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(71) Demandeur/Applicant:
BLUE BOX TECHNOLOGY INC., CA
(72) Inventeurs/Inventors:
DI BELLA, FRANCIS, US;
MERSWOLKE, PAUL, CA
(74) Agent: NORTON ROSE FULBRIGHT CANADA
LLP/S.E.N.C.R.L., S.R.L.

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(54) Title: APPARATUS FOR EXTRACTING ENERGY FROM WASTE HEAT

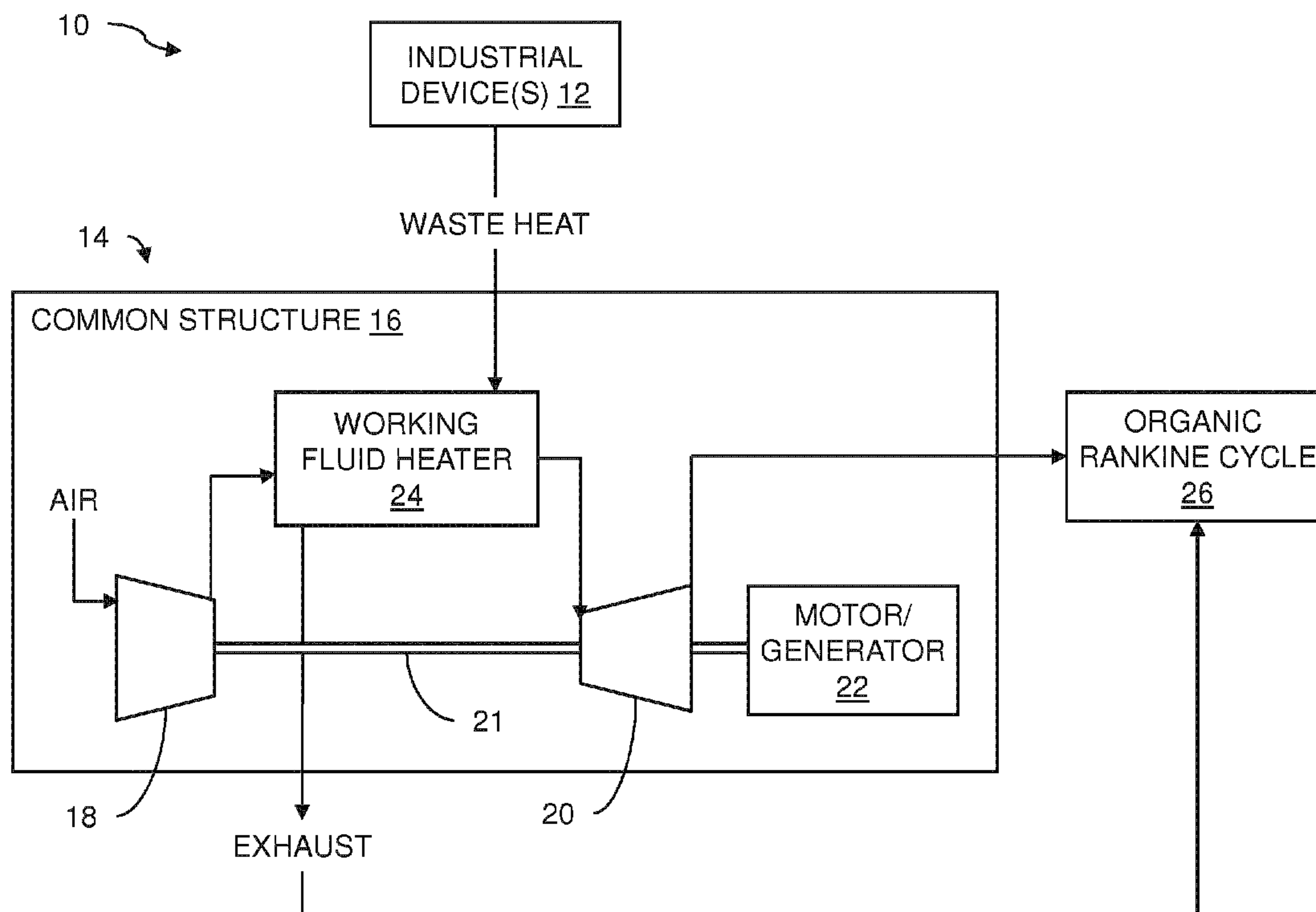


FIG. 1

(57) **Abrégé/Abstract:**

Brayton cycle apparatus for extracting energy from waste heat released by industrial devices are disclosed. An exemplary apparatus comprises a common structure to which the main components of a Brayton cycle are mounted in an in-use configuration to define a transportable unit for integration with an industrial device. Associated systems and methods are also disclosed.

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(71) Applicant: **BLUE BOX TECHNOLOGY INC.**
[CA/CA]; Suite 202, 1051 2nd Ave East, Owen Sound, Ontario N4K 2H8 (CA).

(72) Inventors: **MERSWOLKE, Paul**; R.R. #1, Bognor, Ontario N0H 1E0 (CA). **DI BELLA, Francis**; 1 Haslet Street, Roslindale, Massachusetts (US).

(74) Agent: **NORTON ROSE FULBRIGHT CANADA LLP / S.E.N.C.R.L.**; Suite 2500, 1 Place Ville Marie, Montreal, Québec H3B 1R1 (CA).

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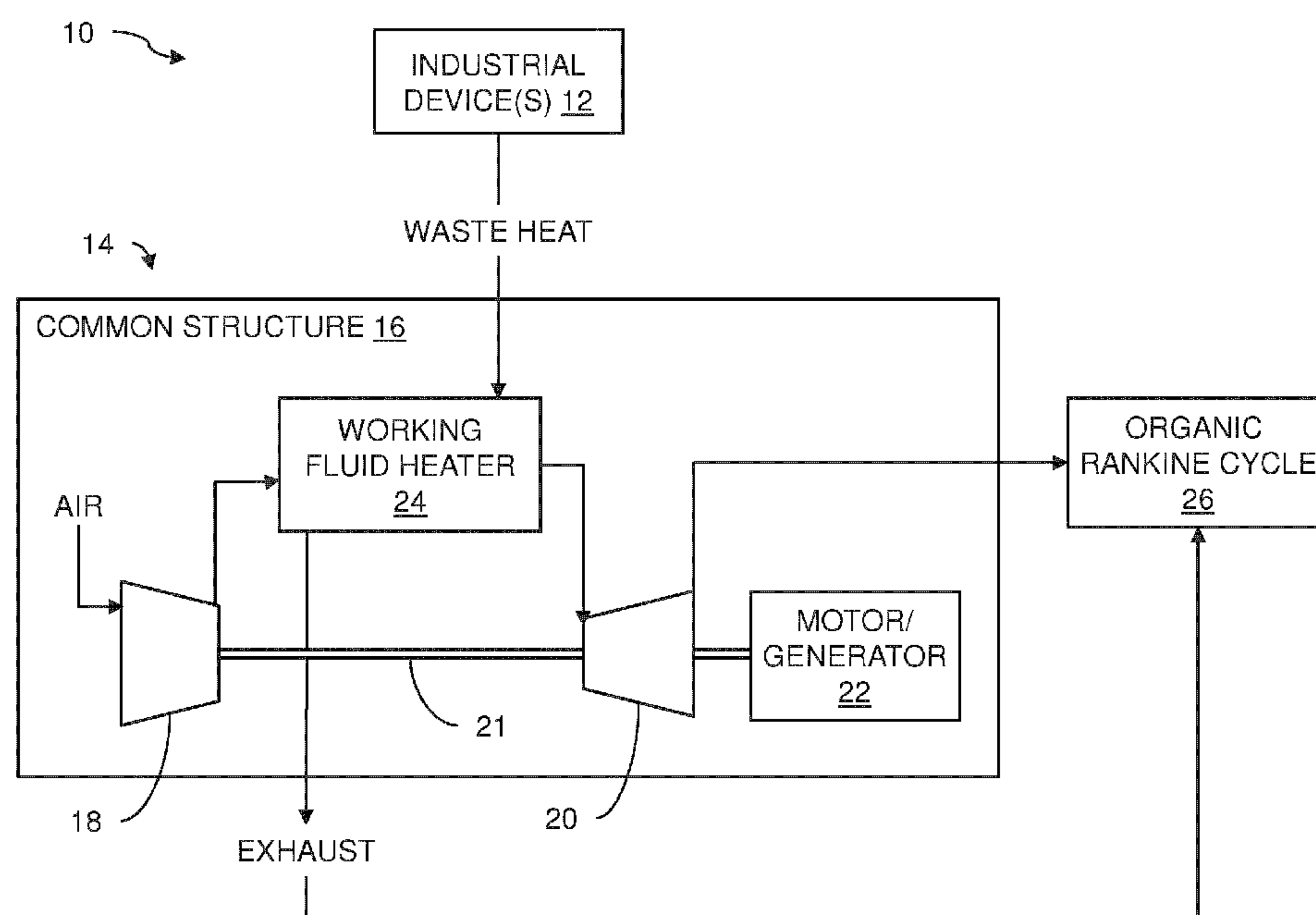


FIG. 1

(57) Abstract: Brayton cycle apparatus for extracting energy from waste heat released by industrial devices are disclosed. An exemplary apparatus comprises a common structure to which the main components of a Brayton cycle are mounted in an in-use configuration to define a transportable unit for integration with an industrial device. Associated systems and methods are also disclosed.

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WO 2018/107279 A1

WO 2018/107279 A1

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APPARATUS FOR EXTRACTING ENERGY FROM WASTE HEAT

CROSS REFERENCE TO RELATED APPLICATION AND CLAIM OF PRIORITY

[0001] The present application claims priority to U.S. provisional patent
5 application no. 62/433,440 filed on December 13, 2016, the entire contents of which are
hereby incorporated by reference.

TECHNICAL FIELD

[0002] The disclosure relates generally to extracting useful energy from waste
heat, and more particularly to extracting useful energy from waste heat using the
10 Brayton thermodynamic cycle.

BACKGROUND OF THE ART

[0003] Some industrial processes produce waste heat as a by-product. There
exists systems that can recuperate some energy from the waste heat but factors such
as costs (e.g., capital and installation), installation constraints and available space can
15 discourage the use of such existing systems. Improvement is desirable.

SUMMARY

[0004] In one aspect, the disclosure describes a Brayton cycle apparatus for
extracting energy from waste heat released from an industrial device. The apparatus
comprises:
20 an air compressor configured to receive ambient air and compress the
ambient air;
an air turbine configured for fluid communication with the air compressor
for receiving the compressed air and extracting energy from the compressed air;
a working fluid heater configured to facilitate transfer of the waste heat to
25 the compressed air at a location upstream of the air turbine during operation;
an electric generator configured to be drivingly coupled to the air turbine
for converting some of the energy extracted by the air turbine into electrical energy; and
a common structure to which the air compressor, the air turbine, the
working fluid heater and the electric generator are mounted in an in-use configuration to
30 define a transportable unit for integration with the industrial device.

[0005] The working fluid heater may be at least partially disposed into a base of the common structure.

[0006] The common structure may comprise a support platform. The air turbine and the air compressor may be disposed on an upper side of the support platform and
5 the working fluid heater may be disposed on a lower side of the support platform.

[0007] The working fluid heater may be disposed vertically below the air compressor and the air turbine.

[0008] The working fluid heater may be disposed vertically below the generator.

[0009] The air compressor may comprise a first compressor stage and a second
10 compressor stage. The apparatus may comprise an intercooler mounted to the common structure. The intercooler may be configured to cool the air between the first compressor stage and the second compressor stage of the air compressor during operation.

[0010] The working fluid heater may comprise a recuperator configured to
15 facilitate heat transfer from exhaust air from the air turbine to the compressed air upstream of the air turbine.

[0011] The apparatus may comprise a steam generator mounted to the common structure and coupled to receive a first heat-carrying fluid from the recuperator and facilitate heat transfer from the first heat-carrying fluid to water to produce steam
20 during operation.

[0012] The steam generator may be coupled to receive a second heat-carrying fluid from the working fluid heater and facilitate heat transfer from the second heat-carrying fluid to the water to produce the steam during operation.

[0013] The apparatus may comprise a steam generator mounted to the
25 common structure and configured to receive a heat-carrying fluid from the working fluid heater and facilitate heat transfer from the heat-carrying fluid to water to produce steam during operation.

[0014] The common structure may comprise an upper portion and a lower portion. The upper portion may be configured to interface with a lower portion of a common structure of another Brayton cycle apparatus to permit vertical stacking.

[0015] The working fluid heater may comprise a fuel-burning auxiliary heater
5 configured to heat the compressed air upstream of the air turbine.

[0016] The common structure may comprise a skid.

[0017] Embodiments may include combinations of the above features.

[0018] In another aspect, the disclosure describes a system comprising:
an industrial device configured to release waste heat; and
10 a Brayton cycle apparatus for extracting energy from the waste heat released by the industrial device, the apparatus comprising:

an air compressor configured to receive ambient air and compress the ambient air;

15 an air turbine in fluid communication with the air compressor for receiving the compressed air and extracting energy from the compressed air;

a working fluid heater configured to facilitate transfer of the waste heat to the compressed air at a location upstream of the air turbine during operation;

20 an electric generator drivingly coupled to the air turbine for converting some of the energy extracted by the air turbine into electrical energy; and

a common structure to which the air compressor, the air turbine, the working fluid heater and the electric generator are mounted to define a transportable unit integrated with the industrial device.

[0019] The working fluid heater may be at least partially disposed in a base of
25 the common structure.

[0020] The common structure may comprise a support platform. The air turbine and the air compressor may be disposed on an upper side of the support platform and the working fluid heater may be disposed on a lower side of the support platform.

- [0021]** The working fluid heater may be disposed vertically below the air compressor and the air turbine.
- [0022]** The working fluid heater may be disposed vertically below the generator.
- [0023]** The air compressor may comprise a first compressor stage and a second compressor stage. The apparatus may comprise an intercooler mounted to the common structure. The intercooler may be operatively coupled to cool the air between the first compressor stage and the second compressor stage of the air compressor.
- [0024]** The working fluid heater may comprise a recuperator configured to facilitate heat transfer from exhaust air from the air turbine to the compressed air upstream of the air turbine.
- [0025]** The system may comprise a steam generator mounted to the common structure and coupled to receive a first heat-carrying fluid from the recuperator and facilitate heat transfer from the first heat-carrying fluid to water to produce steam during operation.
- [0026]** The steam generator may be coupled to receive a second heat-carrying fluid from the working fluid heater and facilitate heat transfer from the second heat-carrying fluid to the water to produce the steam during operation.
- [0027]** The system may comprise a steam generator mounted to the common structure and coupled to receive a heat-carrying fluid from the working fluid heater and facilitate heat transfer from the heat-carrying fluid to water to produce steam during operation.
- [0028]** The common structure may comprise a skid.
- [0029]** The system may comprise an organic Rankine cycle device operatively coupled to receive a flow of air exhausted by the air turbine.
- [0030]** The system may comprise a combustion device operatively coupled to receive a flow of air exhausted by the air turbine.
- [0031]** The industrial device may comprise an incinerator.
- [0032]** The industrial device may comprise a fired heater.

[0033] The common structure of the apparatus may comprise an upper portion and a lower portion. The upper portion may be configured to interface with a lower portion of a common structure of another Brayton cycle apparatus to permit vertical stacking.

5 **[0034]** The Brayton cycle apparatus may be a first Brayton cycle apparatus and the system may comprise a second Brayton cycle apparatus. The first Brayton cycle apparatus and the second Brayton cycle apparatus may be stacked vertically.

[0035] The Brayton cycle apparatus may be a first Brayton cycle apparatus and the system may comprise a second Brayton cycle apparatus. The system may
10 comprise a support structure supporting the first Brayton cycle apparatus above the second Brayton cycle apparatus in a vertically stacked relationship during operation.

[0036] The working fluid heater may comprise a fuel-burning auxiliary heater configured to heat the compressed air upstream of the air turbine.

[0037] Embodiments may include combinations of the above features.

15 **[0038]** In a further aspect, the disclosure describes a method for integrating a Brayton cycle apparatus with an industrial device releasing waste heat. The method comprises:

assembling an air compressor, an air turbine, a working fluid heater and an electric generator in an in-use configuration on a common structure to define a
20 transportable Brayton cycle unit;

transporting the transportable Brayton cycle unit to a location of the industrial device; and

integrating the transportable Brayton cycle unit with the industrial device to permit the transportable Brayton cycle unit to extract energy from the waste heat.

25 **[0039]** The method may comprise installing the working fluid heater to be at least partially disposed in a base of the common structure.

[0040] The method may comprise installing the working fluid heater to be disposed vertically below the air compressor and the air turbine.

- [0041]** The method may comprise operatively installing an intercooler to cool the air between a first compressor stage and a second compressor stage of the air compressor on the common structure prior to transporting the transportable Brayton cycle unit.
- 5 **[0042]** The method may comprise operatively installing a steam generator configured to receive a heat-carrying fluid from the working fluid heater on the common structure prior to transporting the transportable Brayton cycle unit.
- [0043]** The method may comprise integrating the transportable Brayton cycle unit with an organic Rankine cycle device.
- 10 **[0044]** The industrial device may comprise an incinerator.
- [0045]** The industrial device may comprise a fired heater.
- [0046]** Integrating the transportable Brayton cycle unit with the industrial device may comprise vertically stacking the transportable Brayton cycle unit with another transportable Brayton cycle unit.
- 15 **[0047]** The method may comprise integrating the transportable Brayton cycle unit with a combustion device operatively coupled to receive a flow of air exhausted by the air turbine.
- [0048]** Embodiments may include combinations of the above features.
- [0049]** In a further aspect, the disclosure describes a Brayton cycle apparatus
 20 for extracting energy from waste heat released from an industrial device. The apparatus comprises:
- an air compressor configured to receive ambient air and compress the ambient air;
- an air turbine configured for fluid communication with the air compressor for receiving the compressed air and extracting energy from the compressed air;
- 25 an electric generator configured to be drivingly coupled to the air turbine for converting some of the energy extracted by the air turbine into electrical energy; and

a common structure to which the air compressor, the air turbine and the electric generator are mounted in an in-use configuration to define a transportable unit for integration with the industrial device.

5 [0050] The air compressor may comprise a first compressor stage and a second compressor stage and the apparatus may comprise an intercooler mounted to the common structure, the intercooler being configured to cool the air between the first compressor stage and the second compressor stage of the air compressor during operation.

10 [0051] The common structure may comprise an upper portion and a lower portion, the upper portion being configured to interface with a lower portion of a common structure of another Brayton cycle apparatus to permit vertical stacking.

[0052] The common structure may comprise a skid.

[0053] Embodiments may include combinations of the above features.

15 [0054] 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

[0055] Reference is now made to the accompanying drawings, in which:

20 [0056] FIG. 1 is a schematic representation of an exemplary industrial system installation including an exemplary embodiment of an apparatus for extracting useful energy from waste heat;

[0057] FIG. 2 is a schematic representation of another exemplary industrial system installation including another exemplary embodiment of the apparatus for extracting useful energy from waste heat;

25 [0058] FIGS. 3A and 3B are schematic perspective views of another exemplary embodiment of the apparatus respectively showing a side and a front thereof;

[0059] FIGS. 4A and 4B are schematic perspective views of another exemplary embodiment of the apparatus respectively showing a side and a front thereof;

[0060] FIG. 5 is a schematic representation of another exemplary industrial system installation comprising a plurality of energy extraction apparatus vertically stacked relative to each other to promote efficient use of space;

[0061] FIGS. 6A and 6B are isometric views of an exemplary support structure
5 for supporting two energy extraction apparatus in a vertically stacked relationship;

[0062] FIG. 7 illustrates a flowchart of a method for integrating a Brayton cycle apparatus with an industrial device producing waste heat; and

[0063] FIG. 8 is a perspective view of the support structure for supporting two
10 energy extraction apparatus in a vertically stacked relationship as shown in FIGS. 6A and 6B where duct work has been omitted from the two energy extraction apparatus.

DETAILED DESCRIPTION

[0064] In various aspects, the present disclosure relates to apparatus for extracting useful energy from waste heat streams using the Brayton cycle and associated methods. In some embodiments, such apparatus may be packaged to
15 promote efficient use of space and also to facilitate transport and installation. For example, in some embodiments, the main components of the apparatus (e.g., compressor, turbine, heat exchanger and electric generator) may be mounted to a common structure in an in-use configuration permitting the apparatus to be transported as a unit. For example, in some embodiments, the use of the common structure may
20 permit the main components of the apparatus to be pre-assembled on the common structure, transported to a site as a substantially ready-to-use unit and installed in a substantially “plug-and-play” manner. In various embodiments, the apparatus disclosed herein may be appropriate for installation in an industrial environment for extracting useful energy from one or more sources of waste heat released by one or more
25 industrial devices. In some embodiments, the common structure may be configured to permit two or more apparatus to be stacked vertically.

[0065] Aspects of various embodiments are described through reference to the drawings.

[0066] FIG. 1 is a schematic representation of an exemplary industrial system
30 installation 10 including one or more industrial devices 12 (referred hereinafter in the

singular) that may be used in an industrial process and which may release waste heat as a by-product of an industrial process, and, an exemplary apparatus 14 for extracting useful energy from the waste heat. In various embodiments, industrial device 12 may be of any type suitable for use in industrial process(es) associated with: (i) petroleum and coal products, (ii) chemical manufacturing, (iii) cement, lime, glass, tile, or brick manufacturing, (iv) metal manufacturing (e.g., casting foundry), (v) pulp and paper, (vi) wood products, (vii) food manufacturing, (viii) landfill gas production or (ix) bio-waste energy for example. In various embodiments, industrial device 12 may, for example, be an incinerator, furnace or fired heater (e.g., in an oil refinery). In some
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embodiments, industrial device 12 may, for example, be a rotary kiln calciner, a raw material melting furnaces, an annealing oven, a tempering furnace, a coke oven, a blast furnace, an electric arc furnace, a basic oxygen furnace, a melting furnace, a heat treating furnace, or a reverberatory furnace.

[0067] The source of waste heat may comprise a flow of a relatively hot heat-carrying fluid such as flue gas(es) or steam for example. In various embodiments, the
15
source of waste heat may be substantially continuous or intermittent. In various embodiments, the amount of waste heat available may be substantially constant or variable depending on the industrial device 12. In various embodiments, the heat-carrying fluid may have a temperature that is between about 232°C (450°F) and about
20
1232°C (2250°F). In some embodiments, the heat-carrying fluid may have a temperature that is between about 232°C (450°F) and about 650°C (1200°F). In some embodiments, the heat-carrying fluid may have a temperature that is greater than about 538°C (1000°F). In some embodiments, the heat-carrying fluid may have a temperature that is about 816°C (1500°F). In some embodiments, the heat-carrying fluid may have
25
a temperature that is between about 538°C (1000°F) and about 816°C (1500°F). In some embodiments, the heat-carrying fluid may have a temperature that is between about 760°C (1400°F) and about 871°C (1600°F). In some embodiments, the heat-carrying fluid may have a temperature that is between about 704°C (1300°F) and about 927°C (1700°F). In some embodiments, the heat-carrying fluid may have a temperature
30
that is between about 927°C (1700°F) and about 1232°C (2250°F). In some embodiments, the heat-carrying fluid may have a temperature that is greater than about

1232°C (2250°F). In some embodiments, the heat-carrying fluid may have a mass flow rate that is between about 4.5 kg/s and about 29.5 kg/s (10-65 lb/sec).

[0068] In various embodiments, energy extraction apparatus 14 may be configured to operate as a suitable Brayton cycle. In some embodiments, apparatus 14 may be configured to operate as an open Brayton cycle where ambient air may be used as a working fluid. Apparatus 14 may be configured to be disposed relatively proximal to industrial device 12 to facilitate the transfer of the waste heat released by industrial device 12 to apparatus 14. In some embodiments, apparatus 14 may, for example, be disposed in the same facility (e.g., factory, building) as industrial device 12. As explained below, apparatus 14 may be packaged as a pre-assembled and transportable unit that makes efficient use of space (i.e., efficient packaging) and that may have a relatively small footprint.

[0069] Apparatus 14 may comprise common structure 16 which may comprise a base to which at least some components of apparatus 14 may be assembled and directly or indirectly mounted thereto. For example, the main components of apparatus 14 may be assembled and operatively coupled together in a configuration that is substantially ready to be used so that apparatus 14 may be pre-assembled and delivered to the site as a pre-assembled unit. The pre-assemble unit (i.e., apparatus 14) may then be integrated with industrial device 12 in a manner that permits useful energy to be extracted by apparatus 14 from the waste heat released by industrial device 12.

[0070] Apparatus 14 may comprise (e.g., single or multi-stage) air compressor 18 mounted to common structure 16 and configured to receive ambient air and compress the ambient air. Air compressor 18 may, for example, be of the radial or axial type. Apparatus 14 may comprise (e.g., single or multi-stage) air turbine 20 mounted to common structure 16 and configured for fluid communication with air compressor 18 for receiving the compressed air and extracting energy from the compressed air. Air turbine 20 may, for example, be of the radial or axial type. In some embodiments, turbine 20 and compressor 18 may be drivingly coupled together via common shaft 21 or other means so that turbine 20 may drive compressor 18 during operation. In some embodiments, air turbine 20 and air compressor 18 may be drivingly coupled together via a gearbox depending on respective speed requirements. Apparatus 14 may

comprise electric motor/generator 22 mounted to common structure 16 and drivingly coupled to air turbine 20 for converting some of the energy extracted by air turbine 20 into electrical energy. Electric motor/generator 22 may, for example, be of the induction type. Electric motor/generator 22 may be (e.g., selectively) electrically coupled to supply electrical energy to an electrical load during its operation as a generator. Electric motor/generator 22 may be (e.g., selectively) electrically coupled to receive electrical energy from an electrical power source load during its operation as a motor.

[0071] Apparatus 14 may comprise working fluid heater 24 (e.g., air heater) mounted to common structure 16 and configured to facilitate heat transfer from a source of heat that is disposed externally of apparatus 14 (e.g., waste heat being released from nearby industrial device 12) to the working fluid (e.g., compressed air) at a location upstream of air turbine 20 during operation. In various embodiments, working fluid heater 24 or part(s) thereof may be mounted to common structure 16 or may be installed remotely from common structure 16. For example, in some situations, it may be preferable to have working fluid heater 24 installed at a location that is close to the source of waste heat but remote from common structure 16 while still being operatively coupled (e.g., via suitable ducting) to one or more components of system 10 that may be mounted to common structure 16. In some embodiments, working fluid heater 24 may comprise one or more suitable fluid-to-fluid heat exchangers of the shell-and-tube type or of the plate fin type for example. In some embodiments, working fluid heater 24 may comprise one or more relatively compact surface heat exchangers. For example, working fluid heater 24 may be configured to facilitate heat transfer from a flow of fluid (e.g., flue gas, steam) carrying the waste heat to the compressed air at a location downstream of air compressor 18 and upstream of air turbine 20.

[0072] Electric motor/generator 22 may be configured to operate either as a generator or as a motor depending on the state of operation of apparatus 14. For example, during start-up of apparatus 14, electric motor/generator 22 may operate as a motor to initiate the operation of air compressor 18 so that ambient air may be drawn into air compressor 18, compressed and driven through working fluid heater 24 and through air turbine 20. In the exemplary embodiment shown in FIG. 1, electric motor/generator 22 may be operated as a motor to initiate rotation of air turbine 20, which in turn may initiate rotation of air compressor 18 via shaft 21. As more air is

increasingly driven from air compressor 18 to air turbine 20 and the compressed air is being heated between air compressor 18 and air turbine 20 via working fluid heater 24, air turbine 20 will begin to extract energy from the flow of heated air therethrough and can then begin to drive electric motor/generator 22 as an electric generator and can also begin to drive air compressor 18 via shaft 21. Once the operation of air compressor 18 can be sustained mainly by air turbine 20, electric motor/generator 22 may switch from operating as a motor to operating as a generator.

[0073] Alternatively, instead of having an electric motor/generator 22 operable both as a motor or as an electric generator, apparatus 14 may comprise a separate motor (not shown) for driving air compressor 18 during start-up or at other times.

[0074] In some embodiments, system 10 may comprise other subsystems or devices (e.g., heat load(s)) configured to receive the air exhausted from turbine 20 and further extract energy from the exhausted air. For example, a suitable organic Rankine cycle device 26 may be operatively coupled to apparatus 14 to receive a flow of air exhausted from turbine 20.

[0075] FIG. 2 is a schematic representation of another exemplary industrial system installation 10 including another exemplary embodiment of apparatus 14 for extracting useful energy from waste heat. The embodiment shown in FIG. 2 illustrates additional (i.e., optional) components that may be included in apparatus 14 in comparison with the embodiment of FIG. 1. It is understood that FIGS. 1 and 2 only illustrate main components of apparatus 14 in schematic form and that apparatus 14 may comprise one or more control devices (e.g., suitable controllers, instruments and control valves) and additional system integration components that are omitted from the figures for the sake of clarity. It is understood that, in light of the present disclosure, one of ordinary skill would understand the integration of such components.

[0076] In reference to FIG. 2, apparatus 14 may comprise a multi-stage compressor 28 comprising first compressor stage 18A and second compressor stage 18B. Apparatus 14 may comprise intercooler 28 mounted to common structure 16 where intercooler 28 may be operatively coupled to cool the air between first compressor stage 18A and second compressor stage 18B. In some embodiments, the

use of intercooler 28 may promote an increased air charge density which may be desirable in some situations.

[0077] In some embodiments, working fluid heater 24 may comprise main heat exchanger (HX) 30 of suitable type to facilitate heat transfer from the source of waste heat (e.g., flue gas, steam) to the compressed air at a location upstream of air turbine 20. In various embodiments, main heat exchanger 30 of working fluid heater 24 may be mounted to common structure 16 or may be installed remotely from common structure 16 as explained above. Main heat exchanger 30 may be installed to receive a flow of heat-carrying fluid therethrough.

[0078] In some embodiments, working fluid heater 24 may also comprise recuperator 32, which may also be a heat exchanger of suitable type but configured to facilitate heat transfer from air exhausted from air turbine 20 to the compressed air at a location upstream of turbine 20. Recuperator 32 may be integrated into or separate from main heat exchanger 30. In various embodiments, recuperator 32 of working fluid heater 24 may be mounted to common structure 16 or may be installed remotely from common structure 16 as explained above. In some embodiments, recuperator 32 may serve to recover some thermal energy that may be carried by the air exhausted from air turbine 20 and pre-heat the pressurized air upstream of main heat exchanger 30. Alternatively or in addition to the use of recuperator 32, all or a portion of the air exhausted from air turbine 20 may be directed to optional organic Rankine cycle device 26. It is understood that the type(s) of available and beneficial uses for heat recuperated from the air exhausted from air turbine 20 will depend on specific operating conditions.

[0079] In some embodiments, working fluid heater 24 may comprise an optional auxiliary heater 33 to add heat to the compressed air at a location upstream of air turbine 20. In various embodiments, auxiliary heater 33 may be mounted to common structure 16 or may be installed remotely from common structure 16. Auxiliary heater 33 may be configured and disposed to add heat to the compressed air at a location downstream of main heat exchanger 30 and upstream of air turbine 20. Auxiliary heater 33 may be referred to as a “booster” for supplementing the amount of heat transferred to the compressed air. In some embodiments, auxiliary heater 33 may comprise a fuel burner and suitable heat exchange means for transferring heat released from the

combustion of the fuel to the compressed air. In some embodiments, a suitable fuel such as oil or natural gas may be used as a fuel for auxiliary heater 33.

[0080] In some embodiments, apparatus 14 may comprise steam generator 34 mounted to common structure 16 to further make use of waste heat available on apparatus 14. For example, steam generator 34 may be coupled to receive a heat-carrying fluid from working fluid heater 24 and facilitate heat transfer from the heat-carrying fluid to water to produce (e.g., pressurized) steam during operation of apparatus 14 before discharging the heat-carrying fluid out of apparatus 14. In some embodiments, steam generator 34 may be coupled to receive a first heat-carrying fluid from recuperator 32 and facilitate heat transfer from the first heat-carrying fluid to water to produce steam during operation. The first heat-carrying fluid may comprise air exhausted from air turbine 20 that has passed through recuperator 32. In some embodiments, steam generator 34 may be coupled to receive a second heat-carrying fluid from main heat exchanger 30 and facilitate heat transfer from the second heat-carrying fluid to the water to produce the steam during operation. The second heat-carrying fluid may comprise flue gas or steam from industrial device 12 that has passed through main heat exchanger 30. In some embodiments, the first and second heat-carrying fluids may be mixed prior to entering steam generator 34. For example, the first and second heat-carrying fluids may be combined together downstream of recuperator 32 and of main heat exchanger 30 but upstream of steam generator 34.

[0081] Residual heat available within system 10 may be used for one or more secondary applications. For example, instead of or in addition to the use of recuperator 32, steam generator 34 and organic Rankine cycle device 26, heat-carrying air in system 10 may be used as combustion air in an incinerator (e.g. of industrial device 12) for example or used to meet a hot air demand in a heating, ventilating and cooling (HVAC) system of a building. For example, air exhausted from air turbine 20 may be selectively directed to one or more users (e.g., recuperator 32, steam generator 34, organic Rankine cycle device 26, combustion air and hot air demand) by the selective opening and closing of valves V1-V6 shown in FIG. 2.

[0082] When the air exhausted from air turbine 20 is used as combustion air and is directed to a combustion chamber of an associated combustion device 35 via valves V2 and V4 for example, the condition of the combustion air delivered to

combustion device 35 can be tailored to match requirements of combustion device 35. For example, the temperature, pressure and flow rate of the combustion air delivered to the associated combustion device 35 via valve V4 may be monitored and controlled to be within ranges that permit the direct injection of the combustion air into combustion 35
5 device (e.g., directly) without further conditioning. For example, the condition and amount of air being discharged from system 10 via valve V4 may be controlled by way of adjusting the operation of one or more components of system 10. In light of the present disclosure, it is understood that one or more components of system 10 may be controlled to obtain a desired pressure, temperature and flow rate of compressed air at
10 one or more desired locations within system 10 and such control may be used to tailor the condition of the combustion air delivered by system 10 via valve V4.

[0083] Some combustion devices 35 can require combustion blowers sometimes call “induction fans” that supply combustion air at a desired condition to their combustion chambers. However, the ability to tailor the condition of the combustion air
15 supplied by system 10 may eliminate or reduce the need for such combustion blowers since the combustion air supplied may need no further conditioning. Accordingly, in some situations, a combustion device 35 operatively coupled to receive combustion air from system 10 may not necessarily have a combustion blower. Alternatively, a combustion blower of a combustion device 35 operatively coupled to receive
20 combustion air from system 10 may be turned off or adjusted accordingly based on the condition of the combustion air received from system 10. For example, in some situations, such combustion blower may be turned off completely when combustion air is received from system 10 and turned on when combustion air is not received from system 10. Accordingly, such combustion blower may be activated on an as-needed
25 basis and the operation of such combustion blower may be part of a suitable control loop that determines the need for operating the combustion blower and activates the combustion blower accordingly (e.g., based on the presence and/or condition of the combustion air received from system 10).

[0084] FIGS. 3A and 3B are schematic perspective views of another exemplary embodiment of apparatus 14 respectively showing a side and a front thereof. The
30 embodiment of apparatus 14 shown in FIGS. 3A and 3B may contain components previously described above. Like components are identified using like reference

numerals. Instead of being interconnected via a direct shaft 21, air compressor 28 (i.e., stages 28A and 28B), air turbine 20 and electric motor/generator 22 may be drivingly coupled via a suitable gearbox 36. Gearbox 36 may be mounted to common structure 16. Apparatus 14 may also comprise a suitable lubrication system represented
5 schematically at reference numeral 38.

[0085] In some embodiments, common structure 16 may comprise or have a base that resembles a skid so that apparatus 14 may be considered a “skid-mounted” Brayton cycle unit for example. Accordingly, common structure 16 may comprise one or more support platforms 40 and one or more ground-engaging members 42. Ground-
10 engaging members 42 may cause support platform 40 to be elevated from a ground or floor so that apparatus 14 may be transported as a pre-assembled unit using a fork lift truck for example. Various components of apparatus 14 may be mounted directly or indirectly to an upper side of support platform 40. In some embodiments, electric motor/generator 22 may be mounted directly to support platform 40 and air compressor
15 stages 18A, 18B and air turbine 20 may be indirectly mounted to support platform 40 via a housing of gearbox 36.

[0086] In some embodiments, some components of apparatus 14 may be vertically superimposed so as to make efficient use of space and reduce a footprint of apparatus 14. For example, working fluid heater 24 may be disposed vertically above
20 air compressor stages 18A, 18B and vertically above air turbine 20. Similarly, working fluid heater 24 may be disposed vertically above electric motor/generator 22 and vertically above gearbox 36. The elevated position of working fluid heater 24 may be desirable in some situations depending on the position of the source of waste heat. In some cases as might be suitable for the available waste heat, working fluid heater 24
25 may have recuperator 32 integrated therewith.

[0087] In various embodiments, working fluid heater 24 may be integrated in the skid-mounted Brayton cycle unit defined by apparatus 14, or, alternatively, working fluid heater 24 may not be integrated in the skid-mounted unit. For example, as explained above, working fluid heater 24 (or part(s) thereof) may not be mounted to common
30 structure 16 and instead be installed at a location closer to the source of waste heat while still being operatively coupled to (i.e., in fluid communication with) one or more components of apparatus 14.

[0088] FIGS. 4A and 4B are schematic perspective views of another exemplary embodiment of apparatus 14 respectively showing a side and a front thereof. The embodiment of apparatus 14 shown in FIGS. 4A and 4B may contain components previously described above. Like components are identified using like reference numerals. In some embodiments, working fluid heater 24 may be integrated into a base of common structure 16 for packaging efficiency, increased stability of apparatus 14, reduced length of duct work and/or other reasons. For example, the base of common structure 16 may comprise upper platform 40A and lower platform 40B where working fluid heater 24 may be disposed vertically between upper platform 40A and lower platform 40B. Ground engaging members 42 may be disposed on a lower side of lower platform 40B.

[0089] Upper platform 40A may be considered a support platform to which one or more components of apparatus 14 may be mounted. For example, air turbine 20 and air compressor 18 (i.e., first stage 18A and second stage 18B) may be disposed on an upper side of upper platform 40A while working fluid heater 24 may be disposed on a lower side of upper platform 40A. Similarly electric motor/generator 22, gearbox 36 and intercooler 28 may be disposed on an upper side of upper platform 40A and hence above working fluid heater 24.

[0090] FIG. 5 is a schematic representation of an exemplary system installation comprising a plurality of energy extraction apparatus 14A, 14B vertically stacked relative to each other to promote efficient use of space (i.e., efficient packaging). First apparatus 14A and second apparatus 14B may be operatively coupled to the same or to different respective industrial devices 12. Similarly, first apparatus 14A and second apparatus 14B may be operatively coupled to the same or to different respective organic Rankine cycle devices 26.

[0091] In some embodiments, common structure 16B of second (i.e., lower) apparatus 14B may comprise upper portion 16B-U and common structure 16A of first (i.e., upper) apparatus 14A may comprise lower portion 16A-L where upper portion 16B-U of second apparatus 14B may be configured to interface with lower portion 16A-L of first apparatus 14A to permit vertical stacking of two or more apparatus 14. For example, common structure 16B may comprise vertical supports 44 supporting first apparatus 14A vertically above second apparatus 14B. It is understood that common

structure 16A could similarly comprise vertical supports (not shown) for supporting a third apparatus (not shown) vertically above first apparatus 14A in some embodiments.

[0092] FIGS. 6A and 6B are isometric views of an exemplary support structure 46 for supporting two energy extraction apparatus 14A, 14B in a vertically stacked relationship. In various embodiments, suitable structure for permitting stacking of apparatus 14A, 14B may form part of common structure 16 as explained above in relation to FIG. 5. Alternatively, a separate support structure 46 may be used to permit stacking of apparatus 14A, 14B. In some embodiments, support structure 46 may be configured as a shelving unit comprising upper shelf 48A, lower shelf 48B and one or more braces 50 supporting upper shelf 48A in a vertically spaced apart relationship above lower shelf 48B. As shown in FIG. 6A, upper shelf 48A may support upper apparatus 14A above lower apparatus 14B during operation when apparatus 14A, 14B are operatively coupled to industrial device(s) 12 for example.

[0093] FIG. 7 illustrates a flowchart of a method 100 for integrating one or more Brayton cycle apparatus 14 with one or more industrial devices 12 releasing waste heat. In various embodiments method 100 may comprise: assembling components (e.g., air compressor 18, air turbine 20, working fluid heater 24 and electric motor/generator 22) of apparatus 14 in an in-use configuration on common structure 16 to define a transportable Brayton cycle unit (i.e., apparatus 14) (see block 102); transporting the transportable Brayton cycle unit (i.e., apparatus 14) to a location of industrial device 12 (see block 104); and integrating the transportable Brayton cycle unit (i.e., apparatus 14) with industrial device 12 to permit the transportable Brayton cycle unit (i.e., apparatus 14) to extract energy from the waste heat (see block 106).

[0094] It is understood that the installation of various pieces of equipment of apparatus 14 onto common structure 16 in their in-use configuration may comprise the relative positioning and mounting of the pieces of equipment to common structure 16. In some embodiments, some pieces of equipment may be operatively coupled together so that they are in a ready-to use state. Alternatively, some further integration of the pieces of equipment may be required after transporting apparatus 14. For example, some of the duct work and/or other integration device(s) may not necessarily be incorporated into apparatus 14 prior to transport and may need to be incorporated after transport (e.g., during the integration of apparatus 14 with industrial device 12).

- [0095]** In some embodiments, method 100 may comprise installing working fluid heater 24 to be at least partially disposed in a base (e.g., between upper platform 40A and lower platform 40B) of common structure 16 as shown in FIGS. 4A and 4B for example.
- 5 **[0096]** In some embodiments, method 100 may comprise installing working fluid heater 24 to be disposed vertically below air compressor 18 and air turbine 20.
- [0097]** In some embodiments, method 100 may comprise operatively installing intercooler 28 for cooling the air between a first stage 18A and a second stage 18B of air compressor 18 prior to transporting transportable Brayton cycle apparatus 14.
- 10 **[0098]** In some embodiments, method 100 may comprise operatively installing steam generator 34 for receiving a heat-carrying fluid from working fluid heater 24 prior to transporting transportable Brayton cycle apparatus 14.
- [0099]** In some embodiments, method 100 may comprise integrating transportable Brayton cycle apparatus 14 with organic Rankine cycle device 26.
- 15 **[00100]** In some embodiments, method 100 may comprise integrating the transportable Brayton cycle apparatus 14 with combustion device 35 so that combustion device 35 may be operatively coupled to receive a flow of air exhausted by air turbine 20.
- [00101]** In some embodiments of method 100, industrial device 12 may comprise
20 an incinerator.
- [00102]** In some embodiments of method 100, industrial device 12 may comprise a fired heater.
- [00103]** In some embodiments of method 100, integrating transportable Brayton cycle apparatus 14 with industrial device 12 may comprise vertically stacking
25 transportable Brayton cycle apparatus 14A with another transportable Brayton cycle apparatus 14B as shown in FIGS. 5, 6A and 6B for example.
- [00104]** FIG. 8 is a perspective view of the support structure 46 for supporting two energy extraction apparatus 14A and 14B in a vertically stacked relationship as shown in FIGS. 6A and 6B where some duct work has been omitted from the two

apparatus 14A and 14B. Each apparatus 14A, 14B is in an exemplary configuration suitable for transport as a transportable Brayton cycle unit where various pieces of equipment of apparatus 14 are assembled onto common structure 16 in their in-use configurations (e.g., positions and orientations) but some of the duct work and optionally
5 other system integration equipment has not yet been installed.

[00105] The above description is meant to be exemplary only, and one skilled in the relevant arts will recognize that changes may be made to the embodiments described without departing from the scope of the invention disclosed. The present disclosure may be embodied in other specific forms without departing from the subject
10 matter of the claims. The present disclosure is intended to cover and embrace all suitable changes in technology. Modifications which fall within the scope of the present invention will be apparent to those skilled in the art, in light of a review of this disclosure, and such modifications are intended to fall within the appended claims. Also, the scope of the claims should not be limited by the preferred embodiments set forth in the
15 examples, but should be given the broadest interpretation consistent with the description as a whole.

WHAT IS CLAIMED IS:

1. A Brayton cycle apparatus for extracting energy from waste heat released from an industrial device, the apparatus comprising:
 - an air compressor configured to receive ambient air and compress the ambient air;
 - an air turbine configured for fluid communication with the air compressor for receiving the compressed air and extracting energy from the compressed air;
 - a working fluid heater configured to facilitate transfer of the waste heat to the compressed air at a location upstream of the air turbine during operation;
 - an electric generator configured to be drivingly coupled to the air turbine for converting some of the energy extracted by the air turbine into electrical energy; and
 - a common structure to which the air compressor, the air turbine, the working fluid heater and the electric generator are mounted in an in-use configuration to define a transportable unit for integration with the industrial device.
2. The apparatus as defined in claim 1, wherein the working fluid heater is at least partially disposed into a base of the common structure.
3. The apparatus as defined in any one of claims 1 and 2, wherein the common structure comprises a support platform, the air turbine and the air compressor being disposed on an upper side of the support platform and the working fluid heater being disposed on a lower side of the support platform.
4. The apparatus as defined in any one of claims 1 to 3, wherein the working fluid heater is disposed vertically below the air compressor and the air turbine.
5. The apparatus as defined in any one of claims 1 to 4, wherein the working fluid heater is disposed vertically below the generator.
6. The apparatus as defined in any one of claims 1 to 5, wherein the air compressor comprises a first compressor stage and a second compressor stage and the apparatus comprises an intercooler mounted to the common structure, the

intercooler being configured to cool the air between the first compressor stage and the second compressor stage of the air compressor during operation.

7. The apparatus as defined in any one of claims 1 to 6, wherein the working fluid heater comprises a recuperator configured to facilitate heat transfer from exhaust air from the air turbine to the compressed air upstream of the air turbine.

8. The apparatus as defined in claim 7, comprising a steam generator mounted to the common structure and coupled to receive a first heat-carrying fluid from the recuperator and facilitate heat transfer from the first heat-carrying fluid to water to produce steam during operation.

9. The apparatus as defined in claim 8, wherein the steam generator is coupled to receive a second heat-carrying fluid from the working fluid heater and facilitate heat transfer from the second heat-carrying fluid to the water to produce the steam during operation.

10. The apparatus as defined in any one of claims 1 to 7, comprising a steam generator mounted to the common structure and configured to receive a heat-carrying fluid from the working fluid heater and facilitate heat transfer from the heat-carrying fluid to water to produce steam during operation.

11. The apparatus as defined in any one of claims 1 to 10, wherein the common structure comprises an upper portion and a lower portion, the upper portion being configured to interface with a lower portion of a common structure of another Brayton cycle apparatus to permit vertical stacking.

12. The apparatus as defined in any one of claims 1 to 11, wherein the working fluid heater comprises a fuel-burning auxiliary heater configured to heat the compressed air upstream of the air turbine.

13. The apparatus as defined in any one of claims 1 to 12, wherein the common structure comprises a skid.

14. A system comprising:
an industrial device configured to release waste heat; and
a Brayton cycle apparatus for extracting energy from the waste heat released by the industrial device, the apparatus comprising:
an air compressor configured to receive ambient air and compress the ambient air;
an air turbine in fluid communication with the air compressor for receiving the compressed air and extracting energy from the compressed air;
a working fluid heater configured to facilitate transfer of the waste heat to the compressed air at a location upstream of the air turbine during operation;
an electric generator drivingly coupled to the air turbine for converting some of the energy extracted by the air turbine into electrical energy; and
a common structure to which the air compressor, the air turbine, the working fluid heater and the electric generator are mounted to define a transportable unit integrated with the industrial device.
15. The system as defined in claim 14, wherein the working fluid heater is at least partially disposed in a base of the common structure.
16. The system as defined in any one of claims 14 and 15, wherein the common structure comprises a support platform, the air turbine and the air compressor being disposed on an upper side of the support platform and the working fluid heater being disposed on a lower side of the support platform.
17. The system as defined in any one of claims 14 to 16, wherein the working fluid heater is disposed vertically below the air compressor and the air turbine.
18. The system as defined in any one of claims 14 to 17, wherein the working fluid heater is disposed vertically below the generator.

19. The system as defined in any one of claims 14 to 18, wherein the air compressor comprises a first compressor stage and a second compressor stage and the apparatus comprises an intercooler mounted to the common structure, the intercooler being operatively coupled to cool the air between the first compressor stage and the second compressor stage of the air compressor.

20. The system as defined in any one of claims 14 to 19, wherein the working fluid heater comprises a recuperator configured to facilitate heat transfer from exhaust air from the air turbine to the compressed air upstream of the air turbine.

21. The system as defined in claim 20, comprising a steam generator mounted to the common structure and coupled to receive a first heat-carrying fluid from the recuperator and facilitate heat transfer from the first heat-carrying fluid to water to produce steam during operation.

22. The system as defined in claim 21, wherein the steam generator is coupled to receive a second heat-carrying fluid from the working fluid heater and facilitate heat transfer from the second heat-carrying fluid to the water to produce the steam during operation.

23. The system as defined in any one of claims 14 to 22, comprising a steam generator mounted to the common structure and coupled to receive a heat-carrying fluid from the working fluid heater and facilitate heat transfer from the heat-carrying fluid to water to produce steam during operation.

24. The system as defined in any one of claims 14 to 23, wherein the common structure comprises a skid.

25. The system as defined in any one of claims 14 to 24, comprising an organic Rankine cycle device operatively coupled to receive a flow of air exhausted by the air turbine.

26. The system as defined in any one of claims 14 to 25, comprising a combustion device operatively coupled to receive a or the flow of air exhausted by the air turbine.

27. The system as defined in any one of claims 14 to 26, wherein the industrial device comprises an incinerator.

28. The system as defined in any one of claims 14 to 26, wherein the industrial device comprises a fired heater.

29. The system as defined in any one of claims 14 to 28, wherein the common structure of the apparatus comprises an upper portion and a lower portion, the upper portion being configured to interface with a lower portion of a common structure of another Brayton cycle apparatus to permit vertical stacking.

30. The system as defined in any one of claims 14 to 29, wherein the Brayton cycle apparatus is a first Brayton cycle apparatus and the system comprises a second Brayton cycle apparatus, the first Brayton cycle apparatus and the second Brayton cycle apparatus being stacked vertically.

31. The system as defined in any one of claims 14 to 28, wherein:
the Brayton cycle apparatus is a first Brayton cycle apparatus and the system comprises a second Brayton cycle apparatus; and
the system comprises a support structure supporting the first Brayton cycle apparatus above the second Brayton cycle apparatus in a vertically stacked relationship during operation.

32. The system as defined in any one of claims 14 to 31, wherein the working fluid heater comprises a fuel-burning auxiliary heater configured to heat the compressed air upstream of the air turbine.

33. A method for integrating a Brayton cycle apparatus with an industrial device releasing waste heat, the method comprising:

assembling an air compressor, an air turbine, a working fluid heater and an electric generator in an in-use configuration on a common structure to define a transportable Brayton cycle unit;

transporting the transportable Brayton cycle unit to a location of the industrial device; and

integrating the transportable Brayton cycle unit with the industrial device to permit the transportable Brayton cycle unit to extract energy from the waste heat.

34. The method as defined in claim 33, comprising installing the working fluid heater to be at least partially disposed in a base of the common structure.

35. The method as defined in any one of claims 33 and 34, comprising installing the working fluid heater to be disposed vertically below the air compressor and the air turbine.

36. The method as defined in any one of claims 33 to 35, comprising operatively installing an intercooler to cool the air between a first compressor stage and a second compressor stage of the air compressor on the common structure prior to transporting the transportable Brayton cycle unit.

37. The method as defined in any one of claims 33 to 36, comprising operatively installing a steam generator configured to receive a heat-carrying fluid from the working fluid heater on the common structure prior to transporting the transportable Brayton cycle unit.

38. The method as defined in any one of claims 33 to 37, comprising integrating the transportable Brayton cycle unit with an organic Rankine cycle device.

39. The method as defined in any one of claims 33 to 38, wherein the industrial device comprises an incinerator.

40. The method as defined in any one of claims 33 to 38, wherein the industrial device comprises a fired heater.

41. The method as defined in any one of claims 33 to 40, wherein integrating the transportable Brayton cycle unit with the industrial device comprises vertically stacking the transportable Brayton cycle unit with another transportable Brayton cycle unit.

42. The method as defined in any one of claims 33 to 41, comprising operatively coupling a combustion device to receive a flow of air exhausted by the air turbine of the transportable Brayton cycle unit.

43. A Brayton cycle apparatus for extracting energy from waste heat released from an industrial device, the apparatus comprising:

- an air compressor configured to receive ambient air and compress the ambient air;

- an air turbine configured for fluid communication with the air compressor for receiving the compressed air and extracting energy from the compressed air;

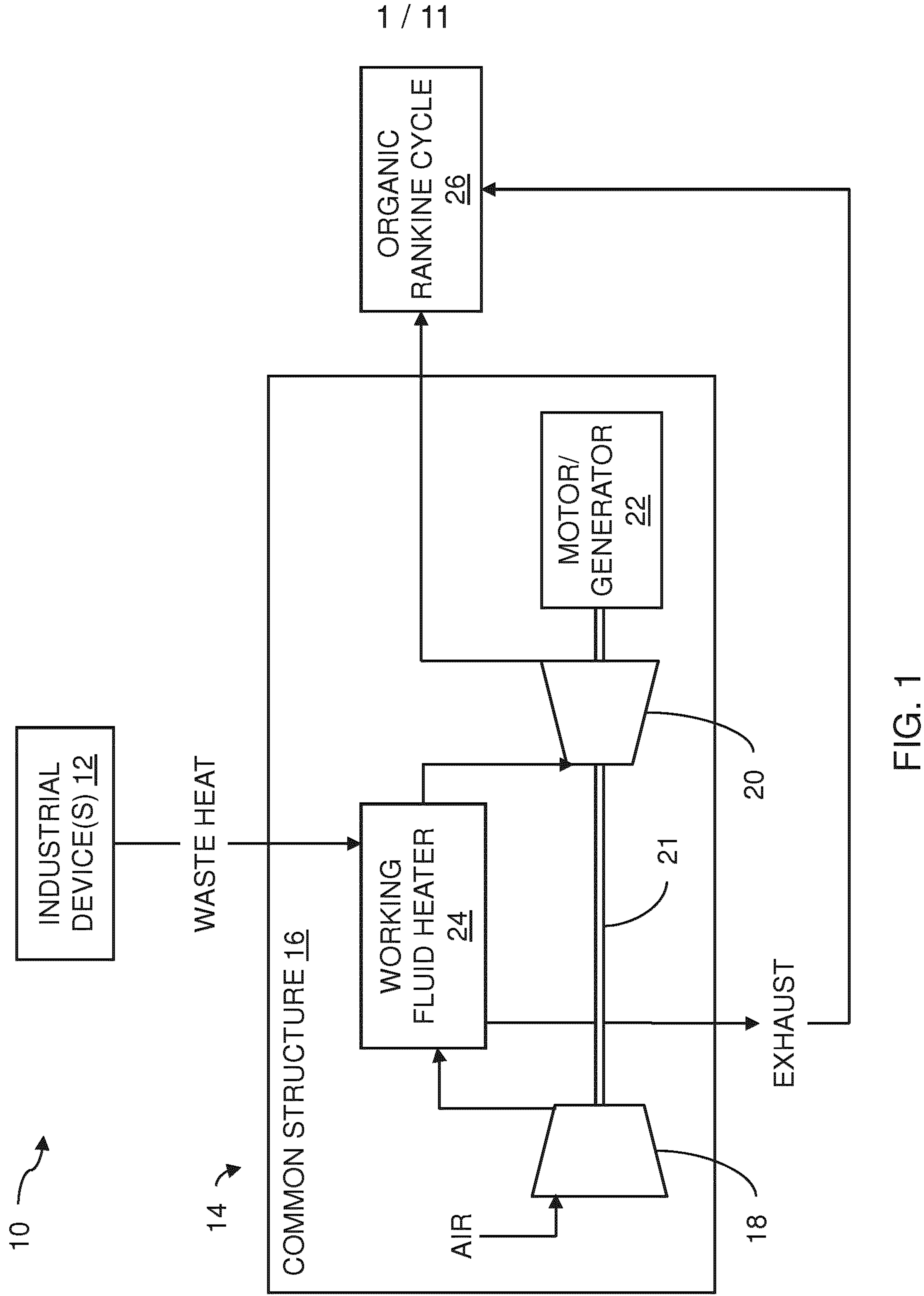
- an electric generator configured to be drivingly coupled to the air turbine for converting some of the energy extracted by the air turbine into electrical energy; and

- a common structure to which the air compressor, the air turbine and the electric generator are mounted in an in-use configuration to define a transportable unit for integration with the industrial device.

44. The apparatus as defined in claim 43, wherein the air compressor comprises a first compressor stage and a second compressor stage, and the apparatus comprises an intercooler mounted to the common structure, the intercooler being configured to cool the air between the first compressor stage and the second compressor stage of the air compressor during operation.

45. The apparatus as defined in any one of claims 43 to 44, wherein the common structure comprises an upper portion and a lower portion, the upper portion being configured to interface with a lower portion of a common structure of another Brayton cycle apparatus to permit vertical stacking.

46. The apparatus as defined in any one of claims 43 to 45, wherein the common structure comprises a skid.



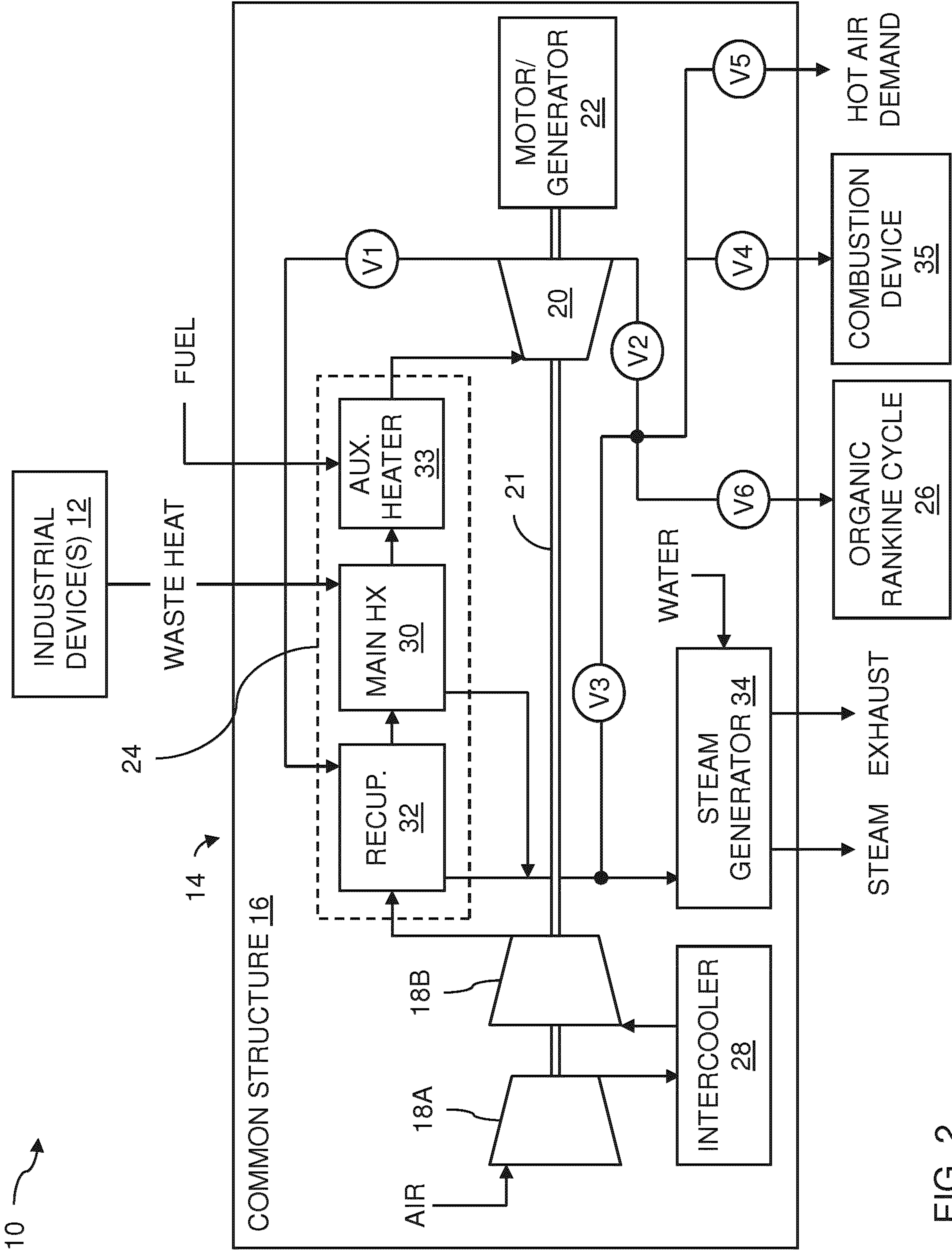


FIG. 2

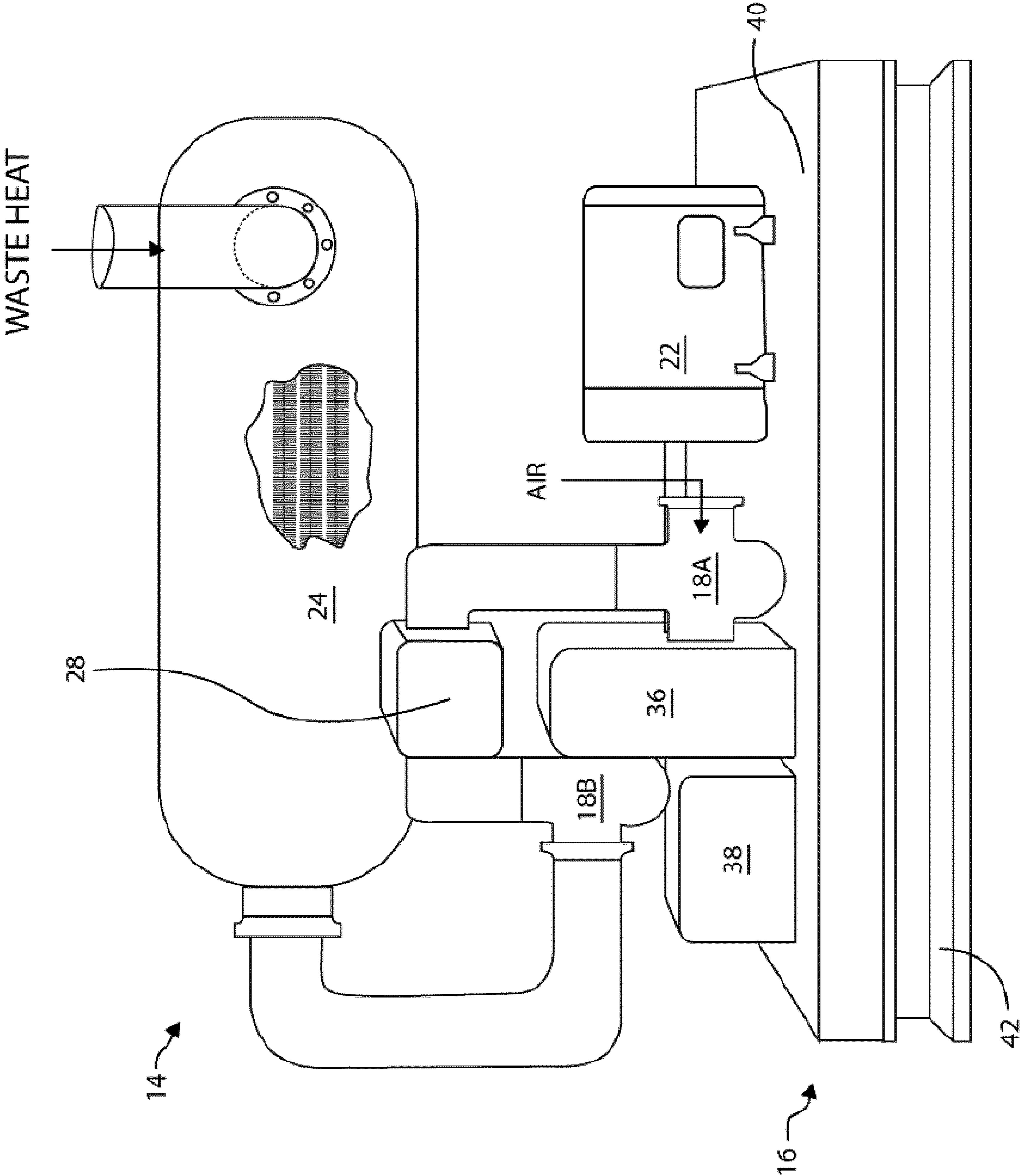


FIG. 3A

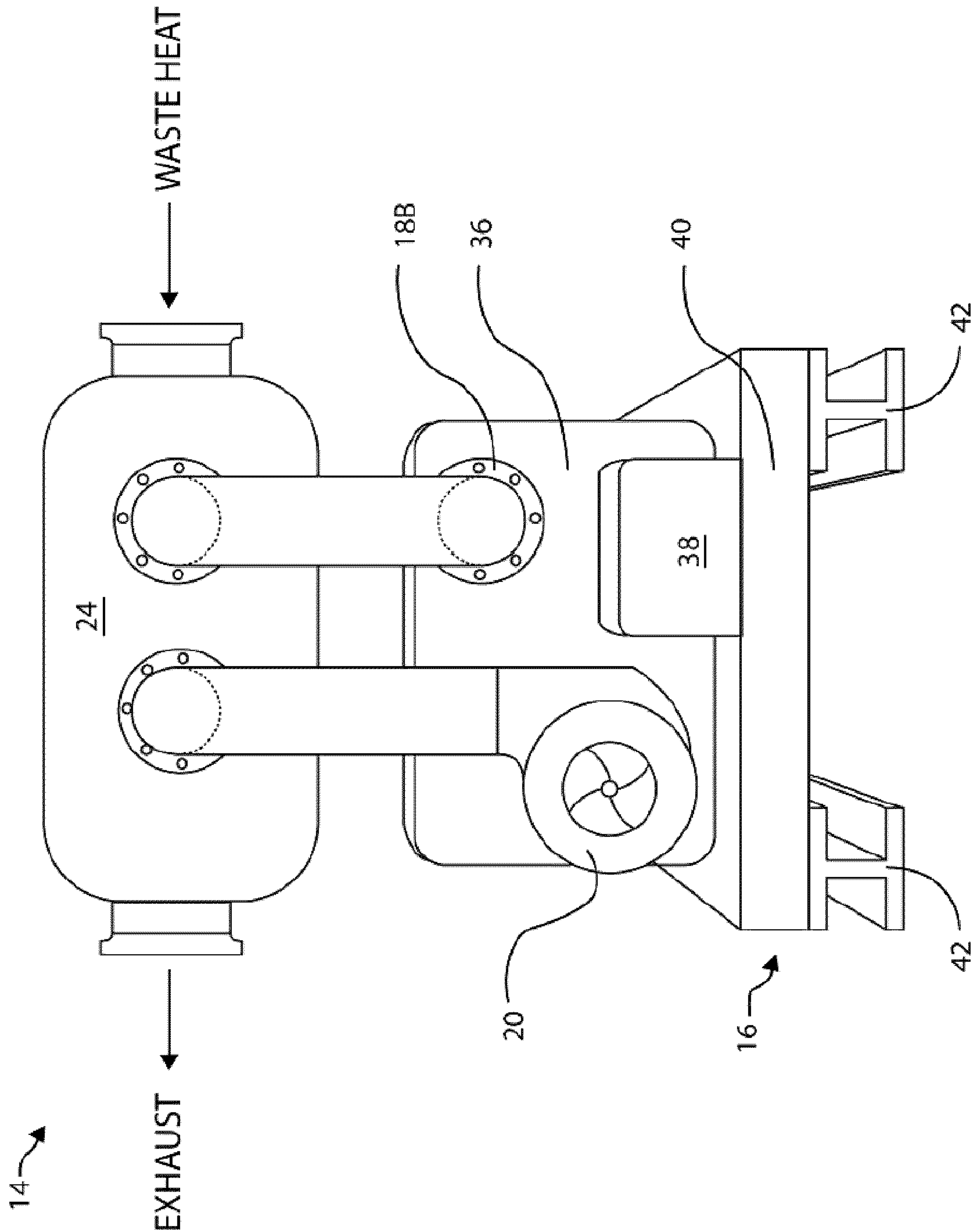


FIG. 3B

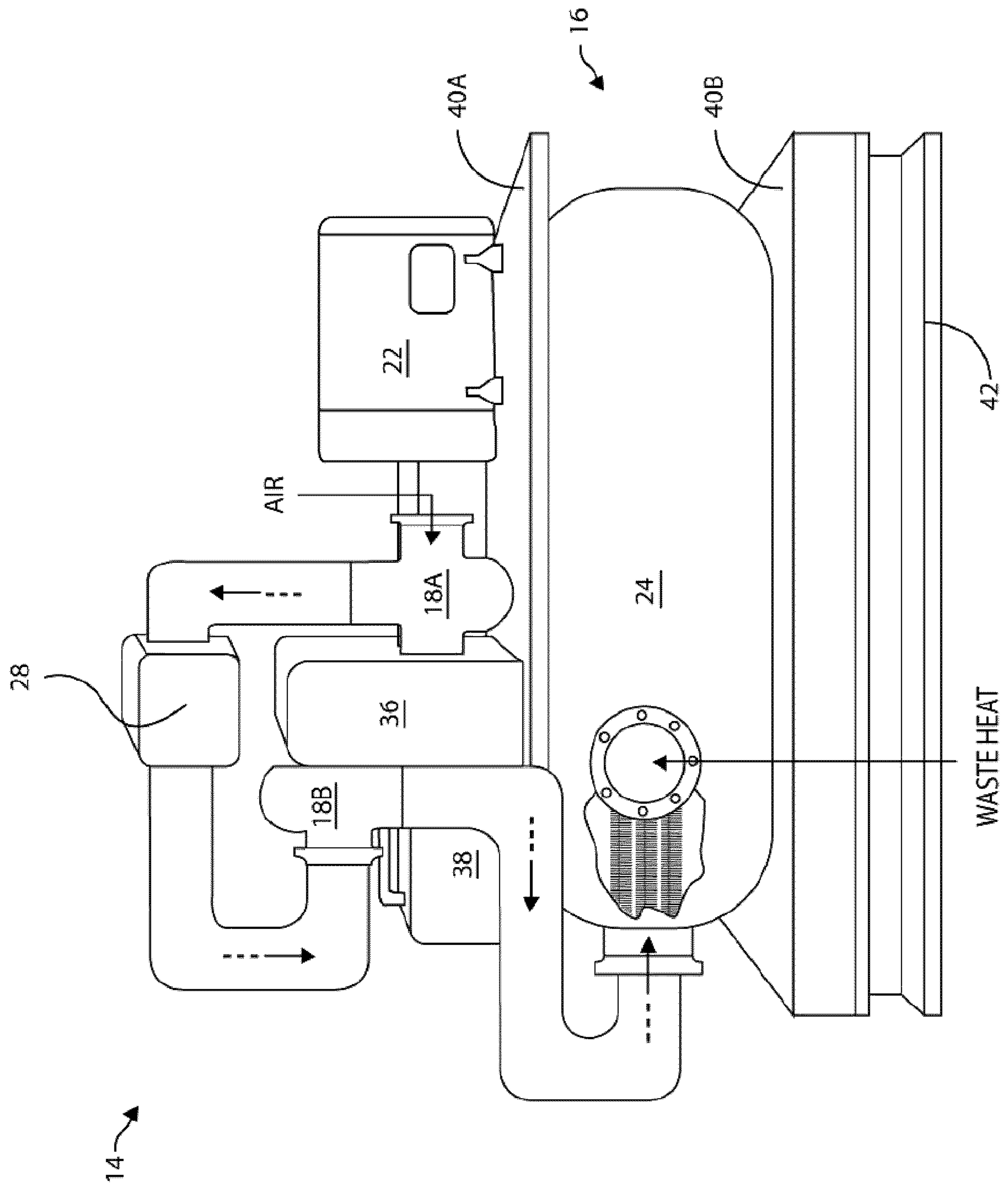


FIG. 4A

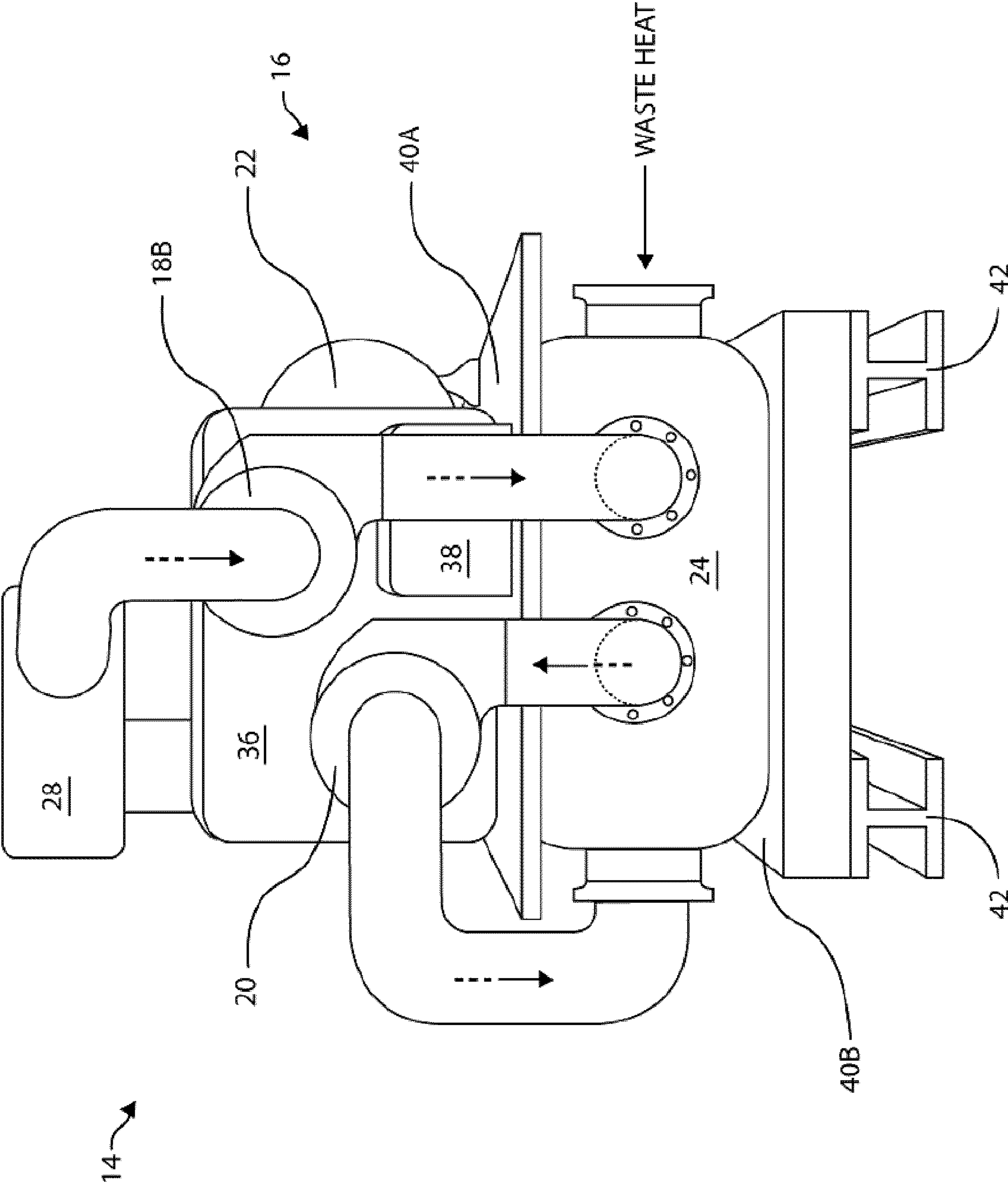


FIG. 4B

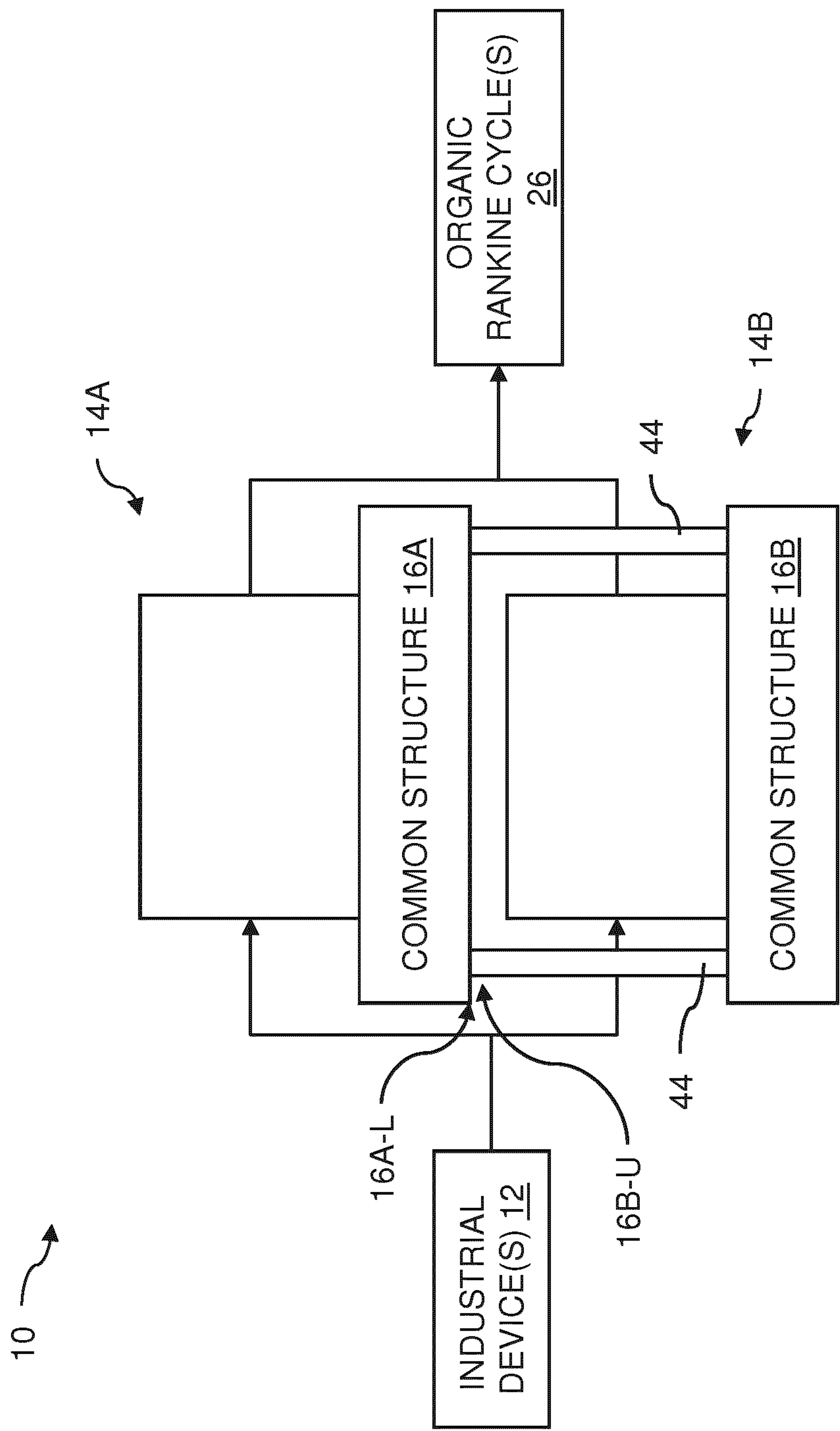


FIG. 5

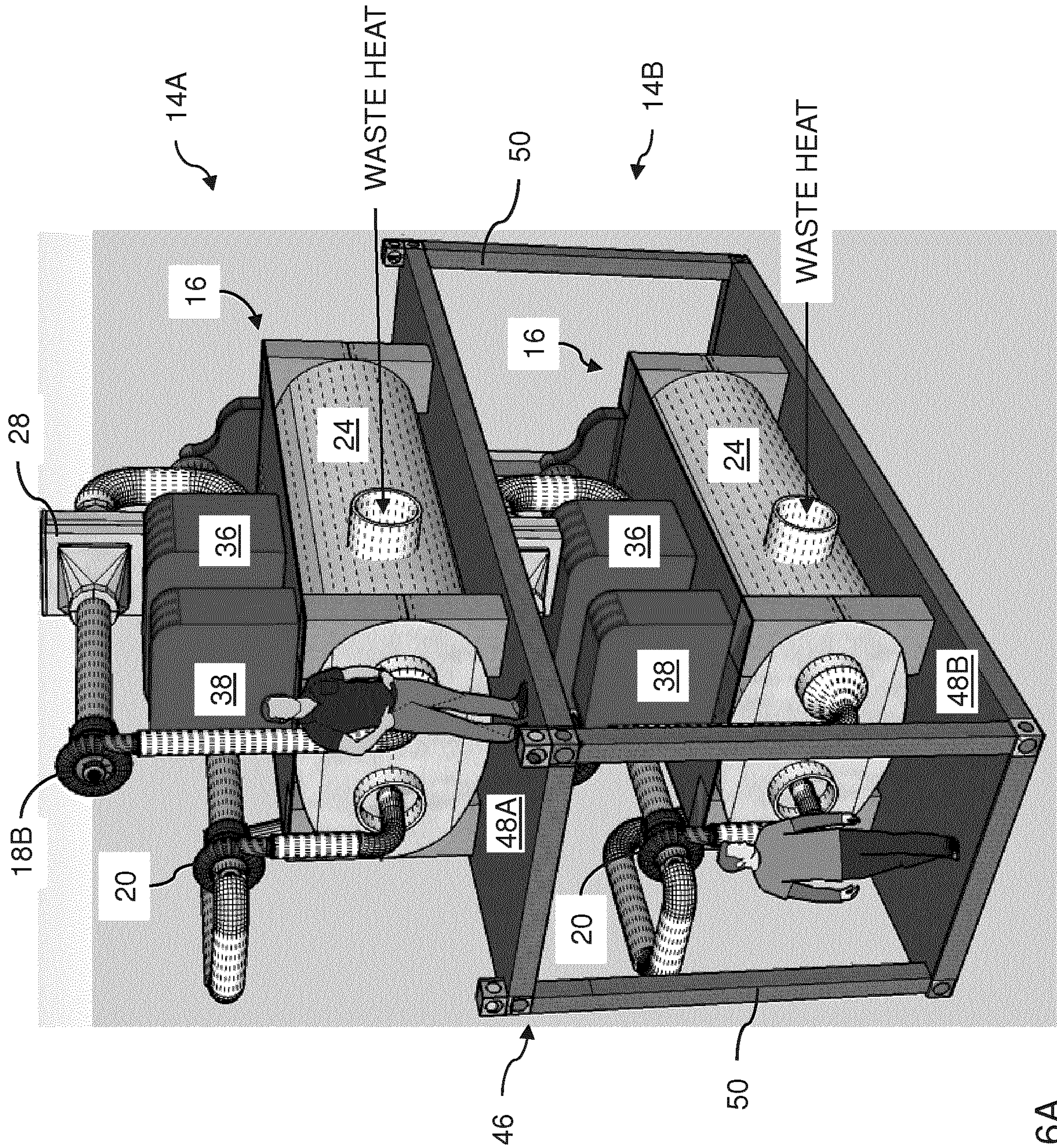
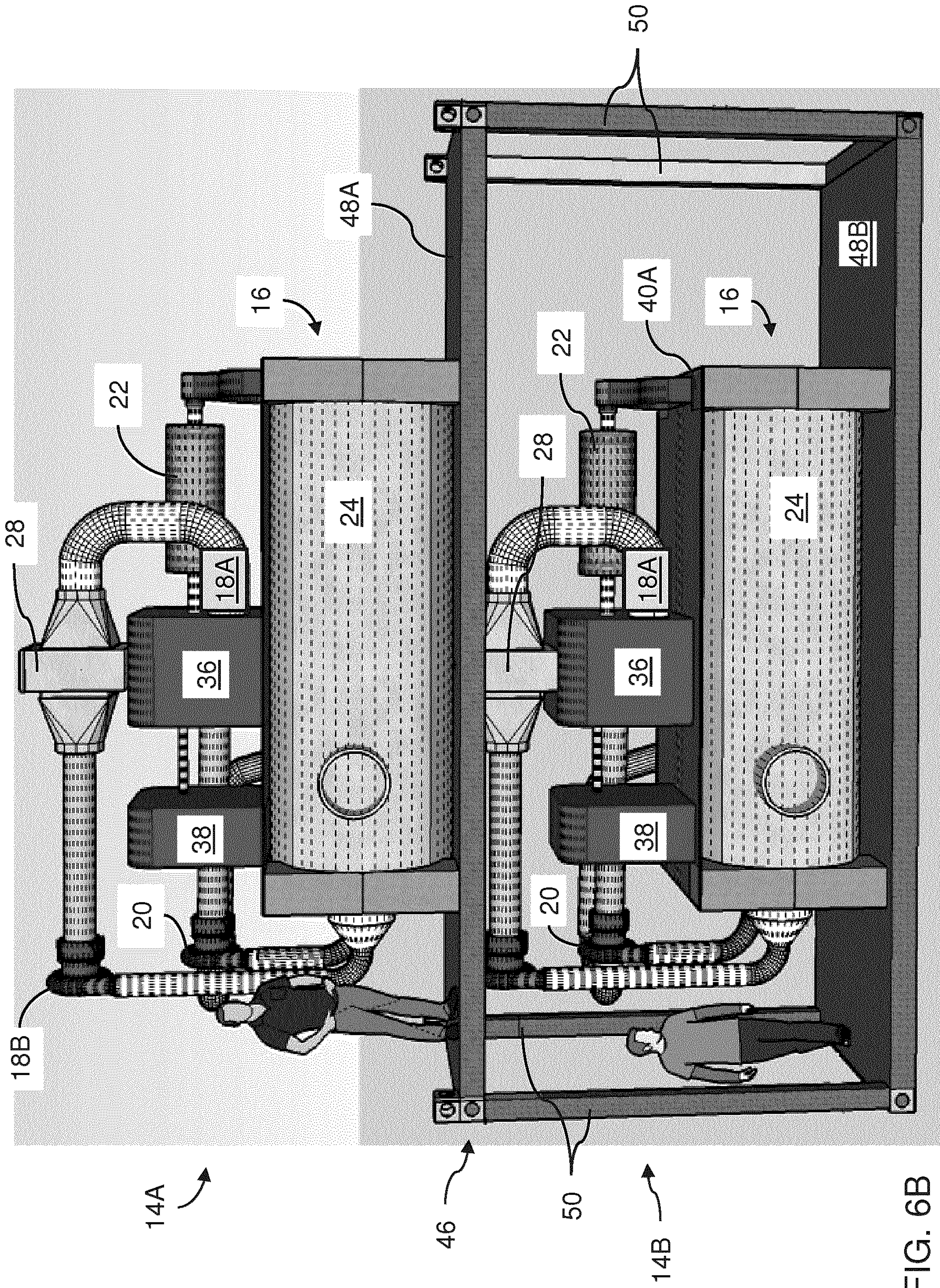


FIG. 6A



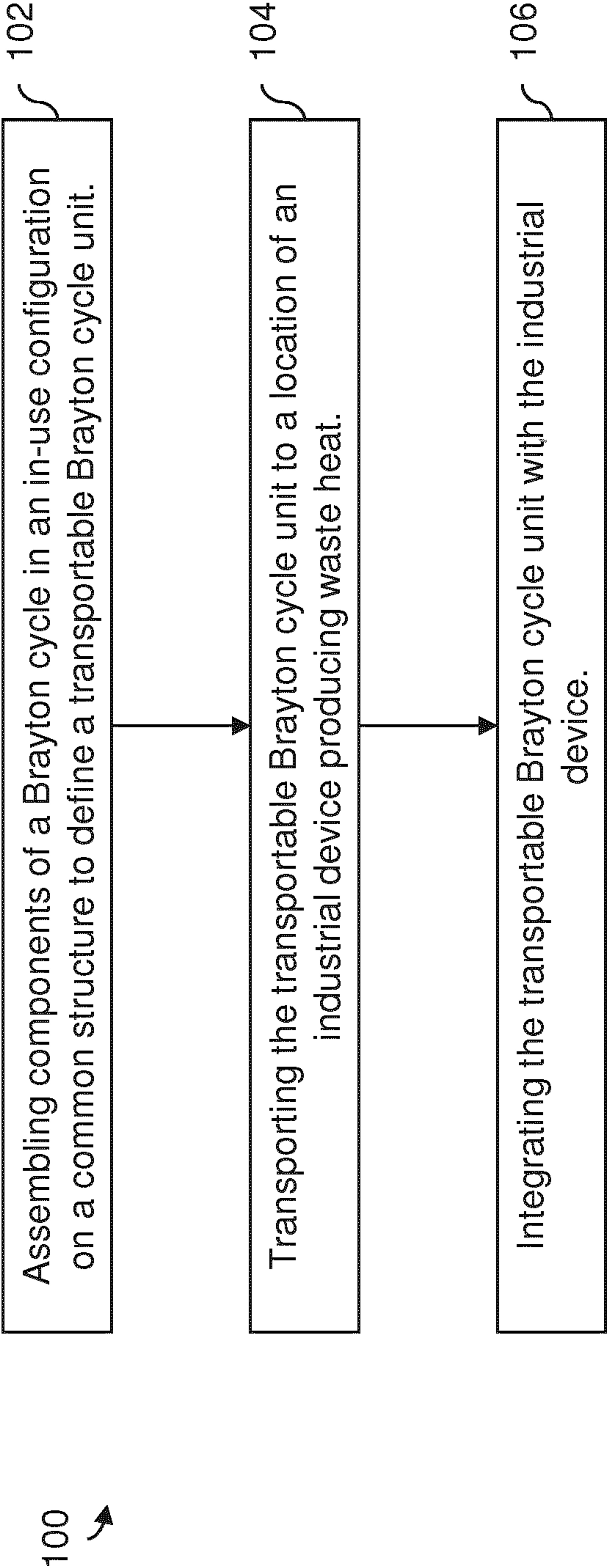


FIG. 7

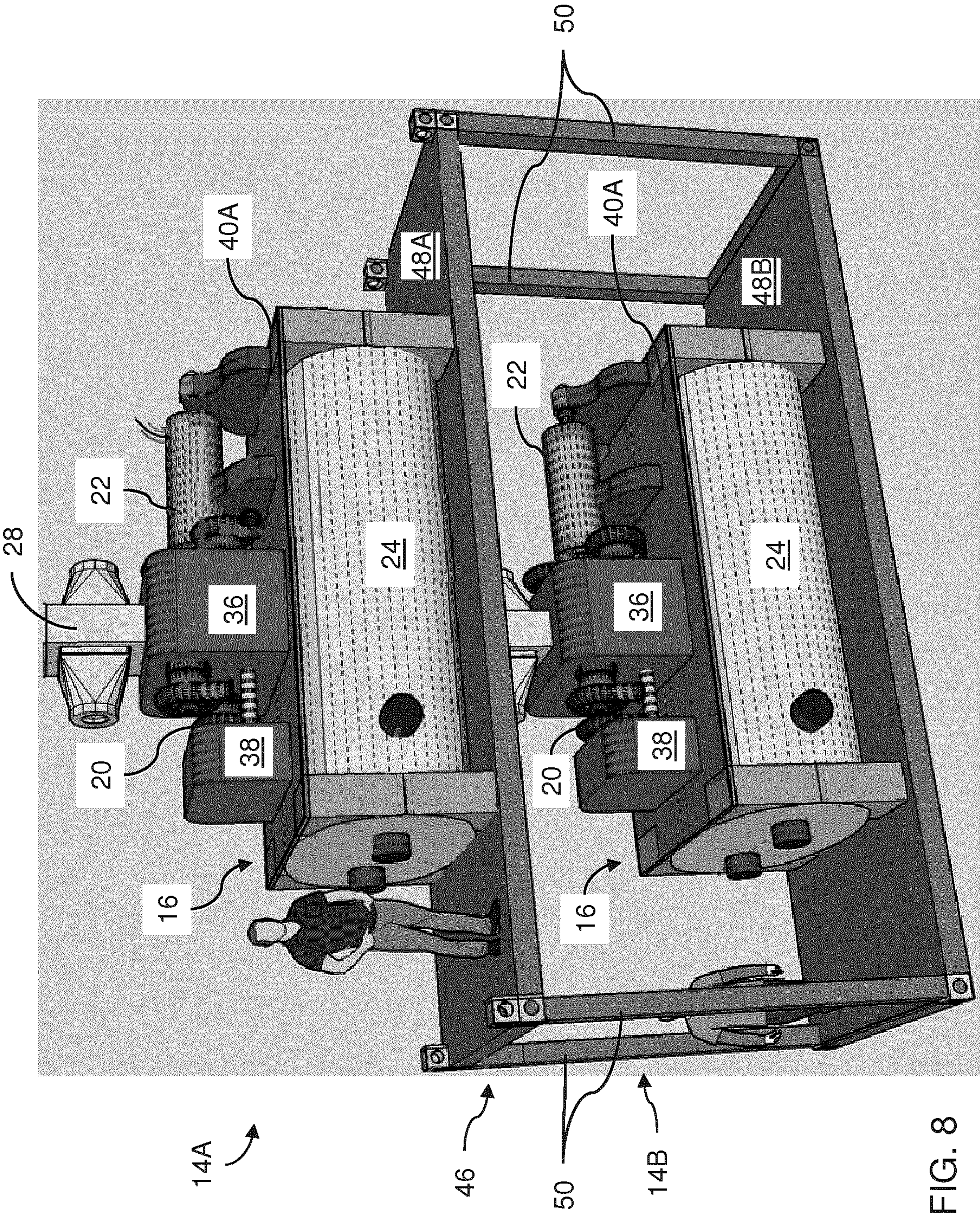


FIG. 8

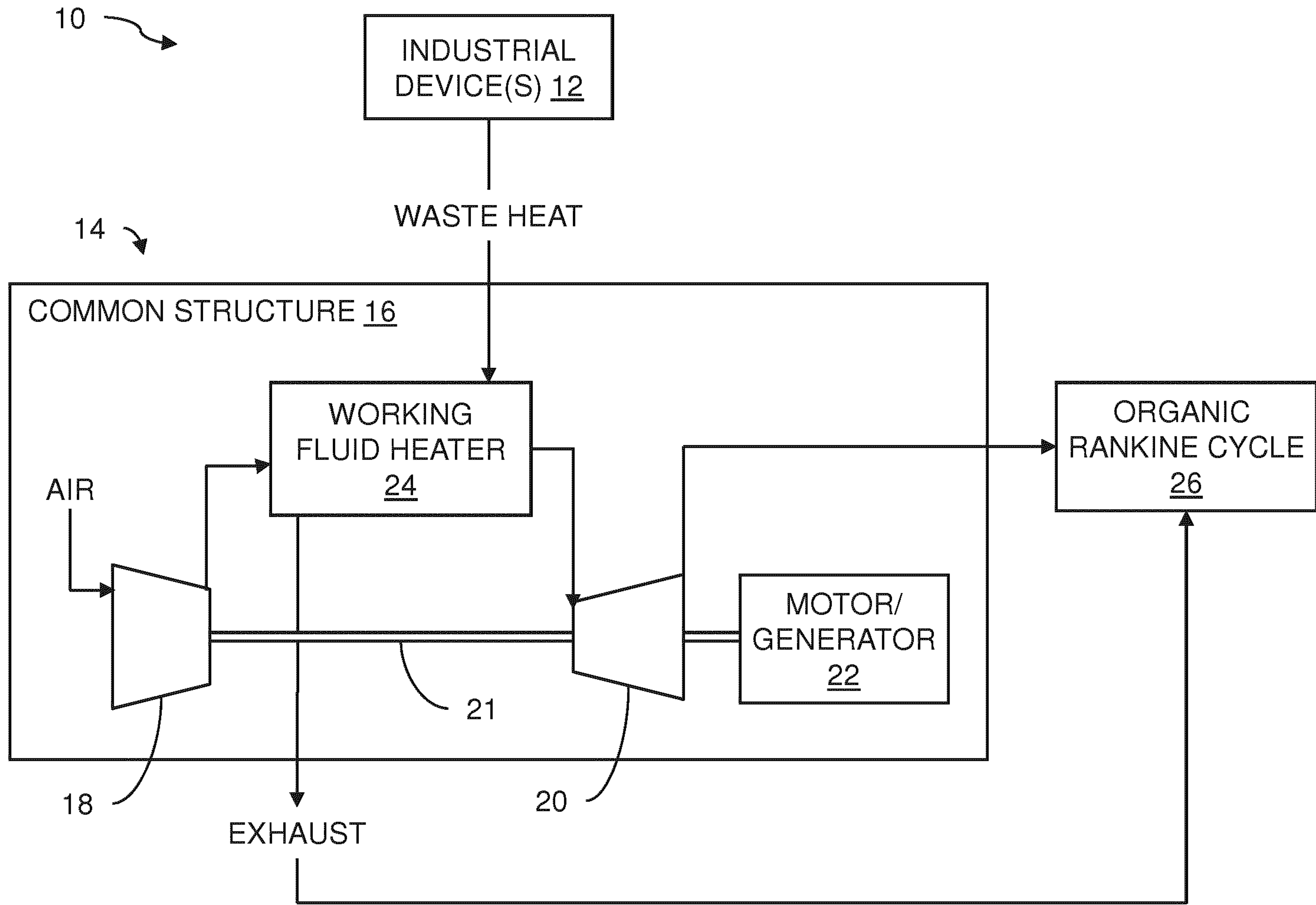


FIG. 1