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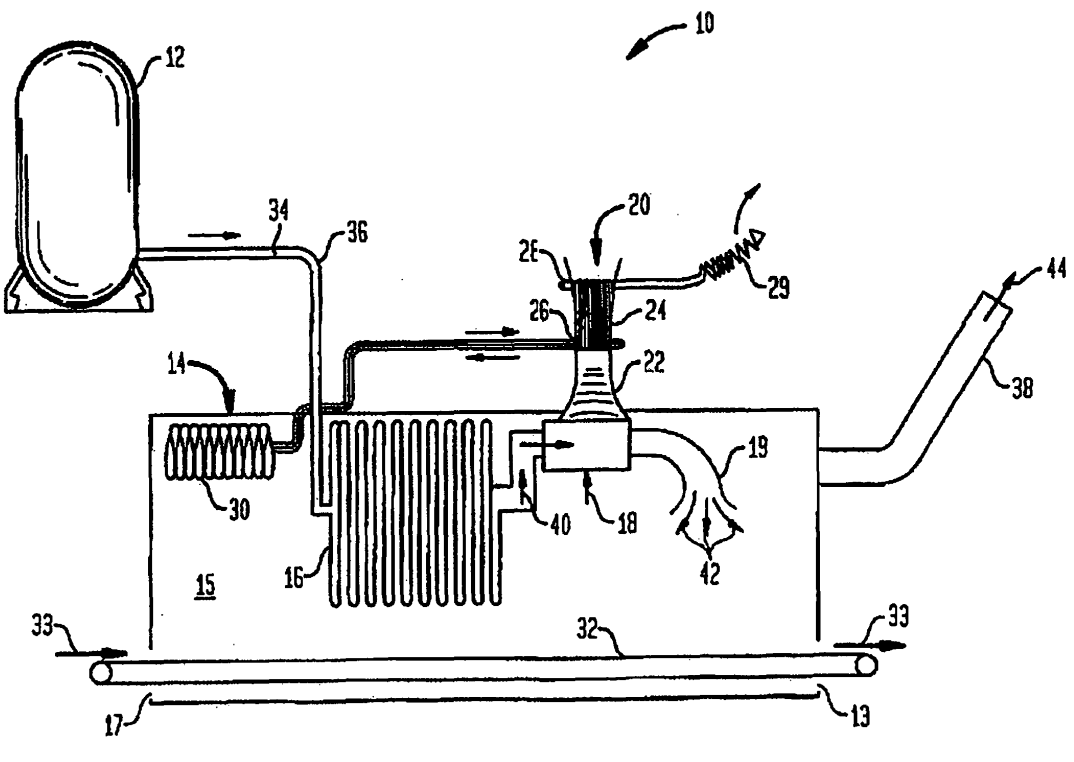
(54) Thermoacoustic refrigerator for cryogenic freezing

(57) A refrigeration system includes a cooler or freezer enclosure; a heat exchanger within the enclosure; a bulk storage tank (12) in fluid communication with the heat exchanger (16); a sound generator (18) in fluid communication with the heat exchanger (16); a thermoacoustic refrigerator (20) in acoustic communication with the sound generator (18); and an indirect heat exchange loop (68) in heat transfer contact with the thermoacoustic refrigerator. The heat exchanger (16) is adapted to receive pressurized fluid from the bulk storage tank (12), and to provide pressurized gas to the sound generator (18).

FIG. 1



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Description

BACKGROUND

[0001] Refrigeration relies on two major thermodynamic principles. First, the temperature of a fluid rises when the fluid is compressed, and falls when the fluid is expanded. Second, when two substances are placed in direct contact, heat will flow from the hotter substance to the cooler substance. While conventional refrigerators use pumps to transfer heat on a macroscopic scale, thermoacoustic refrigerators rely on sound to generate waves of pressure that alternately compress and relax the gas particles within a resonator tube.

[0002] A typical thermoacoustic refrigerator includes a sound generator which is disposed at one end of the resonator tube. A heat transfer stack is disposed within the resonator tube with indirect heat exchangers disposed at either end of the stack. A heat exchanger disposed at the end of the stack proximate to the sound generator will function to remove heat from the stack, while the heat exchanger at the end of the stack distal from the sound generator will function to transfer external heat into the stack.

[0003] The stack includes a large number of closely spaced surfaces or walls that are aligned parallel to the resonator tube. The stack provides a medium for heat transfer as the sound wave, namely a standing sound wave, oscillates through the resonator tube, where the walls are close enough so that each time a packet of gas (a collection of gas molecules that act and move together) moves, the temperature differential is transferred to the wall of the stack.

[0004] The cycle by which such heat transfer occurs is similar to the Stirling cycle. A packet of gas is compressed by the sound wave and moves away from the sound generator within the resonator tube. As the packet is compressed, the sound wave acts upon on the packet of gas, providing the power for the refrigerator. When the gas packet is at maximum compression, the gas ejects the heat into the stack since the temperature of the compressed gas is higher than the temperature of the stack. This phase is the refrigeration part of the cycle, moving the heat farther from the junction of the sound generator and the resonator.

[0005] In the second phase of the cycle, the gas is returned to its initial state. As the gas packet moves back towards the sound generator within the resonator tube, the sound wave expands the gas. Although some work is expended to return the gas to the initial state, the heat released at the end of the stack distal to the sound generator is greater than the work expended to return the gas to the initial state. This process results in a net transfer of heat away from the sound generator within the resonator tube. Finally, the packets of gas reabsorb heat from the cold reservoir to repeat the heat transfer process.

[0006] Typical thermoacoustic refrigerators known in the art have been inherently inefficient. These thermoacoustic refrigerators require induction of standing sound waves to produce a temperature gradient in the stack. Heat exchangers on either end of the stack can then be used to transfer heat to and from the stack. A large amount of power must be used to generate the sound waves used in a typical thermoacoustic refrigerator.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 is a schematic diagram of an embodiment of a system for freezing or cooling using a thermoacoustic refrigerator.

[0008] FIG. 2 is a schematic diagram of another embodiment of a system for freezing or cooling using a thermoacoustic refrigerator.

DESCRIPTION

[0009] System and process embodiments are provided for increasing the efficiency of freezing or cooling by utilizing a thermoacoustic refrigerator, wherein a sound generator utilizes pressurized cryogen or refrigerant fluid to generate sound waves, for example by passing the pressurized cryogen or refrigerant fluid through a pipe. Passing the pressurized fluid through a pipe can create noise through mechanisms which are utilized by musical instruments, for example, through the same mechanism by which a pipe organ operates.

[0010] A sound generator actuated by a gas may comprise a vibrating object which produces sound. One type of sound generator is utilized by wind instruments. At the beginning of the cycle, pressure is normal. Then an aperture, such as a valve, is partially opened and a short stream of air under pressure is released. In the second step of a full cycle, the valve is completely open and pressure is at a maximum. In the third cycle, the valve is partially closed, and the pressure has decreased from the maximum value. Then the valve is closed and the pressure is again the normal pressure. Examples of this type of sound generation include sirens and organs.

[0011] The first sirens powered pipes in an organ, comprising a stopcock that opened and closed a pneumatic tube, the stopcock being driven by the rotation of a wheel. An improved siren comprised two perforated disks that were mounted coaxially at the outlet of a pneumatic tube. One disk was stationary, while the other disk rotated. The rotating disk periodically interrupted the flow of air from the fixed disk, producing a tone. The pneumatic siren comprises a rotating disk with holes in it (a siren disk or rotor), such that the material between the holes interrupts a flow of air from fixed holes on the outside of the unit (a stator). The holes in the rotating disk alternately prevent and allow air to flow, resulting in alternating compressed and rarefied air pressure, i.e. sound. Instead of disks, most modem sirens use two concentric cylinders, which have slots parallel to their length. The inner cylinder rotates while the outer one remains stationary. As gas under pressure flows out of the slots of the inner cylinder and then escapes through the slots of the outer cylinder, the flow is periodically interrupted, creating a tone.

[0012] An air-jet sound generator is described below for the case of an organ pipe; but other air-jet instruments function similarly. A planar air jet emerges from a narrow flue slit and travels across the open mouth of the pipe to impinge on the upper lip. Acoustic flow through the pipe mouth and associated with the pipe modes deflects the jet so that it blows alternately inside and outside the lip, thus generating a fluctuating pressure that serves to drive the mode (fundamental or harmonic). Other sound generators that may be driven by a pressurized gas include, but are not limited to, air horns and steam whistles.

[0013] In one embodiment, a process is provided for at least one of cooling or freezing including: providing liquid refrigerant or cryogen at a pressure greater than one atmosphere; feeding the pressurized liquid refrigerant or cryogen to a freezer comprising at least a first heat exchanger; extracting cooling from the pressurized liquid refrigerant or cryogen and vaporizing the liquid refrigerant or cryogen to form a pressurized gas; passing the pressurized gas through a sound generator and generating sound waves; applying the sound waves to a thermoacoustic refrigerator; and generating additional refrigeration from said applying the sound waves to the thermoacoustic refrigerator. Such additional refrigeration may be used to increase the efficiency of the process or in an independent cooling or freezing process.

[0014] In various embodiments, the process may further include at least one of delivering the gas exiting the sound generator to a cooling section of the freezer; providing sub-cooling from the additional refrigeration to the liquid refrigerant or cryogen prior to entering the at least one heat exchanger; or applying the additional refrigeration to the freezer or to an independent refrigeration loop.

[0015] In certain embodiments, applying the sound waves may include propagating the sound waves in a resonator, creating a standing wave in a stack of the thermoacoustic refrigerator and inducing a temperature gradient across the stack. The process may include transferring heat from the warm end of the stack to the external atmosphere and transferring additional refrigeration so generated into the freezer by an indirect heat exchange loop.

[0016] In certain embodiments, the liquid refrigerant or cryogen, such as for example nitrogen, may be provided from a bulk storage tank. The pressure of the bulk storage tank may be up to 6 bar, or higher if desired.

[0017] Referring now to FIG. 1, one embodiment of a refrigeration system apparatus 10 for carrying out the process includes a refrigerant bulk storage tank 12, which may be maintained at up to about 6 bar (or higher if desired), and a cooler or freezer enclosure or chamber 14 having at least one internal heat exchanger 16 disposed within an interior 15 of the enclosure 14. The enclosure 14 is provided with openings 13, 17 which can be alternated as an inlet and outlet for the enclosure. The bulk storage tank 12 may be constructed and arranged to contain a cryogen or refrigerant fluid, such as at least one of gaseous nitrogen, liquid nitrogen, gaseous carbon dioxide, or liquid carbon dioxide.

[0018] In certain embodiments, the at least one heat exchanger 16 is adapted to receive pressurized fluid, in certain embodiments a liquid, from the bulk storage tank 12, and to provide pressurized gas to a sound generator 18. The sound generator 18 may be disposed within the cooler or freezer enclosure 14.

[0019] The internal heat exchanger 16 may be in fluid communication with the bulk storage tank 12 via a first fluid pathway 34. The sound generator 18 may also be in fluid communication with the internal heat exchanger 16. A thermoacoustic refrigerator 20, functionally connected to the sound generator 18, includes a resonator tube 22, partially cut away to show a stack 24 in acoustic communication with the sound generator, a cold-end heat exchanger 26 and a warm-end heat exchanger 28 in thermal contact with the stack 24. An auxiliary heat exchanger 29 may be connected to the heat exchanger 28 to transfer heat to the atmosphere external to the apparatus 10.

[0020] In one embodiment, liquid nitrogen travels along the fluid pathway 34 which may include a conduit 36 from the bulk storage tank 12 and is passed through internal heat exchanger 16 in the enclosure 14. Warmer high velocity gas in the enclosure 14 passes through the coils of the internal heat exchanger 16 and is cooled via an apparatus such as a fan or blower (not shown) which acts to circulate the air within the enclosure 14. The liquid nitrogen in the conduit 36 is converted to high pressure nitrogen gas within internal heat exchanger 16, providing a cooling effect within the enclosure 14. The high pressure nitrogen gas then passes out of the internal heat exchanger 16 via conduit 40.

[0021] At least a portion of the high pressure nitrogen gas from the internal heat exchanger 16 is used to generate sound waves by the sound generator 18. In certain embodiments, the sound generator 18 may include an exit 19 for a pressurized gas stream 42 to be introduced into the interior 15 of the enclosure 14. The sound waves generated by the sound generator 18 form a standing sound wave within the resonator tube 22, which induces a temperature differential across the stack 24. The warm-end heat exchanger 28, which is disposed on one side of the stack 24 distal to the sound generator 18, is used to vent heat from the refrigeration apparatus 10 to an external atmosphere.

[0022] In certain embodiments, the indirect heat exchange loop is in heat transfer contact with the cold end of the stack 26 of the thermoacoustic refrigerator 20, and is in heat transfer communication with a second internal heat exchanger 30 located at the interior 15 the enclosure 14.

[0023] The cold-end heat exchanger 26, part of the indirect heat exchanger circuit or loop, which is disposed at one end of the stack 24 proximate to the sound generator 18, may be used to provide additional cooling to the enclosure 14. This may be accomplished using an indirect heat exchanger circuit or loop, which is in heat transfer contact with the enclosure 14 via a second fluid pathway, such as by being in heat transfer contact with a second internal heat exchanger 30 within the enclosure 14. The enclosure 14 may be constructed and arranged to accommodate a conveyor 32 upon which products to be cooled or frozen (see FIG. 2) may be carried through the interior 15 of the enclosure 14. Movement of the conveyor 32 may be in a direction indicated by arrows 33 in FIGS. 1 and 2, but said direction may be reversed as necessary. The enclosure 14 may also have an exhaust conduit 38 to allow venting of spent refrigerant or cryogen 44 from the enclosure 14.

[0024] At least a portion of the high pressure nitrogen gas exiting the internal heat exchanger 16 may be exhausted directly into the enclosure 14 in order to provide an additional cooling effect.

[0025] In another embodiment, a process is provided for at least one of cooling or freezing including: providing liquid refrigerant or cryogen at a pressure greater than one atmosphere; separating the liquid refrigerant or cryogen into a first liquid stream and a second liquid stream; vaporizing the first liquid stream to form a pressurized gas stream; feeding the pressurized gas stream to a freezer comprising at least a first heat exchanger; passing the pressurized gas stream through a sound generator and generating sound waves; applying the sound waves to a thermoacoustic refrigerator; generating additional refrigeration from said applying the sound waves to the thermoacoustic refrigerator to sub-cool the second liquid stream; and releasing the sub-cooled second liquid stream into the cooler or freezer.

[0026] Referring now to FIG. 2, in certain embodiments, applying the sound waves may include propagating the sound waves in a resonator tube 62, creating a standing wave in a stack 64 of the thermoacoustic refrigerator 60 and inducing a temperature gradient across the stack 64. The process may include transferring heat from the warm end of the stack 64 via an indirect heat exchange loop 68 in thermal contact with a first liquid nitrogen stream 82 in conduit 83 in a first fluid pathway to effect the vaporization of the first liquid nitrogen stream 82. For example but not limitation, the first liquid nitrogen stream 82 may be fed into the conduit 83 in the first fluid pathway in heat transfer contact with the warm end indirect heat exchange loop 68, converting the liquid nitrogen 82 into saturated, pressurized nitrogen gas 96. The nitrogen gas 96 may then be fed through conduit 86 into another heat exchanger 56 located at an interior 55 of a cooler or freezer enclosure 54, where fans (not shown) blowing across the heat exchanger 56 create a highly convective environment and warm the saturated, pressurized nitrogen gas 96, thereby providing more cooling to the enclosure 54. Pressurized nitrogen gas 98 transferred through conduit 88, which connects a sound generator 58 to the heat exchanger 56, may then be used to power the sound generator 58 which provides energy to the resonator tube 62 and the thermoacoustic refrigerator 60. The spent gas 100 can then be exhausted to the atmosphere via exhaust conduit 90.

[0027] The process may further include transferring the additional refrigeration from the cold end of the stack 64 for sub-cooling a second liquid nitrogen stream 94 via another indirect heat exchange loop 66. In certain embodiments, the sub-cooled second liquid nitrogen stream 94 is released as a spray 71 for contacting products 74 in the enclosure 54. For example but not limitation, the second liquid nitrogen stream 94 may be fed via conduit 84 in a second fluid pathway into the enclosure 54 through a sub-cooler 70. The sub-cooler 70 may be part of the cold-end indirect heat exchange loop 66 which is part of the thermoacoustic refrigerator 60. The subcooler 70 may provide an additional sub-cooling to the liquid nitrogen 94. The liquid nitrogen 94 may then be released as a spray or jet streams 71 into the enclosure 54 by a liquid delivery device 72, such as a sprayer or other impingement device, the liquid optionally distributed within the enclosure 54 by fans (not shown).

[0028] Various impingement devices can be used to accomplish convective heat transfer within food freezing tunnels. For example but not limitation, liquid cryogens may be mixed within an impingement hood located above a conveyor carrying food products. The liquid cryogen is then directed to an impinger, which in turn directs the liquid cryogen through the impingement jets of an impingement plate directly onto food products on the conveyor.

[0029] As shown in FIG. 2, another embodiment of a refrigeration system apparatus 50 for carrying out this embodiment of the process includes the cooler or freezer enclosure or chamber 54, at least one heat exchanger 56 within the enclosure 54; a bulk storage tank 52 in fluid communication with the at least one heat exchanger 56; a sound generator 58 in fluid communication with the at least one heat exchanger 56; a thermoacoustic refrigerator 60 in acoustic communication with the sound generator 58; and an indirect heat exchange loop 68 in heat transfer contact with the thermoacoustic refrigerator 60. The bulk storage tank 52 may be constructed and arranged to contain a refrigerant or cryogen fluid, such as at least one of gaseous nitrogen, liquid nitrogen, gaseous carbon dioxide, or liquid carbon dioxide.

[0030] In certain embodiments, liquid nitrogen 92, such as at -320°F (-196°C), flows from the bulk tank 52 into conduit 80, where it is separated or diverges into two streams 82, 94. The liquid nitrogen 82 flowing through conduit 83 in the first fluid pathway is in heat transfer contact with the warm-end heat exchange loop 68 of the thermoacoustic refrigerator 60 where it is vaporized into high pressure nitrogen gas 96, such as at -320°F (-196°C). The high pressure nitrogen gas 96 then passes via the conduit 86 into internal heat exchanger 56 within the enclosure 54 where warmer high velocity gas in the enclosure 54 passes through the coils of internal heat exchanger 56 and is cooled. The high pressure nitrogen gas 98, which is now at a higher temperature, such as at -80°F (-62°C), passes into the sound generator 58 via conduit 88, where it is utilized to generate sound waves. The sound waves generated by the sound generator 58 form a standing sound wave within the resonator tube 62, which induces a temperature differential across the stack 64. The nitrogen gas 100 exiting the sound generator 58 may be exhausted to the external atmosphere via exhaust conduit 90.

[0031] The cold-end heat exchange loop 66 of the thermoacoustic refrigerator 60 may be in heat transfer contact with the conduit 84 in the second fluid pathway. The cold stream of cold-end heat exchange loop 66 may provide, for example, an inlet temperature of about -400°F (-240°C) to the sub-cooler 70. Liquid nitrogen 92 flowing through the conduit 84 in the second fluid pathway is sub-cooled, to such as -380°F (-229°C), by thermal exchange with heat exchange loop 70 in certain embodiments prior to entering the enclosure 54. After entering the enclosure 54, the sub-cooled liquid nitrogen 94 may be sprayed onto the products 74 within the enclosure 54 via spraying apparatus 72, or another condensed refrigerant or cryogen impingement device.

[0032] In certain embodiments, the refrigeration system 50 further includes a conduit 80 that separates into the conduit 83 for the first liquid nitrogen stream 82 in the first fluid pathway connecting the bulk storage tank 52 with the heat exchanger 56, and the conduit 84 in the second fluid pathway in communication with the interior 55 of the enclosure 54. The first liquid nitrogen stream 82 may be in heat transfer contact with the warm end 68 of the stack 64 of the thermoacoustic refrigerator 60. The indirect heat exchange loop may be in heat transfer contact with the cold end 66 of the stack 64 of the thermoacoustic refrigerator 60, and further may be in heat transfer contact with the conduit 84 and therefore the second liquid nitrogen stream 94.

[0033] The refrigeration system 50 may include a liquid delivery device 72 disposed at the interior 55 of the enclosure 54 and in fluid communication with the conduit 84 in the second fluid pathway. The liquid delivery device 72, such as a spray device or other impingement device, may be disposed proximate (such as for example over) a conveyor 76 moving through the interior 55 of the enclosure 54. Products 74 such as food products carried by the conveyor 76 may be contacted by the sprays or jet streams 71 of condensed refrigerant or cryogen provided by the liquid delivery device 72.

[0034] Although embodiments have been exemplified by describing refrigeration utilizing the phase change from liquid nitrogen to gaseous nitrogen, the use of the phase change of liquid carbon dioxide to gaseous carbon dioxide, or the use of high pressure gaseous cryogen or refrigerant fluids initially are other embodiments useful for thermoacoustic refrigeration systems and processes.

[0035] In certain embodiments, a process is provided for at least one of cooling or freezing in a refrigeration system, comprising delivering a pressurized refrigerant or cryogen fluid from a bulk storage tank to at least one heat exchanger; delivering a pressurized gas exiting the at least one heat exchanger to a sound generator and generating sound waves; applying the sound waves to a thermoacoustic refrigerator; and generating additional refrigeration from said applying the sound waves to the thermoacoustic refrigerator. The pressurized refrigerant or cryogen fluid may be a pressurized refrigerant or cryogen gas.

[0036] It will be understood that the embodiments described herein are merely exemplary, and that one skilled in the art may make variations and modifications without departing from the spirit and scope of the invention. All such variations and modifications are intended to be included within the scope of the invention as described and claimed herein. Further, all embodiments disclosed are not necessarily in the alternative, as various embodiments of the invention may be combined to provide the desired result.

Claims

1. A process for at least one of cooling or freezing comprising:

providing liquid refrigerant or cryogen at a pressure greater than one atmosphere;
feeding the pressurized liquid refrigerant or cryogen to a cooler or freezer comprising at least a first heat exchanger;
extracting cooling from the pressurized liquid refrigerant or cryogen and vaporizing the liquid refrigerant or cryogen to form a pressurized gas;
passing the pressurized gas through a sound generator and generating sound waves;
applying the sound waves to a thermoacoustic refrigerator; and
generating additional refrigeration from said applying the sound waves to the thermoacoustic refrigerator.

2. The process of claim 1, further comprising delivering gas exiting the sound generator to a cooling section of the cooler or freezer.

3. The process of claim 1, further comprising applying the additional refrigeration to an independent refrigeration loop.

4. The process of claim 1, further comprising applying the additional refrigeration to the cooler or freezer.

5. The process of claim 1, wherein said applying the sound waves comprises propagating the sound waves in a resonator; creating a standing wave in a stack of the thermoacoustic refrigerator; and inducing a temperature gradient across the stack.

6. The process of claim 5, further comprising transferring heat from a warm end of the stack to an external atmosphere and transferring the additional refrigeration into the freezer by an indirect heat exchange loop.

7. The process of claim 1, wherein the refrigerant or cryogen is at least one of nitrogen or carbon dioxide.

8. A refrigeration system comprising:

an enclosure;
at least one heat exchanger within the enclosure;
a bulk storage tank in fluid communication with the at least one heat exchanger;
a sound generator in fluid communication with the at least one heat exchanger;
a thermoacoustic refrigerator in acoustic communication with the sound generator; and
an indirect heat exchange loop in heat transfer contact with the thermoacoustic refrigerator.

9. The refrigeration system of claim 8, wherein the at least one heat exchanger is adapted to receive pressurized fluid from the bulk storage tank, and to provide pressurized gas to the sound generator.

10. The refrigeration system of claim 8 or 9, wherein the indirect heat exchange loop is in heat transfer contact with a cold end of a stack of the thermoacoustic refrigerator, and is in heat transfer communication with a second heat exchanger located within the enclosure.

11. The refrigeration system of any of claims 8 to 10, wherein the sound generator further comprises an exit for the pressurized gas to be introduced into the enclosure.

12. The refrigeration system of any of claims 8 to 11,, further comprising a conduit separating into a first fluid pathway connecting the bulk storage tank with the at least one heat exchanger, and a second fluid pathway in communication with an interior of the enclosure.

13. The refrigeration system of claim 12, wherein the first fluid pathway is in heat transfer contact with a warm end of a stack of the thermoacoustic refrigerator.

14. The refrigeration system of claim 12 or 13, wherein the indirect heat exchange loop is in heat transfer contact with a cold end of a stack of the thermoacoustic refrigerator, and is in heat transfer contact with the second fluid pathway.

15. The refrigeration system of any of claims 12 to 14, further comprising a liquid nitrogen delivery device disposed within the enclosure and in fluid communication with the second fluid pathway.

16. The refrigeration system of any of caims 8 to 15, wherein the bulk storage tank is constructed and arranged to contain a fluid which is at least one of gaseous nitrogen, liquid nitrogen, gaseous carbon dioxide, or liquid carbon dioxide.

FIG. 1

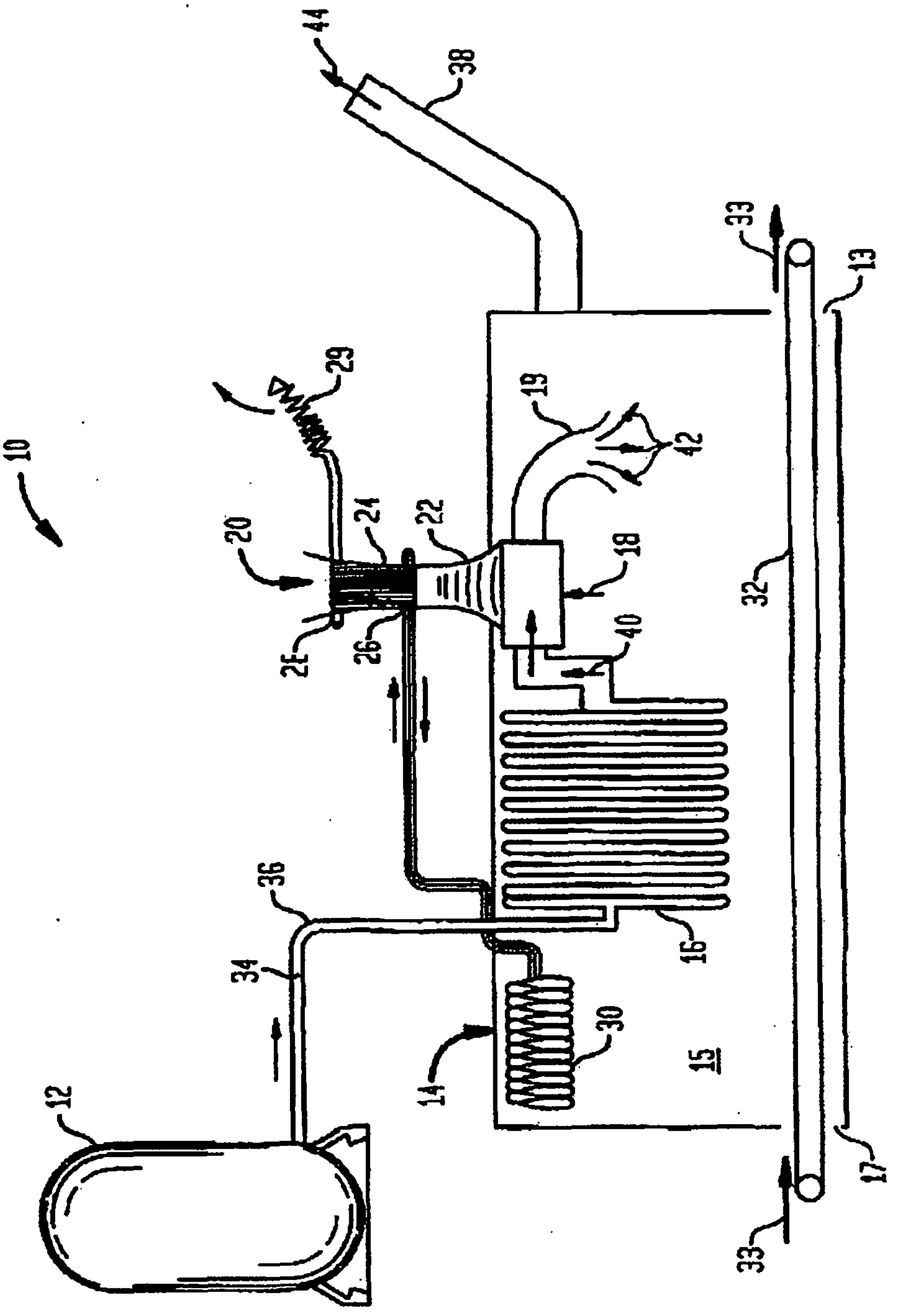
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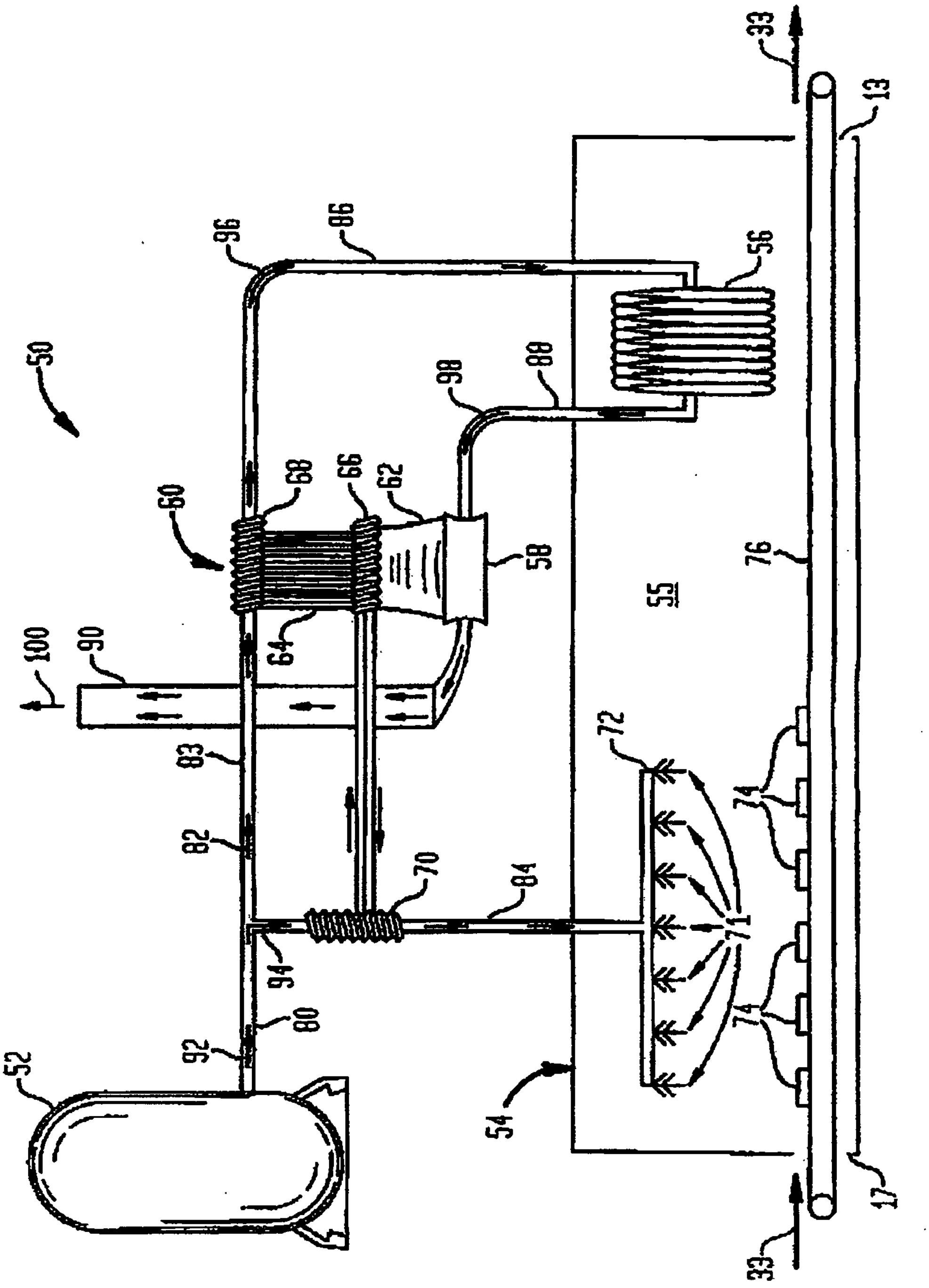
FIG. 2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