall via frictionally engaging the first duct wall and the second duct wall with the working fluid in the duct to exchange energy with the working fluid to cause condensation of the working fluid to generate the condensate.

70. The method of claim 69, wherein a protrusion from the first duct wall radially extends to the second duct wall and spirally extends at least partially along the longitudinal axis to draw the working fluid along the duct.

71. The method of claim 69, further comprising:
using the shaft power to drive an electric generator; and
cooling the electric generator using the condensate to preheat the condensate.

72. The method of claim 69, wherein imparting heat to the condensate to cause at least partial vaporization of the condensate to generate the working fluid includes using a heater configured to receive the condensate, the method further comprising:

using the shaft power to drive an electric generator;
preheating the condensate in a heat exchanger using heat from the electric generator; and

receiving the condensate into the heater via the heat exchanger.

73. The method of claim 69, wherein the working fluid is imparted energy via compression to cause condensation to generate the condensate.

74. A system for generating power, comprising:

a heater for transferring heat to condensate to generate fluid that is at least partially vaporized;

a first boundary-layer turbine including a first plurality of ducts configured to receive the fluid from the heater and at least partially defined by a corresponding plurality of first duct walls that are configured for drivable rotation about a longitudinal axis of the first boundary-layer turbine by the fluid frictionally dragging the first plurality of duct walls at least partially azimuthally around the longitudinal axis of the first boundary-layer turbine, the first plurality of duct walls configured to transfer energy from the fluid flowing in the first plurality of ducts;

an axial turbine coupled to the first boundary-layer turbine to receive the fluid from the first boundary-layer turbine to extract energy from the fluid; and

a second boundary-layer turbomachine coupled to the axial turbine to receive the fluid from the axial turbine into a second plurality of ducts at least partially defining the second boundary-layer turbomachine, the second plurality of ducts at least partially defined by a corresponding plurality of second duct walls that are frictionally engaged with the fluid and configured for drivable rotation about a longitudinal axis of the second boundary-layer turbomachine, the second plurality of duct walls configured to transfer energy to, or from, the fluid flowing in the second plurality of ducts to condense the fluid to generate the condensate for the heater.

75. The system of claim 74, wherein the second plurality of duct walls circumferentially extend around the longitudinal axis and are elongated along the longitudinal axis, and a duct of the second plurality of duct walls includes a protrusion from a first duct wall of the duct radially extending to a second duct wall of the duct and spirally extending at least partially along the longitudinal axis to draw the fluid along the duct.
76. A system for generating power, comprising:
- a heater for transferring heat to condensate to generate fluid that is at least partially vaporized;
 - a first boundary-layer turbine including a first plurality of ducts configured to receive the fluid from the heater and at least partially defined by corresponding first duct walls that are configured for drivable rotation about a longitudinal axis of the first boundary-layer turbine by the fluid frictionally dragging the first duct walls at least partially azimuthally around the longitudinal axis of the first boundary-layer turbine, the first duct walls configured to transfer energy from the fluid flowing in the first plurality of ducts; and
 - a second boundary-layer turbomachine spaced apart from and coupled to the first boundary-layer turbine to receive the fluid from the first boundary-layer turbine into a second plurality of ducts at least partially defining the second boundary-layer turbomachine, the second plurality of ducts at least partially defined by corresponding second duct walls that are frictionally engaged with the fluid and configured for drivable rotation about a longitudinal axis of the second boundary-layer turbomachine, the second duct walls configured to transfer energy to, or from, the fluid flowing in the second plurality of ducts to condense the fluid to generate the condensate for the heater.

77. The system of claim 76, wherein the second duct walls circumferentially extend around the longitudinal axis and are elongated along the longitudinal axis, and a duct of the second duct walls includes a protrusion from a first duct wall of the duct radially extending to a second duct wall of the duct and spirally extending at least partially along the longitudinal axis to draw the fluid along the duct.

78. A turbomachine, comprising:

- a first body elongated along a longitudinal axis and rotatable around the longitudinal axis;

- a second body elongated at least partially concentrically with the first body along the longitudinal axis and coupled for common rotation with the first body, the second body arranged at least partially within the first body to define a duct extending longitudinally in-between the first body and the second body;

- a flow inlet configured to receive fluid at least partially azimuthally around the longitudinal axis in accordance with the common rotation of the first body and the second body, the fluid being frictionally engaged with the first body and the second body to transfer mechanical energy to, or from, the fluid; and

- one or more protrusions on the first body extending longitudinally at least partially along the duct and radially towards the second body in the duct to define a channel in the duct, the channel configured to receive and draw the fluid from the flow inlet into the duct.

79. The turbomachine of claim 78, wherein the one or more protrusions includes a first protrusion and a second protrusion separate from the first protrusion, the channel being defined between the first protrusion and the second protrusion, the first protrusion and second protrusion being at least

partially azimuthally oriented to receive the fluid supplied by the flow inlet into the channel.

80. The turbomachine of claim 78, wherein the one or more protrusions includes a protrusion extending radially from the first body to the second body in the duct and spirally extending along and around the longitudinal axis in the duct to draw the fluid along the duct.
81. The turbomachine of claim 80, wherein the channel is a spiral channel, and the protrusion defines walls of the spiral channel defined around the longitudinal axis in the duct, an inlet of the spiral channel azimuthally oriented to receive the fluid supplied by the flow inlet.
82. The turbomachine of claim 80, wherein the channel is a spiral channel, and the protrusion defines walls of the spiral channel defined around the longitudinal axis in the duct, a pitch of the spiral channel decreasing from the flow inlet.
83. The turbomachine of claim 78, further comprising:
a plurality of blades disposed in the duct, downstream of the one or more protrusions and extending radially from the first body to the second body, the plurality of blades configured to reorient flow received between the plurality of blades from a first direction having a first azimuthal component to a second direction having a second azimuthal component, the first azimuthal component opposed to the second azimuthal component.
84. The turbomachine of claim 78, the first body and the second body are drivably rotatable to draw the fluid through the turbomachine to achieve pumping of the fluid.
85. A system for generating power using a first fluid and a second fluid fluidly isolated from each other, the system comprising:

a heater configured to transfer heat to the first fluid to at least partially vaporize the first fluid;

a first heat exchanger fluidly connected to the heater to receive the first fluid from the heater, the first heat exchanger configured to transfer heat from the first fluid to the second fluid to at least partially vaporize the second fluid;

an expander fluidly connected to the first heat exchanger to receive the second fluid from the first heat exchanger and configured to rotatably drive a rotor of the expander using the second fluid to generate power; and

a second heat exchanger fluidly connected to the expander to receive the second fluid from the expander and fluidly connected to the first heat exchanger to receive the first fluid from the first heat exchanger, the second heat exchanger configured to generate condensate of the second fluid by transferring heat from the second fluid to the first fluid.

86. The system of claim 85, further comprising:

a pump drivably coupled to the expander, and fluidly connected to the first heat exchanger and the second heat exchanger, the pump configured to draw the condensate of the second fluid from the second heat exchanger into the first heat exchanger for vaporization; and

a compressor drivably coupled to the expander, and fluidly connected to the first heat exchanger and the second heat exchanger, the compressor configured to receive the first fluid from second heat exchanger and to draw the first fluid from the first heat exchanger to the second heat exchanger.

87. The system of claim 85, wherein the expander is a boundary-layer turbine including a plurality of ducts configured to receive the second fluid

from the heater and at least partially defined by a corresponding plurality of duct walls that are configured for drivable rotation about a longitudinal axis of the boundary-layer turbine by the second fluid frictionally dragging the plurality of duct walls at least partially azimuthally around the longitudinal axis of the boundary-layer turbine, the plurality of duct walls configured to transfer energy from the fluid flowing in the plurality of ducts.

88. The system of claim 85, wherein the rotor drives an electric generator to generate electricity, a heat exchanger of the electric generator configured to receive the second fluid from the expander to draw heat away from the electric generator.
89. The system of claim 85, wherein the first fluid is ammonia.
90. The system of claim 89, wherein the first fluid is cooled in the first heat exchanger from between 300 °F and 400 °F to -10 °F and -20 °F.
91. The system of claim 85, wherein the second fluid is carbon dioxide.
92. The system of claim 89, wherein the first fluid is cooled in the first heat exchanger by between 200 °C and 400 °C and heated in the second heat exchanger by between 50 °C and 100 °C.
93. The system of claim 85, wherein the first heat exchanger is configured to transfer heat from the first fluid to the second fluid to substantially completely vaporize the second fluid.
94. The system of claim 85, wherein the heater includes a heat exchanger configured to receive a third fluid to transfer heat from the third fluid to the first fluid.
95. The system of claim 86, wherein the compressor and pump are drivably connected to the expander via a common drive shaft.

96. The system of claim 85, further comprising a pressure control valve disposed between the first heat exchanger and the second heat exchanger to control a pressure of the first fluid flowing from the first heat exchanger to the second heat exchanger.
97. The system of claim 96, wherein the pressure control valve is configured to control the pressure of the first fluid to achieve substantially complete vaporization of the first fluid in the second heat exchanger.
98. The system of claim 96, wherein the pressure control valve is configured to depressurize the first fluid to achieve substantially complete vaporization of the first fluid in the second heat exchanger.
99. A method for generating power using a first fluid and a second fluid fluidly isolated from each other, the method comprising:
- (a) heating the first fluid to at least partially vaporize the first fluid;
 - (b) transferring heat, in a first heat exchanger, from the first fluid to the second fluid to at least partially vaporize the second fluid;
 - (c) rotatably driving a rotor using the second fluid to generate power;
 - (d) transferring heat, in a second heat exchanger, from the second fluid to the first fluid to generate condensate of the second fluid; and
 - (e) using the power generated by driving the rotor to at least partially draw the condensate of the second fluid from the second heat exchanger into the first heat exchanger, and to draw the first fluid from the first heat exchanger into the second heat exchanger.
100. The method of claim 99, wherein using the power generated by driving the rotor to at least partially draw the condensate of the second fluid from the second heat exchanger into the first heat exchanger, and to draw the first fluid from the first heat exchanger into the second heat exchanger includes

driving a pump using the rotor to draw the condensate of the second fluid from the second heat exchanger into the first heat exchanger for vaporization; and

driving a compressor using the rotor to draw the first fluid from the first heat exchanger to the second heat exchanger.

101. The method of claim 99, wherein the rotor is a rotor of an expander.
102. The method of claim 101, wherein the expander is a boundary-layer turbine.
103. The method of claim 99, further comprising:

driving an electric generator using the rotor to generate electricity; and

transferring heat from electric generator to the second fluid to cool the electric generator.
104. The method of claim 99, wherein the first fluid is ammonia.
105. The method of claim 104, wherein the first fluid is cooled in the first heat exchanger from between 300 °F and 400 °F to -10 °F and -20 °F.
106. The method of claim 99, wherein the second fluid is carbon dioxide.
107. The method of claim 104, wherein the first fluid is cooled in the first heat exchanger by between 200 °C and 400 °C and heated in the second heat exchanger by between 50 °C and 100 °C.
108. A turbomachine, comprising:

a first body elongated along a longitudinal axis and rotatable around the longitudinal axis;

a second body elongated at least partially concentrically with the first body along the longitudinal axis and coupled for common rotation with the first body, the second body arranged at least partially

within the first body to define a duct extending longitudinally in-between the first body and the second body;

a flow inlet configured to receive fluid at least partially azimuthally around the longitudinal axis in accordance with the common rotation of the first body and the second body, the fluid being frictionally engaged with the first body and the second body to transfer mechanical energy to, or from, the fluid;

a slot opening into the duct and radially spaced apart from the first body to receive a first portion of the fluid to draw the first portion of the fluid out of the duct while allowing a second portion of the fluid to remain in the duct, the first portion of the fluid being separated from the second portion of the fluid by being drawn centrifugally towards the slot relative to the second portion of the fluid; and

an outlet port configured to receive the second portion of the fluid from the duct to discharge the second portion of the fluid out of the turbomachine.

109. The turbomachine of claim 108, wherein the slot extends radially through the second body to open radially into the duct.

110. The turbomachine of claim 108, wherein the outlet port is downstream of the slot in the duct.

111. The turbomachine of claim 108, wherein the fluid is a multiphase fluid, and the first portion includes more liquid than the second portion.

112. The turbomachine of claim 111, wherein the first portion is substantially completely liquid and the second portion is substantially completely gas.

113. The turbomachine of claim 108, wherein the duct is a first duct and the slot is a first slot, the turbomachine further comprising:

a third body elongated at least partially concentrically with the second body along the longitudinal axis and coupled for common rotation with the second body, the third body arranged at least partially within the second body to define a second duct extending longitudinally in-between the second body and the third body, the first slot opening into the second duct to convey the first portion of the fluid from the first duct into the second duct; and

a second slot opening into the second duct and radially spaced apart from the second body to receive a further portion of the first portion of the fluid to centrifugally draw the further portion of the fluid out of the second duct.

114. The turbomachine of claim 113, wherein the first slot and second slot are longitudinally spaced apart from each other to allow the further portion of the first portion of the fluid to be drawn into the second slot.

115. The turbomachine of claim 108, wherein the first body and the second body are rotatably driven by frictional engagement of the fluid with the first body and the second body, the fluid at least partially changing phase while in the duct.

116. A method of operating a turbomachine, comprising:

receiving fluid at least partially azimuthally around a longitudinal axis in a duct defined between a first duct wall and a second duct wall via an inlet end of the turbomachine;

frictionally engaging the fluid with the first duct wall and the second duct wall;

rotating, in common, the first duct wall and the second duct wall, in accordance with the fluid; and

discharging the fluid via an outlet end of the turbomachine.

117. The method of claim 116, further comprising:
- rotating a plurality of blades around the longitudinal axis in common with the first duct and the second duct wall; and
- receiving the fluid from the duct on to the plurality of blades at least partially azimuthally to redirect the fluid generally parallel to the longitudinal axis.
118. The method of claim 116, further comprising supporting the first duct wall and the second duct wall at a longitudinal end to cantilever the first duct wall and the second duct wall along the longitudinal axis.
119. The method of claim 116, further comprising issuing jets of the fluid into the duct at least partially azimuthally to rotatably drive the first duct wall and the second duct wall.
120. The method of claim 116, wherein receiving the fluid at least partially azimuthally around the longitudinal axis in the duct includes drawing the fluid through a channel in the duct that is defined by one or more protrusions extending radially from the first duct wall to the second duct wall.
121. The method of claim 116, wherein the first duct wall is a radially-inner wall and the second duct wall is a radially-outer wall, the method further comprising:
- drawing the fluid in the duct azimuthally around the longitudinal axis to centrifugally push relatively dense portions of the fluid away from the longitudinal axis; and
- discharging the relatively dense portions of the fluid out of the duct via a slot radially spaced apart from the radially-inner wall.
122. The method of claim 116, further comprising constricting the fluid in the duct as the fluid flows from the inlet end towards the outlet end.