



- (51) **International Patent Classification:**
F25B 15/02 (2006.01) *F01K 25/06* (2006.01)
C09K 5/04 (2006.01)
- (21) **International Application Number:**
PCT/US2012/026313
- (22) **International Filing Date:**
23 February 2012 (23.02.2012)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
61/446,010 23 February 2011 (23.02.2011) US
61/500,594 23 June 2011 (23.06.2011) US
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- (81) **Designated States** (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ,

CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

- *with international search report (Art. 21(3))*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) **Title:** THERMALLY ACTIVATED PRESSURE BOOSTER FOR HEAT PUMPING AND POWER GENERATION

(57) **Abstract:** Thermally activated systems and related processes for raising the pressure of a gaseous working fluid are described. The systems and processes can be used for both winter heating and summer cooling with increased efficiency. They can also be used for other applications in need of an efficient thermally driven compressor, such as a power generation process.



WO 2012/116174 A1

[0001] Thermally Activated Pressure Booster for Heat Pumping and Power Generation

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] This application is entitled to priority pursuant to 35 U.S.C. § 119(e) to U.S.

5 Provisional Patent Application No. 61/446,010, filed on February 23, 2011, and U.S. Provisional Patent Application No. 61/500,594, filed on June 23, 2011, which are hereby incorporated by reference herein in its entirety.

STATEMENT OF GOVERNMENT LICENSE RIGHTS

[0003] This invention was made in part with government support under Grant No. 1113100
10 awarded by the National Science Foundation Small Business Innovation Program. The U.S. government has certain rights in this invention.

BACKGROUND OF THE INVENTION

[0004] Heating and cooling in buildings use over 20% of the total energy consumed in the United States. Vehicle air conditioners also consume a significant portion of the transportation
15 fuel. In addition, heating and cooling of process streams are also performed in the process industry, especially chemical industry and power generation industry. As the price of energy goes up, it becomes more desirable to run heating and cooling systems with solar thermal energy. Solar energy is plentiful during the hot summer days when the demand for air conditioning is greatest, and when the load on the electrical grid reaches its peak. Uses of solar water heaters are
20 taking off in many places, including southern Europe and China. Such systems typically have a large excess supply of heat on hot summer days. It would be desirable to use this excess heat for air conditioning to meet the high demand for cooling at such time.

[0005] However, the state-of-art lithium bromide (LiBr)-water absorption system, a thermally activated heat pump (TAHP) for cooling applications, is not suitable for use in
25 residential and light commercial heating and cooling applications, because it uses water as the refrigerant and a salt solution as the absorbent. Water has a low vapor pressure. Any living space heating and cooling systems using water as the working fluid would have to operate at a rather deep vacuum, which makes the systems bulky. Furthermore, LiBr is a salt, which is corrosive and can freeze out if the operating conditions are not well controlled, which means
30 skilled personnel is often needed to service such TAHP systems. In addition, the LiBr-water absorption system is not suitable for winter heating when the ambient temperature is below water freezing temperature, because water freezes at 0° C. Thus, LiBr-water absorption heat pumps are often called “LiBr chillers,” i.e., they are used for chilling only. The LiBr-water absorption

system typically needs heat of greater than 88° C in order to avoid freeze out issues, rendering the system unsuitable for many solar water heaters.

[0006] A TAHP can have a heating coefficient of performance (heating COP) significantly greater than 1, while a conventional gas or oil furnace only has a heating COP of less than 1. A good single-effect TAHP in theory can have a heating COP of greater than 1.7, while a double-effect TAHP in theory can have a heating COP of even greater. Therefore, by using a TAHP, the thermal energy needs for heating can be reduced more than 40% with a single effect TAHP system and even more with a double effect TAHP system. Considering the huge amount of energy consumed by heating, a TAHP for space heating is extremely attractive.

[0007] Unfortunately, such promising heat efficient technologies have not been commercialized despite many years of research and development efforts. This is in part because of the lack of safe and efficient TAHPs. The currently available TAHPs based on LiBr-water absorption or its derivatives use pure water as the working fluid. They cannot be used when the space heating is most needed, i.e., when the ambient temperature is close to or below 0° C, because water freezes below 0° C.

[0008] In theory, ammonia can be used as a working fluid in both vapor compression heat pumps and thermally activated heat pumps. However, one of the problems with ammonia is that it is highly toxic, therefore is not very desirable for residential and vehicular applications. A secondary loop is needed in order to mitigate the toxicity issue, which adds to the cost of the system. In addition, the heat of absorption of ammonia in water is much greater than the latent heat of ammonia vaporization. This requires large heat exchange duties for absorption cooling and distillation column boiling in an ammonia-water absorption heat pump system, which means a very large heat exchanger cost and significant thermal energy degradation in the heat exchangers. This in turn increases the cost and decreases the COP of such TAHPs. Even with the so-called GAX system, which utilizes more effectively the heat released during the absorption process for distillation separation, the single effect heating COP of the ammonia-water system is only at about 1.6, or a cooling COP of about 0.6, which is significantly lower than that of the LiBr absorption system, whose cooling COP is on the order of 0.75. Ammonia also has other problems such as its corrosivity with copper and aluminum, two of the best materials for making heat exchangers, and the needs for very clean, oil-free surface for heat transfer. These problems have greatly constrained the use of thermally activated heat pumps with ammonia as the working fluid for heating and for air conditioning.

[0009] Murphy and Phillips proposed a thermally activated heat pump with $\text{CClF}_2\text{CHClF}$ as the working fluid and ETFE (ethyl tetrahydro-furfuryl ether), a high boiling organic oxygenate with a molecular weight of 130, as the solvent. See Kevin P. Murphy and Benjamin A. Phillips,

“DEVELOPMENT OF A RESIDENTIAL GAS-ABSORPTION HEAT PUMP”, submitted for presentation at the 18th Intersociety Energy Conversion Engineering Conference August 21-26, 1983, Orlando, Florida. Such a system does not have some of the shortcomings suffered by the LiBr absorption chillers and ammonia-water absorption heat pumps in terms of freezeout, corrosion, and toxicity. Based on their development work, Murphy and Phillips projected a cooling COP of 0.65 and a heating COP of 1.50. However, such a process has not been commercialized, possibly in part due to the suboptimal heat exchange scheme used by the developers and the higher viscosity and heat capacity of the solvent they chose. In addition, the working fluid, $\text{CClF}_2\text{CHClF}$, has ozone depleting potential, thus is not desirable.

[00010] There is an unmet need to improve the efficiency of heating and cooling. In particular, there is an unmet need of a TAHP for heating that can replace the fuel burning heaters and electrical resistive heaters to thereby greatly reduce the energy consumption for heating, and a TAHP for cooling that can use the heat provided by solar water heaters or the cooling water coming from a vehicle engine to thereby drastically reduce the energy need for cooling. The present invention meets such unmet needs by providing a thermally activated system for increasing the pressure of a gaseous working fluid, i.e., a thermally activated pressure booster, and its uses in applications such as a TAHP. Such a system can also be used for power generation using low level heat.

BRIEF SUMMARY OF THE INVENTION

[00011] In one general aspect, the present invention relates to a thermally activated system for increasing the pressure of a gaseous working fluid. The system comprises a working fluid having a bubble point of less than 20°C when the working fluid is at 1 atm pressure, and a solvent comprising an organic oxygenate containing in its molecule at least one oxygen atom (O) and at least one atom selected from the group consisting of nitrogen (N), sulfur (S), phosphorus (P), fluorine (F), and a combination thereof, and the dew point of the solvent is greater than 130°C when the solvent is at 1 atm.

[00012] According to an embodiment of the present invention, the thermally activated system comprises:

an absorber, in which a lower pressure, substantially gaseous stream of a working fluid is absorbed into a lower pressure, liquid stream of an absorbent to form a liquid solution;
a cooler that removes heat from the absorber;
a pressure boosting device that increases the pressure of the liquid solution to obtain a higher pressure liquid solution; and

a generator that separates the higher pressure liquid solution into at least a higher pressure, substantially vaporized stream of the working fluid and a higher pressure, liquid stream of the absorbent;

wherein the working fluid has a bubble point of less than 20° C when the working fluid is at 1 atm pressure; and the absorbent comprises components of the working fluid and a solvent comprising an organic oxygenate containing in its molecule at least one oxygen atom (O) and at least one atom selected from the group consisting of nitrogen (N), sulfur (S), phosphorus (P), fluorine (F), and a combination thereof, and the dew point of the solvent is greater than 130° C when the solvent is at 1 atm.

[00013] In another embodiment, the present invention relates to a thermally activated system for increasing the pressure of a gaseous working fluid, comprising:

an absorber, in which a lower pressure, substantially gaseous stream of a working fluid is absorbed into a lower pressure, liquid stream of an absorbent to form a liquid solution, wherein the working fluid is selected from the group consisting of R134a, dimethyl ether, R152a, CH₃I (R131I), propane, isopropane, propylene, isobutane, n-butane, HFO1234yf, and a combination thereof, and the absorbent comprises components of the working fluid and a solvent selected from the group consisting of N-methyl-2-pyrrolidone (NMP), dimethyl sulfoxide (DMSO), dimethylformamide (DMF), dimethylacetamide (DMAc), and a combination thereof;

a cooler that removes heat from the absorber;

a pressure boosting device that increases the pressure of at least a portion of the liquid solution to obtain a higher pressure liquid solution;

a generator that separates the higher pressure liquid solution into at least a higher pressure, substantially vaporized stream of the working fluid and a higher pressure, liquid stream of the absorbent;

a condenser that substantially condenses at least a portion of the higher pressure, substantially vaporized stream of the working fluid to obtain a substantially condensed stream of the working fluid;

a heat exchanger that cools at least a portion of the substantially condensed stream of the working fluid to obtain a sub-cooled stream of the working fluid, while heating another stream,

a pressure reducing device that reduces the pressure of at least a portion of the sub-cooled stream of the working fluid to obtain a lower pressure stream of the working fluid;

an evaporator that at least partially vaporizes at least a portion of the lower pressure stream of the working fluid to obtain an at least partially vaporized stream of the working fluid, while removing heat from another heat source, wherein

the other heat source is heat from environment of an enclosed space or a process stream when the thermally activated system is used for heating the enclosed space or the process stream, or heat from an enclosed space or a process stream when the thermally activated system is used for cooling the enclosed space or the process stream, and

5 the other stream in the heat exchanger comprises at least a portion of the at least partially vaporized stream of the working fluid, heating of which results in the lower pressure, substantially gaseous stream of the working fluid, at least a portion of which is fed to the absorber;

10 a second heat exchanger that cools at least a portion of the higher pressure, liquid stream of the absorbent to obtain a sub-cooled, liquid stream of the absorbent; and

a second pressure reducing device that reduces the pressure of at least a portion the sub-cooled, liquid stream of the absorbent to obtain the lower pressure, liquid stream of the absorbent, at least a portion of which is fed to the absorber.

[00014] In another general aspect, the present invention relates to a thermally activated process for increasing the pressure of a gaseous working fluid. The process comprises using a working fluid having a bubble point of less than 20° C when the working fluid is at 1 atm pressure, and a solvent comprising an organic oxygenate containing in its molecule at least one oxygen atom (O) and at least one atom selected from the group consisting of nitrogen (N), sulfur (S), phosphorus (P), fluorine (F), and a combination thereof, and the dew point of the solvent is greater than 130° C when the solvent is at 1 atm.

[00015] According to an embodiment of the present invention, the thermally activated process comprises:

absorbing a lower pressure, substantially gaseous stream of a working fluid into a lower pressure, liquid stream of an absorbent in an absorber to obtain a liquid solution;

25 removing heat from the absorber;

increasing the pressure of the liquid solution to obtain a higher pressure liquid solution; and

30 separating at least a portion of the higher pressure liquid solution in a generator to obtain at least a higher pressure, substantially vaporized stream of the working fluid and a higher pressure, liquid stream of the absorbent;

wherein the working fluid has a bubble point of less than 20° C when the working fluid is at 1 atm pressure; and the absorbent comprises components of the working fluid and a solvent comprising an organic oxygenate containing in its molecule at least one oxygen atom (O) and at least one atom selected from the group consisting of nitrogen (N), sulfur (S), phosphorus

(P), fluorine (F), and a combination thereof, and the dew point of the solvent is greater than 130° C when the solvent is at 1 atm.

[00016] According to another embodiment, the present invention relates to a thermally activated process for increasing the pressure of a gaseous working fluid, comprising:

- 5 absorbing a lower pressure, substantially gaseous stream of a working fluid into a lower pressure, liquid stream of an absorbent in an absorber to obtain a liquid solution, wherein the working fluid is selected from the group consisting of R134a, dimethyl ether, R152a, CH₃I (R1311), propane, isopropane, propylene, isobutane, n-butane, HFO1234yf, and a combination thereof, and the absorbent comprises components of the working fluid and a solvent selected
- 10 from the group consisting of N-methyl-2-pyrrolidone (NMP), dimethyl sulfoxide (DMSO), dimethylformamide (DMF), dimethylacetamide (DMAc), and a combination thereof;
 - removing heat from the absorber;
 - increasing the pressure of at least a portion of the liquid solution by a pressure boosting device to obtain a higher pressure liquid solution;
- 15 separating at least a portion of the higher pressure liquid solution in a generator to obtain at least a higher pressure, substantially vaporized stream of the working fluid and a higher pressure, liquid stream of the absorbent;
 - substantially condensing at least a portion of the higher pressure, substantially vaporized stream of the working fluid in a condenser to obtain a substantially condensed stream
 - 20 of the working fluid;
 - cooling at least a portion of the substantially condensed stream of the working fluid in a heat exchanger to obtain a sub-cooled stream of the working fluid, while heating another stream;
 - reducing the pressure of at least a portion of the sub-cooled stream of the working
 - 25 fluid to obtain a lower pressure stream of the working fluid;
 - vaporizing at least a portion of the lower pressure stream of the working fluid in an evaporator to obtain an at least partially vaporized stream of the working fluid, while removing heat from another heat source, wherein
 - the other heat source in the vaporizing step is heat from environment of an
 - 30 enclosed space or a process stream when the thermally activated process is used for heating the enclosed space or the process stream, or heat from an enclosed space or a process stream when the thermally activated process is used for cooling the enclosed space or the process stream, and
 - the other stream in the heat exchanger comprises the at least partially vaporized stream of the working fluid from the evaporator, heating of which results in the lower pressure,
 - 35 substantially gaseous stream of the working fluid;

feeding at least a portion of the lower pressure, substantially gaseous stream of the working fluid to the absorber;

cooling at least a portion of the higher pressure, liquid stream of the absorbent in a second heat exchanger to obtain a sub-cooled, liquid stream of the absorbent;

5 reducing the pressure of at least a portion of the sub-cooled, liquid stream of the absorbent to obtain the lower pressure, liquid stream of the absorbent; and

feeding at least a portion of the lower pressure, liquid stream of the absorbent to the absorber.

[00017] Other aspects, features and advantages of the invention will be apparent from the following disclosure, including the detailed description of the invention and its preferred
10 embodiments and the appended claims.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[00018] The foregoing summary, as well as the following detailed description of the invention, will be better understood when read in conjunction with the appended drawings. For
15 the purpose of illustrating the invention, there are shown in the drawings embodiments which are presently preferred. It should be understood, however, that the invention is not limited to the precise arrangements and instrumentalities shown.

[00019] In the drawings:

[00020] Fig 1 shows an example of a single effect system according to an embodiment of the
20 present invention;

[00021] Fig 2 shows an example of a double effect system according to an embodiment of the present invention; and

[00022] Figure 3 shows an example of a power generation system according to an embodiment of the present invention.

25 DETAILED DESCRIPTION OF THE INVENTION

[00023] Various publications, articles and patents are cited or described in the background and throughout the specification; each of these references is herein incorporated by reference in its entirety. Discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is for the purpose of providing context for the present
30 invention. Such discussion is not an admission that any or all of these matters form part of the prior art with respect to any inventions disclosed or claimed.

[00024] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood to one of ordinary skill in the art to which this invention pertains. Otherwise, certain terms used herein have the meanings as set in the specification. All

patents, published patent applications and publications cited herein are incorporated by reference as if set forth fully herein. It must be noted that as used herein and in the appended claims, the singular forms “a,” “an,” and “the” include plural reference unless the context clearly dictates otherwise.

5 **[00025] DEFINITIONS**

[00026] Absorbent: an absorbent is a liquid that absorbs a gas to form a liquid solution in an absorber, typically accompanied by heat removal.

[00027] Absorber: an absorber is a piece of a process equipment in which a gas is dissolved in an absorbent, forming a liquid solution.

10 **[00028]** Bubble point: the temperature at which a liquid starts to vaporize. For a pure component, the bubble point at 1 atm is its boiling point.

[00029] Coefficient of performance (COP) or cooling COP: the amount of heat lifted divided by the amount of energy used in the heat pumping process.

15 **[00030]** Heating COP: the amount of heat available for heating divided by the amount of energy used.

[00031] COP and heating COP are related by the following mathematical formula: Heating COP = 1 + COP

20 **[00032]** Cooling water: cooling water in the context of the present invention refers to a heat transfer medium. It comprises mainly of water, and can contain other components such as ethylene glycol, alcohols, salt, etc.

[00033] Countercurrent heat exchanger: a heat exchanger in which the stream being heated flows in the opposite direction from that being cooled, wherein the streaming being heated and the stream being cooled are separated by a thermally conductive solid material, such as a sheet material.

25 **[00034]** Desuperheating: cooling a vapor from a higher temperature to or close to its dew point.

[00035] Dew point of a fluid: the temperature at which a gas starts to condense. The dew point of a pure component at 1 atm is the same as the boiling point for the pure component.

30 **[00036]** Generator: a piece of process equipment in which a mixture is separated into two (or more) streams of different compositions. The fundamental behind separation in a generator in the context of this patent is the volatility difference between the different components of the mixture. A process unit operating on the same principle of the generator in the context of the present invention can also be called desorber or distillation unit or evaporation unit or evaporator in some other places. It differs from an electric generator which refers to an electro-mechanical device that converts mechanical energy to electrical energy.

[00037] Heat pump: a process system that can move heat from a lower temperature to a higher temperature. A conventional air conditioner is considered an example of a heat pump in the context of the present invention, as is a conventional refrigerator and a conventional heat pump that is used for space heating when the outdoor temperature is below that of the space to be heated.

[00038] Heat pumping: a process that moves heat from a lower temperature to a higher temperature.

[00039] HFC: fluorohydrocarbon, a chemical compound comprising hydrogen (H), carbon (C), and fluorine (F) in its molecule.

[00040] Organic oxygenate: an organic compound comprising one or more oxygen (O) atoms in its molecule.

[00041] Polyol: an alcohol comprising multiple –OH groups in its molecule. Examples of polyol include, but are not limited to, ethylene glycol, diethylene glycol, and propylene glycol.

[00042] Solvent: a liquid that can dissolve a liquid and/or a gas component.

[00043] Subcooler: a heat exchanger that cools a liquid to a temperature lower than its dew point.

[00044] Superheating: heating a vapor from its dew point or close to its dew point to a higher temperature.

[00045] Thermally activated heat pump (TAHP): a heat pump that is principally driven by the heat flow from a higher temperature heat source to a lower temperature heat sink. For example, a conventional LiBr chiller is a thermally activated heat pump.

[00046] Working fluid: a fluid in a heat pump, power generation system, or heat activated pressure booster that changes its phase. In heating, air conditioning, and refrigeration applications, a working fluid is also called refrigerant. The working fluid may contain up to 5% of a solvent in certain embodiments in this patent.

[00047] Embodiments of the present invention relate to a non-ozone depleting or essentially non-ozone depleting working fluid and a solvent that improves the performance of a heat activated pressure booster, which can be used in applications such as a TAHP or a power generator. The present invention relates to a lower cost, highly efficient thermally activated heat pump and air conditioning system that works at a higher pressure than the conventional LiBr chillers. They are capable of working at below sub water freezing temperatures, and can be thermally activated, especially with low level of heat, such as that from commercial solar water heaters and the cooling water from vehicle engines. The heat activated pressure booster according to embodiments of the present invention does not use corrosive materials, and has no potential issue of absorbent freeze out during operation.

[00048] In one general aspect, the present invention relates to a thermally activated system for increasing the pressure of a gaseous working fluid. The thermally activated system comprises:

an absorber, in which a lower pressure, substantially gaseous stream of a working fluid is absorbed into a lower pressure, liquid stream of an absorbent to form a liquid solution;

5 a cooler that removes heat from the absorber;

a pressure boosting device that increases the pressure of at least a portion of the liquid solution to obtain a higher pressure liquid solution; and

a generator that separates at least a portion of the higher pressure liquid solution into at least a higher pressure, substantially vaporized stream of the working fluid and a higher
10 pressure, liquid stream of the absorbent;

wherein the working fluid has a bubble point of less than 20° C when the working fluid is at 1 atm pressure; and the absorbent comprises components of the working fluid and a solvent comprising an organic oxygenate containing in its molecule at least one oxygen atom (O) and at least one atom selected from the group consisting of nitrogen (N), sulfur (S), phosphorus
15 (P), fluorine (F), and a combination thereof, and the dew point of the solvent is greater than 130° C when the solvent is at 1 atm.

[00049] According to another embodiment of the present invention, the thermally activated system further comprises:

a condenser that substantially condenses at least a portion of the higher pressure, substantially vaporized stream of the working fluid to obtain a substantially condensed stream of the working fluid;

a pressure reducing device that reduces the pressure of at least a portion of the substantially condensed stream of the working fluid to obtain a lower pressure stream of the working fluid; and

25 an evaporator that at least partially vaporizes at least a portion of the lower pressure stream of the working fluid to obtain an at least partially vaporized stream of the working fluid, while removing heat from another heat source,

wherein the other heat source in the evaporator is heat from environment of an enclosed space or a process stream when the thermally activated system is used for heating the enclosed space or the process stream, or heat from an enclosed space or a process stream when the thermally activated system is used for cooling the enclosed space or the process stream.
30

[00050] It is readily understood by those of ordinary skill in the art that when a thermally activated system is used for heating an enclosed space or process stream, it can be used to heat the enclosed space or a process stream directly, or indirectly by heating a stream or medium that

is used to heat the enclosed space or process stream. Thus, the other heat source in the evaporator can be heat directly or indirectly from the environment.

[00051] Similarly, when a thermally activated system is used for cooling an enclosed space or process stream, it can be used to cool the enclosed space or a process stream directly, or
5 indirectly by cooling a stream or medium that is used to cool the enclosed space or process stream. Thus, the other heat source in the evaporator can be heat directly or indirectly from the enclosed space or process stream.

[00052] Examples of the enclosed space or a process stream include, but are not limited to, the space within a room or a building, or the space within a vehicle, or a process stream in an
10 industrial plant or installation. The environment of an enclosed space or a process stream can be the space outside of the enclosed space or process stream.

[00053] In another embodiment, the thermally activated system further comprises a heat exchanger that cools at least a portion of the substantially condensed stream of the working fluid to obtain a sub-cooled stream of the working fluid, while heating another stream. At least a
15 portion of the sub-cooled stream of the working fluid is then fed to the pressure reducing device to obtain the lower pressure stream of the working fluid. The other stream heated in the heat exchanger comprises at least a portion of the at least partially vaporized stream of the working fluid from the evaporator, heating of which results in the lower pressure, substantially gaseous stream of the working fluid, at least a portion of which is used in the absorber.

[00054] In another embodiment of the present invention, the thermally activated system further comprises: a second pressure reducing device in fluid communication with the absorber, wherein the second pressure reducing device reduces the pressure of at least a portion of the
20 higher pressure, liquid stream of the absorbent from the generator to obtain the lower pressure, liquid stream of the absorbent, at least a portion of which is used in the absorber.

[00055] In yet another embodiment of the present invention, the thermally activated system further comprises a second heat exchanger in fluid communication with the pressure boosting device, an intermediate location of the generator, the bottom section of the generator, and the
25 second pressure reducing device, wherein the second heat exchanger cools at least a portion of the higher pressure, liquid stream of the absorbent from the bottom section of the generator to obtain a sub-cooled liquid stream of the absorbent, while heating and partially vaporizing at least
30 a portion of the higher pressure, liquid solution from the pressure boosting device to obtain a higher pressure, two-phase stream, which is subsequently fed to the intermediate location of the generator; and at least a portion of the sub-cooled liquid stream of the absorbent is then fed to the second pressure reducing device to obtain the lower pressure, liquid stream of the absorbent.

[00056] The intermediate location of the generator can be any location of the generator that is in between of the top and the bottom sections of the generator.

[00057] According to an embodiment of the present invention, the thermally activated system comprises more than one generator. For example, a thermally activated system according to an embodiment of the present invention can comprise a higher pressure generator, and a medium pressure generator having an operating pressure lower than that of the higher pressure generator, wherein there is thermal communication between the top section of the higher pressure generator and the medium pressure generator.

[00058] In another embodiment, the present invention relates to a power generation system, which comprises the thermally activated system according to an embodiment of the present invention and an expander, wherein at least a portion of the higher pressure, substantially vaporized stream of the working fluid from the generator is expanded in the expander to generate mechanical energy, and at least a portion of the exhaust stream of the working fluid from the expander is absorbed into the lower pressure, liquid stream of the absorbent in the absorber.

[00059] In another general aspect, the present invention relates to a thermally activated process for increasing the pressure of a gaseous working fluid. The method comprises:

absorbing a lower pressure, substantially gaseous stream of a working fluid into a lower pressure, liquid stream of an absorbent in an absorber to obtain a liquid solution;

removing heat from the absorber;

increasing the pressure of at least a portion of the liquid solution to obtain a higher pressure liquid solution; and

separating at least a portion of the higher pressure liquid solution in a generator to obtain at least a higher pressure, substantially vaporized stream of the working fluid and a higher pressure, liquid stream of the absorbent;

wherein the working fluid has a bubble point of less than 20° C when the working fluid is at 1 atm pressure; and the absorbent comprises components of the working fluid and a solvent comprising an organic oxygenate containing in its molecule at least one oxygen atom (O) and at least one atom selected from the group consisting of nitrogen (N), sulfur (S), phosphorus (P), fluorine (F), and a combination thereof, and the dew point of the solvent is greater than 130° C when the solvent is at 1 atm.

[00060] According to another embodiment of the present invention, the thermally activated process further comprises:

substantially condensing at least a portion of the higher pressure, substantially vaporized stream of the working fluid in a condenser to obtain a substantially condensed stream of the working fluid;

reducing the pressure of at least a portion of the substantially condensed stream of the working fluid to obtain a lower pressure stream of the working fluid; and

vaporizing at least a portion of the lower pressure stream of the working fluid in an evaporator to obtain an at least partially vaporized stream of the working fluid, while removing
5 heat from another heat source,

wherein the other heat source in the vaporizing step is heat from environment of an enclosed space or a process stream when the thermally activated process is used for heating the enclosed space or process stream, or heat from the enclosed space or a process stream when the thermally activated process is used for cooling the enclosed space or process stream.

10 **[00061]** According to another embodiment of the present invention, the thermally activated process further comprises cooling at least a portion of the substantially condensed stream of the working fluid in a heat exchanger to obtain a sub-cooled stream of the working fluid, while heating another stream, wherein at least a portion of the sub-cooled stream of the working fluid is then fed to the pressure reducing device, and the other stream comprises at least a portion of
15 the at least partially vaporized stream of the working fluid from the evaporator, heating of at least a portion of which results in the lower pressure, substantially gaseous stream of the working fluid, at least a portion of which is used in the absorber.

[00062] In another embodiment of the present invention, the thermally activated process further comprises:

20 reducing the pressure of at least a portion of the higher pressure, liquid stream of the absorbent from the generator to obtain the lower pressure, liquid stream of the absorbent; and
feeding at least a portion of the lower pressure, liquid stream of the absorbent to the absorber.

[00063] In yet another embodiment of the present invention, the thermally activated process
25 further comprises:

cooling at least a portion of the higher pressure, liquid stream of the absorbent obtained from the bottom section of the generator in a second heat exchanger to obtain a sub-cooled, liquid stream of the absorbent, while heating and partially vaporizing at least a portion of the higher pressure, liquid solution from the pressure boosting device to obtain a higher pressure,
30 two-phase stream;

feeding at least a portion of the higher pressure, two-phase stream to an intermediate location of the generator; and

feeding at least a portion of the sub-cooled liquid stream of the absorbent to the second pressure reducing device to obtain the lower pressure, liquid stream of the absorbent.

[00064] According to an embodiment of the present invention, the thermally activated process utilizes more than one generators in the separating step. For example, a thermally activated process according to an embodiment of the present invention can comprise using a higher pressure generator, and a medium pressure generator having an operating pressure lower than that of the higher pressure generator in the separating step, wherein there is thermal communication between the top section of the higher pressure generator and the medium pressure generator.

[00065] In another embodiment, the thermally activated process is used for generate a power. The process further comprises:

expanding at least a portion of a higher pressure, substantially vaporized stream of the working fluid in an expander to generate mechanical energy; and

absorbing at least a portion of the exhaust stream of the working fluid from the expander into the lower pressure, liquid stream of the absorbent in the absorber.

[00066] In an embodiment of the present invention, the working fluid comprises a component selected from the group consisting of R134a (1,1,1,2-tetrafluoroethane), dimethyl ether, R152a ($\text{F}_2\text{HC}-\text{CH}_3$), CH_3I (R1311), propylene, propane, cyclopropane, isobutane, n-butane, HFO1234yf, and a combination thereof.

[00067] In another embodiment of the present invention, the solvent is selected from the group consisting of an organic oxygenate containing in its molecule at least one atom selected from the group consisting of nitrogen (N), phosphorus (P), fluorine (F), and sulfur (S), and a combination thereof, has a dew point of greater than 130°C when the solvent is at 1 atm, and has a viscosity of less than 2.5 cP at 20°C .

[00068] In an embodiment of the present invention, the solvent is selected from the group consisting of N-methyl-2-pyrrolidone (NMP), dimethyl sulfoxide (DMSO), dimethylformamide (DMF), dimethylacetamide (DMAc), and a combination thereof.

[00069] The absorbent contains both the working fluid and the solvent. The absorbent is also referred to as the working fluid lean solution in the present application.

[00070] The absorption of a working fluid into an absorbent in the absorber or the absorbing step forms a liquid solution rich in the working fluid. The liquid solution is also referred to as the weak solution in the present application.

[00071] In an embodiment of the present invention, the higher pressure, liquid solution from the pressure boosting device is split into at least a major stream and a minor stream. The minor stream constitutes 1-20% (mol) of the total flow of the higher pressure, liquid solution and is fed to the top of the generator. The major stream is heated and partially vaporized in a heat

exchanger to obtain a two-phase stream, i.e., liquid and vapor, which is fed to an intermediate location of the generator.

[00072] In another embodiment of the present invention, a subcooler is used to cool at least a portion of the substantially condensed working fluid from the condenser, and heat and further vaporize at least a portion of the at least partially vaporized stream of the working fluid from the evaporator, which can contain 0.1-5% (mol) liquid.

[00073] Figure 1 shows an example of a single effect absorption heat pump process according to an embodiment of the present invention. In this process, a lower pressure, substantially gaseous stream of a working fluid (306) and a lower pressure, liquid stream of an absorbent (314) are fed into an absorber (31) to obtain a liquid solution (308). The resultant working fluid-rich solution or weak solution (308) is fed to a pump (32) to obtain a higher pressure weak solution (309), which is subsequently split into a major stream (310) and a minor stream (312). The major weak solution stream (310), typically 80-99% (mol) of the weak solution, is heated and partially vaporized in a substantially countercurrent heat exchanger (33), and the resultant higher pressure two-phase stream in (311) is fed to the lower feeding port of the generator (34), located in an intermediately position of the generator (34), while the minor higher pressure weak solution (312), typically 1-20% (mol) of the total of the weak solution, is fed to a higher feeding port of the generator (34) without being heated. The generator (34), which is a distillation column, produces a higher pressure vapor working fluid (301), and a bottoms liquid (313), i.e., the absorbent that is lean in the components of the working fluid.

[00074] The overhead higher pressure vapor working fluid (301) is condensed in condenser (35), releasing heat. The resultant substantially condensed working liquid is split into two streams: the reflux (315), which flows back to the top of the generator (34); and the rest (303) to be subcooled in a substantially countercurrent heat exchanger or Subcooler (30). The reflux stream (315) for this system is a very small fraction of the total working fluid coming out of the condenser, typically smaller than 10% (mol) of the total working fluid flow in the condenser. Heat, Q_g , is supplied to the base or the bottom section of the generator (34) to provide the reboiling heat of the distillation column. This heat transfer can be carried out in a heat exchanger inside or outside the generator.

[00075] The substantially condensed working fluid (303) is cooled by the lower pressure, mostly vaporized stream (305a) of the working fluid from the evaporator (13) in a subcooler (30) that is a substantially counter-current heat exchanger. The resultant sub-cooled or cooler working fluid (304) is reduced in pressure in throttle valve (12). This results in a two phase stream at a lower temperature (305). This lower temperature, two phase stream (305) is heated and mostly vaporized in the evaporator (13). External heat (110), which can be from the environment when

the system is used for heating, or room air or a process stream to be cooled when the system is used for cooling, is used to vaporize most of the two phase stream (305). Cooling of the external heat stream (110) results in a lower temperature stream (112). The temperature of the lower temperature stream (112) is lower than that of stream 303. The mostly vaporized working fluid (305a) is first substantially completely vaporized and further heated in the subcooler (30). The resultant lower pressure, substantially gaseous working liquid (306) is then used for absorption by the absorbent (314) in the absorber 31, releasing heat (Q_b) at a temperature higher than that of stream 112. This heat removal can be carried out in one or more heat exchanger(s) inside the absorber.

[00076] The higher pressure absorbent (313) is cooled in the substantially counter-current heat exchanger (33), and let down in pressure in a throttle valve (36) to produce the lower pressure absorbent stream (314), which is used for absorption in the absorber (31).

[00077] The unique heat exchange schemes in this process allows for a significantly higher efficiency. Due to the very low pressure in LiBr chillers, the LiBr chillers are not suitable to perform at least some of the technical features of heat exchange schemes according to embodiments of the present invention.

[00078] To simplify the system, the reflux stream (315) to the top of the generator (34) can be eliminated, and the minor feed stream (312) is fed to where reflux is typically fed in the generator (34). In that case, the working fluid (301) will contain some small fraction of the solvent. To mitigate this situation, the working fluid (305a) coming out of the evaporator (13) is allowed to contains some liquid, typically in 0.1-5% (mol) range. We discovered that when a substantially countercurrent subcooler (30) is used to cool the substantially condensed working fluid (303) from the condenser with the further vaporization and heating of the mostly vapor working fluid (305a) coming from the evaporator, essentially all of the remaining liquid in the working fluid (305a) can be vaporized in the subcooler (30). It is surprisingly discovered from our simulation study that such a simplification not only does not cause efficiency penalties, but on the contrary, the cooling COP value is increased by about 1%. We therefore consider this a preferred embodiment.

[00079] Embodiments of the present invention also include two or more effect heat pumps and their uses thereof.

[00080] Fig 2 shows an example of a double effect system. The difference between this process and that in Fig 1 described as follows. The higher pressure liquid solution coming out of the pump (55) is split into two streams. The stream (409) is let down in pressure in throttle valve (67) to a medium pressure that is higher than that of the solution (408) upstream of the pump (55). The resultant medium pressure solution is further split into the major portion (410) and the

minor portion (412). The major portion (410) of the medium pressure solution is heated and partially vaporized in a substantially countercurrent medium pressure heat exchanger (56), and the resultant medium pressure two phase stream (411) is fed to the lower feeding port of a medium pressure generator (57). The minor medium pressure stream (412) is fed directly to the higher feeding port of the medium pressure generator (57). The medium pressure generator (57) generates an overhead, medium pressure, substantially vaporized stream (431) of the working fluid. It also generates a medium pressure absorbent (413), which is lean in the working fluid components, from the bottom. The medium pressure absorbent (413) is then cooled in the medium pressure bottom subcooler (56), which is a substantially countercurrent heat exchanger. The resultant subcooled medium pressure lean liquid is further let down in pressure in throttle valve (59).

[00081] Another portion of the high pressure solution (420) from the pump (55) is first heated in a substantially countercurrent high pressure heat exchanger (68). A side stream (422) is taken out of the heat exchanger (68) and fed to a higher feeding port in a higher pressure generator (69). The remaining portion of the heated higher pressure liquid solution is further heated and partially vaporized in the substantially countercurrent high pressure heat exchanger (68), and the resultant two phase high pressure stream (421), is fed to the lower feeding port of the higher pressure generator (69). The higher pressure generator (69) is heated by heat Q_g at the base or the lower section. The higher pressure generator (69) produces a higher pressure vapor stream (423) that is substantially composed of the working fluid from the top, and a working fluid-lean stream or absorbent (425) from the bottom.

[00082] The higher pressure overhead vapor stream (423) is condensed in the reboiler/condenser (60), which resides in the bottom section of the medium pressure column (57). The resultant higher pressure condensate, which is essentially pure working fluid, is split into two streams: the reflux (433), which is sent back to the top of the higher pressure generator (69), and the rest (424) is further subcooled in the subcooler (61). This subcooler (61) can be a part of the medium pressure generator (57). That is to say, the higher pressure working fluid solution can be subcooled in the medium pressure generator (57) by the substantially countercurrent heat exchanger 61. The subcooled, higher pressure liquid working fluid is then let down in pressure in throttle valve 62, forming a two phase stream, and join the overhead working fluid vapor (431) from the medium pressure generator (57).

[00083] The combined medium pressure working fluid (401), formed from the vaporized working fluid from the top of the medium pressure column and the two phase mixture from valve (62) is fed to the condenser (58), releasing heat. The resultant condensed liquid working fluid, is split into two streams: the reflux (432), which is fed back to the top of the medium pressure

generator (57), and the liquid working fluid (403), to be subcooled in a medium pressure top subcooler (50), which is a substantially countercurrent heat exchanger.

[00084] The absorbent stream (425) from the high pressure generator (69) is subcooled in a higher pressure, substantially countercurrent heat exchanger (68). The resultant subcooled absorbent stream (426), is first let down in pressure higher pressure in throttle valve (63). The thus resultant lower pressure absorbent stream (427) is then combined with the absorbent stream from throttle valve (59) and form a low pressure absorbent stream (428), which is then fed to the absorber (54) for reuse.

[00085] The other parts of this process are similar to those of Fig . 1.

[00086] Similarly, one or both of the refluxes (433) and (432) to the high and medium pressure generators, respectively, can also be eliminated, and the minor feed streams (422) and (412) can be fed to the tops of the high and medium pressure generators, respectively. In such a case, the working fluid (431) and (423), coming out of the tops of the generators will contain some solvent, typically in 10 ppm – 5% range. In such a case, the working fluid stream (305a) leaving the evaporator (53) should preferably contains 0.1 – 5% (mol) liquid, and is then substantially completely vaporized in the subcooler (50).

[00087] In view of the present disclosure, those skilled in the art would readily appreciate that systems and processes according to embodiments of the present invention can be used for heating or cooling an enclosed space or process stream, such as the interior of a building or a vehicle or a process stream in an industrial process. When the systems are used for cooling, the evaporator removes heat from the enclosed space or a process stream while heat from the condenser and the absorber is expelled to the environment. When the systems are used for heating, the evaporator absorbs heat from the environment while the condenser and the absorber provide heat to the enclosed space or process stream. A unitary system can be built such that the same system can be used for both winter heating and summer cooling, e.g., by switching the roles of the condenser and the evaporator as season changes.

[00088] In order to reduce the global warming potential (GWP) of the working fluid and still keep the working fluid inflammable, in a preferred embodiment, the work fluid comprises a blend of one or more organic components, such as R134a, CF₃I, DMF, or HFO1234yf. DME is selected in the example due to its excellent thermodynamic properties, low cost, non-toxicity, low GWP nature, and a slightly higher boiling point than that of R134a. R134a is used to make the working fluid inflammable. Due to the very close boiling points of the components, such mixtures behave very much like azeotropes. CF₃I has a GWP value of 1. Therefore, a mixture of CF₃I and DME has a very low GWP value. On the other hand, the mixture of CF₃I and DME is considered to have some ozone depleting potential (ODP) although its ODP value is very small

(less than 0.008, likely less than 0.0001 of R11). HFO1234yf has a GWP of about 4, vs. the 1430 value for R134a, but is slightly flammable.

[00089] Many hydrocarbons and organic oxygenates have the desired properties of having a boiling point of greater than 130° C (or dew point of greater than 130°C at 1 atm for mixed solvents), that are relatively inexpensive and miscible with the above-mentioned working fluids, thus can be used as the solvent. Examples include the base oil of lube oils, polyols such as ethylene glycol, triethylene glycol, propylene glycol, dipropylene glycol, glymes such as tetraglyme, or the products of the condensation reactions between glycols and ketones or aldehydes. The base oils of lube oils, tetraglyme (or a combination of glymes such as that used in the Solexol process), ethylene glycol, and triethylene glycol are among the common commodity chemicals with relatively low unit price and low toxicity and therefore are among our initial candidates for study.

[00090] Simulations of the system with several solvents, including cetane, ethylene glycol, diethylene glycol, triethylene glycol, and tetraglyme were run. It was found that the systems with low molecular weight organic oxygenates containing atoms selected from N, P, F, and S, and whose boiling points are greater than 130°C such as N-methyl-2-pyrrolidone (NMP), dimethyl sulfoxide (DMSO), dimethylformamide (DMF), and dimethylacetamide (DMAc), as the solvent have higher COP values and much lower heat exchanger UA values due to their smaller molecular mass (e.g., 99 g/mol for NMP, 78 for DMSO, 73 for DMF, and 87 for DMAc vs. 280 g/mol for tetraglyme) and lower specific heat (e.g., 0.40 for NMP, vs. 0.49 for tetraglyme). They should also have much greater heat transfer coefficients due to the relatively low viscosity (1.65 cP for NMP, 2.0 for DMSO, 0.92 for DMF, and 2.0 for DMAc vs. 5.8 cP for tetraglyme at 20°C).

[00091] For example, the other physical, health, and flammability properties of NMP are shown below:

BOILING POINT:	396° F (202 ° C)
FREEZING POINT:	-11 ° F (-24 ° C)
FLASH POINT:	199° F (93 ° C)
AUTOIGNITION:	518°F (270°C)
EXPLOSION LIMITS:	LEL: 0.99%, UEL: 3.9%
TOXICITY DATA:	3,914 mg/kg oral-rat LD50

[00092] Those for DMSO are as follows:

BOILING POINT:	372° F (189°C)
FREEZING POINT:	66 ° F (19°C)
FLASH POINT:	192 ° F (89°C)

	AUTOIGNITION:	419°F (215°C)
	EXPLOSION LIMITS:	LEL: 2.6%, UEL: 42%
	TOXICITY DATA:	Acute oral toxicity (LD50): 7920 mg/kg [Mouse]
5	Acute dermal toxicity (LD50):	40000 mg/kg [Rat]
[00093]	Those for DMF are as follows:	
	BOILING POINT:	307° F (153°C)
	FREEZING POINT:	-78° F (-61° C)
	FLASH POINT:	136.4°F (58°C)
10	AUTOIGNITION:	833°F (445°C)
	EXPLOSION LIMITS:	LEL: 2.2%, uel: 15.2%
	TOXICITY DATA:	ORL-RAT LD50 2800 mg kg ⁻¹
	IPR-RAT LD50	1400 mg kg ⁻¹
	IVN-RAT LD50	2000 mg kg ⁻¹
15	IPR-RBT	LD50 1000 mg kg ⁻¹
[00094]	Those for DMAc are as follows:	
	BOILING POINT:	325.4° F (165°C)
	FREEZING POINT:	-1.5° F (-18.6° C)
20	FLASH POINT:	150.8°F (66°C)
	AUTOIGNITION:	914°F (490°C)
	EXPLOSION LIMITS:	LEL: 1.8%, UEL: 11.5%
	TOXICITY DATA:	Acute oral toxicity (LD50): 7920 mg/kg [Mouse].
25	Acute dermal toxicity (LD50):	40000 mg/kg [Rat].
[00095]	In a preferred embodiment, NMP was chosen as the solvent in the description below because of its overall superior performance. However, other components in the family can also have more desirable values on certain properties. Thus, components, including, but not limited to, DMSO, DMF, DMAc, NMP, or a combination of one or more of these components, can be	
30	the preferred solvent under certain specific conditions.	
[00096]	While the flow sheets in Figures 1 and 2 show that the bottoms liquids of the generators are cooled by exchanging heat with the feed streams to the generators in substantially counter-current heat exchangers outside the generators, these streams can also be cooled inside the column against the falling liquids in the generators. In the absorber, the work fluid rich liquid	

from the bottom of the absorber after it is reduced in pressure can be used to absorb some of the heat released from the absorption by exchanging heat with the streams inside the absorber.

[00097] A heat pump system according to an embodiment of the present invention is suitable for living space cooling or heating in residential and vehicular applications as well as in commercial applications. Use of such a system for heating can greatly decrease the fuel consumption, while for air conditioning applications it can use solar water heater or the cooling water coming out of the vehicle engines, thereby drastically reducing the electricity demand for air conditioning during the hot summer days when the demand for electricity reaches peaks, or that generated by burning liquid fuel, which is expensive and is becoming even more expensive.

[00098] Note that a thermally activated system according to embodiments of the present invention is based on the principle that such an absorption system can act as a thermally driven compressor. There can be other uses of such a thermal compressor. For example, in principle, an expander can be used for power generation in the place of the condenser-vaporizer.

[00099] Figure 3 shows such a process. In this process, the absorption – separation parts are the same as those in the process in Figure 1. The difference is that in this process a vapor stream (501) is directly taken out of the top of the generator (34), and expanded in an expander (70). The work obtained from expander (70) can be used to generate electricity by an electric generator (72), which is mechanically connected to the expander (70). The resultant low pressure vapor (502), is then sent to the absorber (31) for further use. The vapor stream (501) coming out of the generator can be further heated before it is fed to the expander (70). This is not shown in Figure 3.

[000100] It is possible to have the components of a heat pump: the condenser, subcooler, pressure reducing valve, and evaporator, and an expander in parallel with switching valves so that the system can be used as a thermally activated heat pump when heating or cooling is needed, and can be used as a power generation system when either heating nor cooling is needed, or even used both as a heat pump and a power generation system.

[000101] The following examples are provided to enable one skilled in the art to practice the invention and are merely illustrative of the invention. The examples should not be read as limiting the scope of the invention as defined in the claims.

[000102] **Example:**

[000103] The system in Fig 1 with NMP as the solvent and R134a-DME mix as the working fluid was simulated for heating and cooling applications. The results are listed in Table 1.

[000104] In table 1, subscript b stands for absorber cooler, c for generator condenser, e for evaporator, and g for the generator heater. Note the generator heat duty is distributed among the feeding stage and the 3 stages in the stripping section (including the bottom stage) in the

simulation, so most of the heat absorption takes place at temperatures below T_g . That can be important if the heat is provided in the form of sensible heat. The CCOP and HCOP values are the thermal COP values: $CCOP = \text{evaporator duty} / \text{reboiler duty}$, $HCOP = (\text{condenser duty} + \text{absorber cooler duty}) / \text{reboiler duty}$.

- 5 **[000105]** Table 1. The temperatures of the absorber cooler, condenser, evaporator, and generator reboiler, pressures, working fluid composition, as well as the CCOP and HCOP values

Case (mode)	T _b (°C)	T _c (°C)	T _e (°C)	T _g (°C)	p _e atm	P _g Atm	DME/R134a (mass)	HCOP (CCOP)
1. Heating	27.3	27.3	4.6	87	3.3	6.8	23.2/76.8	1.90
2. Heating	27.4	27.2	-8.3	226.2	2.0	6.8	23.9/76.1	1.81
3. Cooling	36.4	36.7	14.3	75.9	4.4	8.7	38.0/62.0	(0.83)
4. Cooling	36.4	36.7	14.3	71	4.4	8.7	56.6/43.4	(0.78)

- [000106]** Table 2. Composition of the weak and strong absorbent in the four cases

Case	1	2	3	4
Weak solution composition (mol frac)				
DME	.09690	.1690	.2722	.2722
R134a	.09690	.1690	.1270	.1270
NMP	.8062	.6619	.6007	.6007
Absorbent composition (mol frac)				
DME	.06975	.1125	.2307	.2481
R134a	.05204	.07036	.08626	.1018
NMP	.8782	.8172	.6831	.6501

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- [000107]** The other conditions used in the simulation were as follows: the generator had 6 theoretical stages (2 stages in the rectifying section, and 4 in the stripping section including the feed stage), and the absorber had only one stage (i.e., it is a mixer). Our later study showed that the number of stages in the generator could be reduced to 3 to 4 stages without significantly impacting the performance of the system when the working fluid coming out of the evaporator was allowed to contain a few percent of liquid, which was then substantially vaporized in the substantially countercurrent subcooler. The pump work (60% pump efficiency and 95% motor
- 15

efficiency were assumed) values were respectively 0.8%, 2.1 %, 1.4% %, and 2.3% of the generator reboiler duties of the respective cases.

[000108] The compositions of the strong absorbent and weak absorbent for the four cases are shown in Table 2.

5 [000109] As can be seen, a HCOP of 1.90 can be achieved for heating when the evaporator temperature is 40.4° F (4.7° C), the condenser and absorber cooler temperatures are about 81° F (27° C), and the generator reboiler temperature is 188° F (87° C). When the ambient temperature is lower, such as when the evaporator temperature is 17° F (- 8° C), the HCOP is reduced while the temperature of the generator reboiler is increased to 226.5° F (108° C). When the unit is used
10 for cooling, if the evaporator temperature is 57.7° F (14.3° C), and the condenser and absorber cooler temperature are at about 98° F (37° C), the CCOP can be 0.83 if the generator reboiler is at 170° F (76.7° C), or 0.78 if the generator reboiler is at 160° F (71° C).

[000110] The latter two cases showed that such a chiller can be driven by the hot water from the low cost flat panel solar collectors and the system can still give a CCOP of significantly
15 greater than the typical 0.6-0.75 value of the LiBr absorption chillers and aqua-ammonia absorption heat pumps driven by higher temperature heat sources.

[000111] It will be appreciated by those skilled in the art that changes could be made to the embodiments described above without departing from the broad inventive concept thereof. It is
20 understood, therefore, that this invention is not limited to the particular embodiments disclosed, but it is intended to cover modifications within the spirit and scope of the present invention as defined by the appended claims.

CLAIMS

I/we claim:

1. A thermally activated system for increasing the pressure of a gaseous working fluid, comprising a working fluid having a bubble point of less than 20° C when the working fluid is at 1 atm pressure, and a solvent comprising an organic oxygenate containing in its molecule at least one oxygen atom (O) and at least one atom selected from the group consisting of nitrogen (N), sulfur (S), phosphorus (P), fluorine (F), and a combination thereof, and the dew point of the solvent is greater than 130° C when the solvent is at 1 atm.

2. The thermally activated system of claim 1, comprising:

an absorber, in which a lower pressure, substantially gaseous stream of the working fluid is absorbed into a lower pressure, liquid stream of an absorbent to form a liquid solution, wherein the absorbent comprises components of the working fluid and the solvent;

a cooler that removes heat from the absorber;

a pressure boosting device that increases the pressure of at least a portion of the liquid solution to obtain a higher pressure liquid solution; and

a generator that separates at least a portion of the higher pressure liquid solution into at least a higher pressure, substantially vaporized stream of the working fluid and a higher pressure, liquid stream of the absorbent.

3. The thermally activated system of claim 2, further comprising:

a condenser that substantially condenses at least a portion of the higher pressure, substantially vaporized stream of the working fluid to obtain a substantially condensed stream of the working fluid;

a pressure reducing device that reduces the pressure of at least a portion of the substantially condensed stream of the working fluid to obtain a lower pressure stream of the working fluid; and

an evaporator that at least partially vaporizes at least a portion of the lower pressure stream of the working fluid to obtain an at least partially vaporized stream of the working fluid, while removing heat from another heat source,

wherein the other heat source in the evaporator is heat from environment of an enclosed space or a process stream when the thermally activated system is used for heating the enclosed space or the process stream, or heat from an enclosed space or a process stream when the thermally activated system is used for cooling the enclosed space or the process stream.

4. The thermally activated system of claim 3, further comprising a heat exchanger that cools at least a portion of the substantially condensed stream of the working fluid from the condenser

to obtain a sub-cooled stream of the working fluid, while heating another stream, wherein at least a portion of the sub-cooled stream of the working fluid is subsequently fed to the pressure reducing device to obtain the lower pressure stream of the working fluid, and the other stream in the heat exchanger comprises at least a portion of the at least partially vaporized stream of the working fluid from the evaporator, heating of which results in the lower pressure, substantially gaseous stream of the working fluid, at least a portion of which is fed to the absorber.

5 5. The thermally activated system of claim 3, wherein the working fluid is selected from the group consisting of R134a, dimethyl ether, R152a, CH₃I (R131I), propane, isopropane, propylene, isobutane, n-butane, HFO1234yf, and a combination thereof, and the solvent has a viscosity of less than 2.5 cP at 20°C.

10 6. The thermally activated system of claim 3, wherein the solvent is selected from N-methyl-2-pyrrolidone (NMP), dimethyl sulfoxide (DMSO), dimethylformamide (DMF), dimethylacetamide (DMAc), and a combination thereof.

15 7. A thermally activated system for increasing the pressure of a gaseous working fluid, comprising:

an absorber, in which a lower pressure, substantially gaseous stream of a working fluid is absorbed into a lower pressure, liquid stream of an absorbent to form a liquid solution, wherein the working fluid is selected from the group consisting of R134a, dimethyl ether, R152a, CH₃I (R131I), propane, isopropane, propylene, isobutane, n-butane, HFO1234yf, and a combination thereof, and the absorbent comprises components of the working fluid and a solvent selected from the group consisting of N-methyl-2-pyrrolidone (NMP), dimethyl sulfoxide (DMSO), dimethylformamide (DMF), dimethylacetamide (DMAc), and a combination thereof;

a cooler that removes heat from the absorber;

25 a pressure boosting device that increases the pressure of at least a portion of the liquid solution to obtain a higher pressure liquid solution;

a generator that separates the higher pressure liquid solution into at least a higher pressure, substantially vaporized stream of the working fluid and a higher pressure, liquid stream of the absorbent;

30 a condenser that substantially condenses at least a portion of the higher pressure, substantially vaporized stream of the working fluid to obtain a substantially condensed stream of the working fluid;

a heat exchanger that cools at least a portion of the substantially condensed stream of the working fluid to obtain a sub-cooled stream of the working fluid, while heating another stream,

a pressure reducing device that reduces the pressure of at least a portion of the sub-cooled stream of the working fluid to obtain a lower pressure stream of the working fluid;

an evaporator that at least partially vaporizes at least a portion of the lower pressure stream of the working fluid to obtain an at least partially vaporized stream of the working fluid,
5 while removing heat from another heat source, wherein

the other heat source is heat from environment of an enclosed space or a process stream when the thermally activated system is used for heating the enclosed space or the process stream, or heat from an enclosed space or a process stream when the thermally activated system is used for cooling the enclosed space or the process stream, and

10 the other stream in the heat exchanger comprises at least a portion of the at least partially vaporized stream of the working fluid, heating of which results in the lower pressure, substantially gaseous stream of the working fluid, at least a portion of which is fed to the absorber;

a second heat exchanger that cools at least a portion of the higher pressure, liquid
15 stream of the absorbent to obtain a sub-cooled, liquid stream of the absorbent; and

a second pressure reducing device that reduces the pressure of at least a portion the sub-cooled, liquid stream of the absorbent to obtain the lower pressure, liquid stream of the absorbent, at least a portion of which is fed to the absorber.

8. The thermally activated system of claim 7, wherein the second heat exchanger cools at
20 least a portion of the higher pressure, liquid stream of the absorbent from the bottom section of the generator to obtain the sub-cooled liquid stream of the absorbent, while heating and partially vaporizing at least a portion of the higher pressure, liquid solution from the pressure boosting device to obtain a higher pressure, two-phase stream, which is subsequently fed to an intermediate location of the generator.

25 9. The thermally activated system of claim 1, comprising more than one generators.

10. A power generation system, comprising the thermally activated system of claim 2 and an expander, wherein at least a portion of the higher pressure, substantially vaporized stream of the working fluid from the generator is expanded in the expander to generate mechanical energy, and at least a portion of the exhaust stream of the working fluid from the expander is absorbed into
30 the lower pressure, liquid stream of the absorbent in the absorber.

11. A thermally activated process for increasing the pressure of a gaseous working fluid, comprising using a working fluid having a bubble point of less than 20° C when the working fluid is at 1 atm pressure, and a solvent comprising an organic oxygenate containing in its molecule at least one oxygen atom (O) and at least one atom selected from the group consisting

of nitrogen (N), sulfur (S), phosphorus (P), fluorine (F), and a combination thereof, and the dew point of the solvent is greater than 130° C when the solvent is at 1 atm.

12. The thermally activated process of claim 11, comprising:

absorbing a lower pressure, substantially gaseous stream of the working fluid into a lower pressure, liquid stream of an absorbent in an absorber to obtain a liquid solution, wherein the absorbent comprises components of the working fluid and the solvent;

removing heat from the absorber;

increasing the pressure of at least a portion of the liquid solution to obtain a higher pressure liquid solution; and

separating at least a portion of the higher pressure liquid solution in a generator to obtain at least a higher pressure, substantially vaporized stream of the working fluid and a higher pressure, liquid stream of the absorbent.

13. The thermally activated process of claim 12, further comprising:

substantially condensing at least a portion of the higher pressure, substantially vaporized stream of the working fluid in a condenser to obtain a substantially condensed stream of the working fluid;

reducing the pressure of at least a portion of the substantially condensed stream of the working fluid to obtain a lower pressure stream of the working fluid; and

vaporizing at least a portion of the lower pressure stream of the working fluid in an evaporator to obtain an at least partially vaporized stream of the working fluid, while removing heat from another heat source,

wherein the other heat source in the vaporizing step is heat from environment of an enclosed space or a process stream when the thermally activated process is used for heating the enclosed space or the process stream, or heat from the an enclosed space or a process stream when the thermally activated process is used for cooling the enclosed space or the process stream.

14. The thermally activated process of claim 13, further comprising:

cooling at least a portion of the substantially condensed stream of the working fluid in a heat exchanger to obtain a sub-cooled stream of the working fluid, while heating another stream, wherein the other stream in the heat exchanger comprises at least a portion of the at least partially vaporized stream of the working fluid from the evaporator, and heating of which results in the lower pressure, substantially gaseous stream of the working fluid;

feeding at least a portion of the lower pressure, substantially gaseous stream of the working fluid to the absorber; and

reducing the pressure of at least a portion of the sub-cooled stream of the working fluid to obtain the lower pressure stream of the working fluid.

15. A thermally activated process for increasing the pressure of a gaseous working fluid, comprising:

absorbing a lower pressure, substantially gaseous stream of a working fluid into a lower pressure, liquid stream of an absorbent in an absorber to obtain a liquid solution, wherein
5 the working fluid is selected from the group consisting of R134a, dimethyl ether, R152a, CH₃I (R1311), propane, isopropane, propylene, isobutane, n-butane, HFO1234yf, and a combination thereof, and the absorbent comprises components of the working fluid and a solvent selected from the group consisting of N-methyl-2-pyrrolidone (NMP), dimethyl sulfoxide (DMSO), dimethylformamide (DMF), dimethylacetamide (DMAc), and a combination thereof;

10 removing heat from the absorber;

increasing the pressure of at least a portion of the liquid solution by a pressure boosting device to obtain a higher pressure liquid solution;

separating at least a portion of the higher pressure liquid solution in a generator to obtain at least a higher pressure, substantially vaporized stream of the working fluid and a higher
15 pressure, liquid stream of the absorbent;

substantially condensing at least a portion of the higher pressure, substantially vaporized stream of the working fluid in a condenser to obtain a substantially condensed stream of the working fluid;

cooling at least a portion of the substantially condensed stream of the working fluid in
20 a heat exchanger to obtain a sub-cooled stream of the working fluid, while heating another stream;

reducing the pressure of at least a portion of the sub-cooled stream of the working fluid to obtain a lower pressure stream of the working fluid;

vaporizing at least a portion of the lower pressure stream of the working fluid in an
25 evaporator to obtain an at least partially vaporized stream of the working fluid, while removing heat from another heat source, wherein

the other heat source in the vaporizing step is heat from environment of an enclosed space or a process stream when the thermally activated process is used for heating the enclosed space or the process stream, or heat from an enclosed space or a process stream when
30 the thermally activated process is used for cooling the enclosed space or the process stream, and

the other stream in the heat exchanger comprises the at least partially vaporized stream of the working fluid from the evaporator, heating of which results in the lower pressure, substantially gaseous stream of the working fluid;

feeding at least a portion of the lower pressure, substantially gaseous stream of the
35 working fluid to the absorber;

cooling at least a portion of the higher pressure, liquid stream of the absorbent in a second heat exchanger to obtain a sub-cooled, liquid stream of the absorbent;

reducing the pressure of at least a portion of the sub-cooled, liquid stream of the absorbent to obtain the lower pressure, liquid stream of the absorbent; and

5 feeding at least a portion of the lower pressure, liquid stream of the absorbent to the absorber.

16. The thermally activated process of claim 15, wherein the second heat exchanger cools at least a portion of the higher pressure, liquid stream of the absorbent from the bottom section of the generator to obtain the sub-cooled, liquid stream of the absorbent, while heating and partially
10 vaporizing at least a portion of the higher pressure, liquid solution from the pressure boosting device to obtain a higher pressure, two-phase stream, at least a portion of which is subsequently fed to an intermediate location of the generator.

17. The thermally activated process of claim 16, wherein the portion of the higher pressure, liquid solution being heated and partially vaporized constitutes 80-99% (mol) of the higher
15 pressure, liquid solution, and 1 – 20% (mol) of the higher pressure, liquid solution is sent to the top of the generator without being heated and partially vaporized.

18. The process of claim 17, wherein the higher pressure, substantially vaporized stream of the working fluid obtained from the generator contains up to 5% (mol) of the solvent, and the at least partially vaporized stream of the working fluid obtained from the evaporator contains 0.1-
20 5% (mol) liquid.

19. The thermally activated process of claim 11, wherein the separating step utilizes more than one generators.

20. A power generation process, comprising

- a. the thermally activated process of claim 12,
- 25 b. expanding at least a portion of the higher pressure, substantially vaporized stream of the working fluid in an expander to generate mechanical energy, and
- c. absorbing at least a portion of the exhaust stream of the working fluid from the expander into the lower pressure, liquid stream of the absorbent in the absorber.

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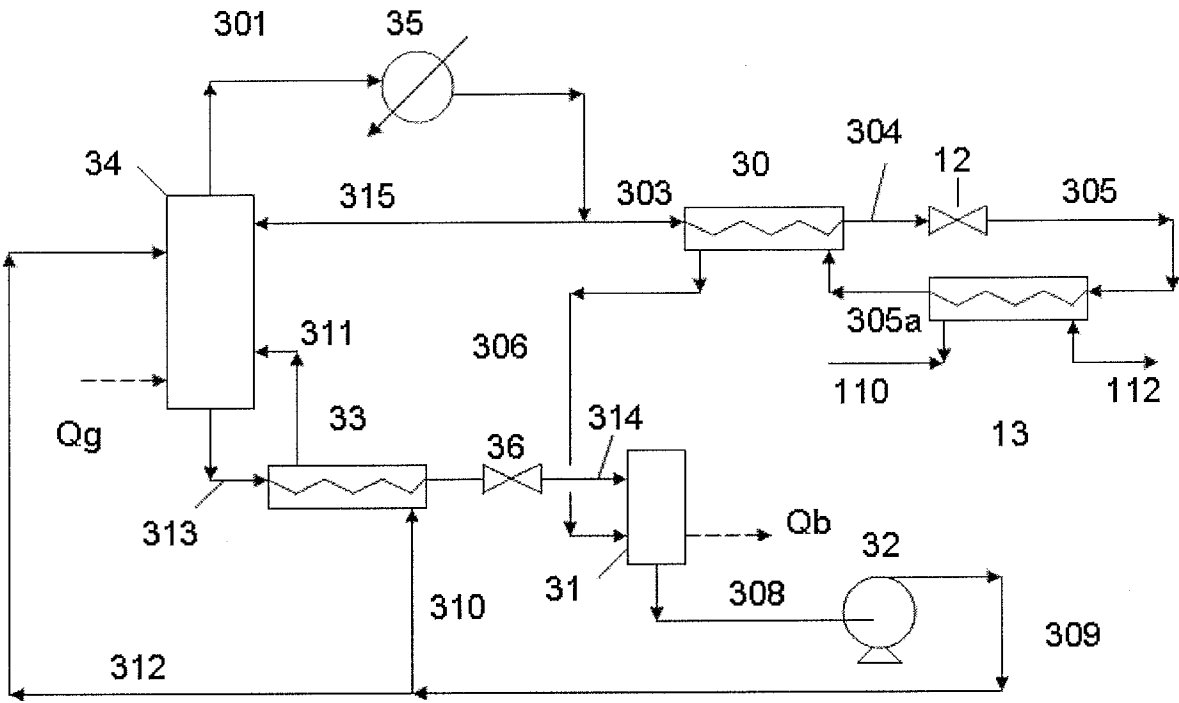


Figure 1

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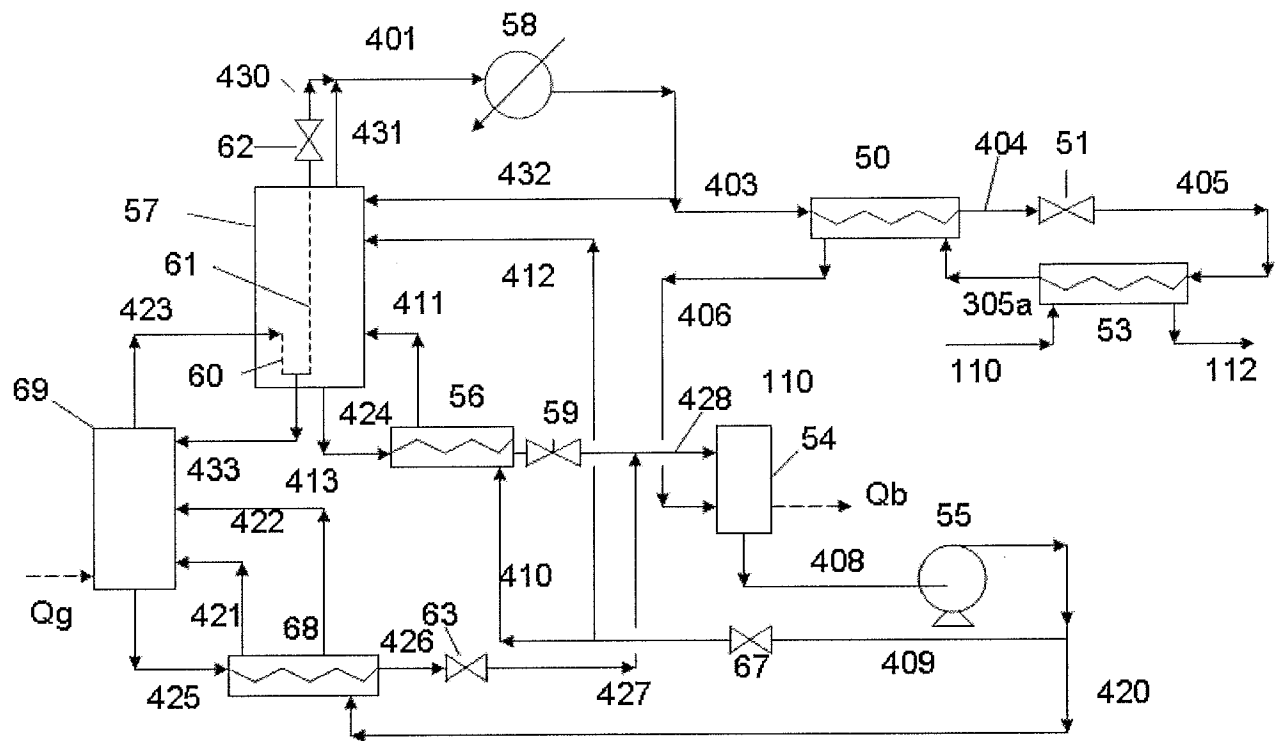


Figure 2

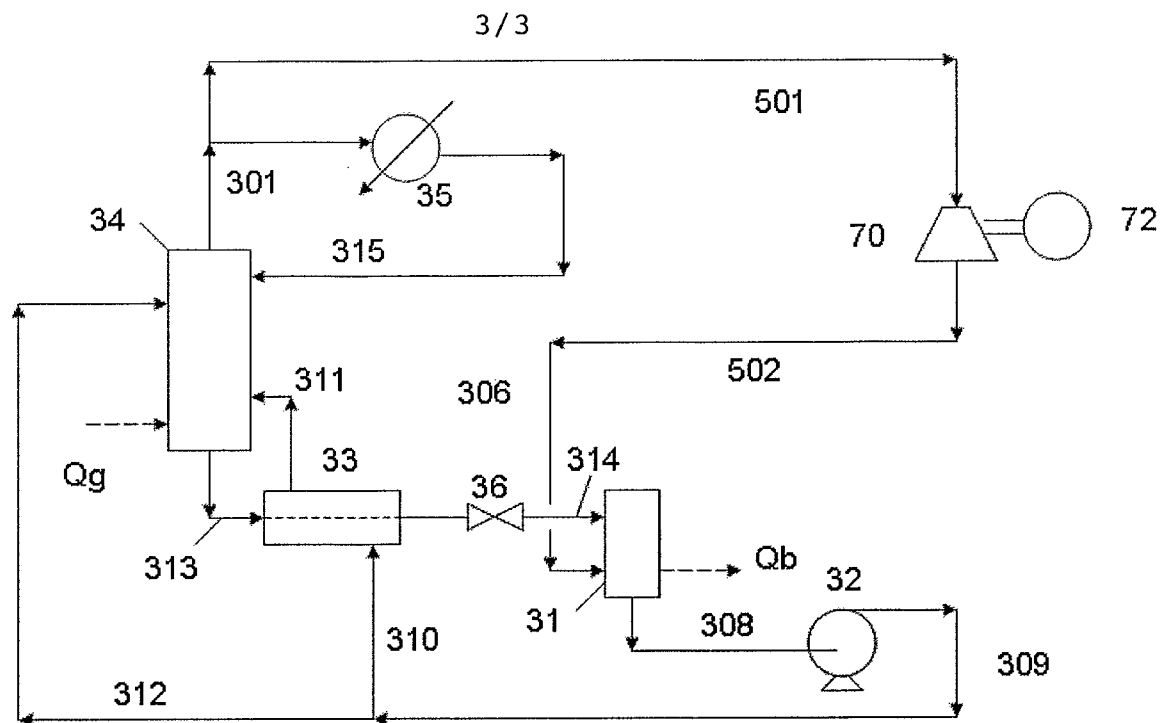


Figure 3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2012/026313

A. CLASSIFICATION OF SUBJECT MATTER		<i>F25B 15/02 (2006.01)</i> <i>C09K 5/04 (2006.01)</i> <i>F01K 25/06 (2006.01)</i>																					
According to International Patent Classification (IPC) or to both national classification and IPC																							
B. FIELDS SEARCHED																							
Minimum documentation searched (classification system followed by classification symbols)																							
F25B 15/00, 15/02, C09K 5/00, 5/02, 5/04, F01K 25/00, 25/06																							
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched																							
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)																							
Esp@cenet, FI/F-term Search, PatFT, RUPAT, RUPATABRU, RUPAT-OLD, RUPM, RUPMAB																							
C. DOCUMENTS CONSIDERED TO BE RELEVANT																							
Category*	Citation of document, with indication, where appropriate, of the relevant passages		Relevant to claim No.																				
X Y	US 2010/0154419 A1 (E.I. DU PONT DE NEMOURS AND COMPANY) 24.06.2010, fig. 1, paragraphs [0006], [0012]-[0016], claims		1, 2, 9-12, 19, 20 3-6, 13, 14																				
Y	SU 1800244 A1 (ODESSKIY INSTITUT NIZKOTEMPERATURNNOY TEKHNIKI I ENERGETIKI) 07.03.1993, fig., col. 4, line 1 - col. 6, line 8		3-6, 7, 8, 13-14, 15-18																				
Y	US 4428854 A (DAIKIN KOGYO CO., LTD.) 31.01.1984, col. 1, lines 10-44, col.2, line 16 - col. 3, line 16, table 1		5, 6, 7, 8, 15-18																				
Y	SU 1092336 A (OSHOVSKIY V. YA et al.) 15.05.1984, col. 2, line 37 - col. 3, line 17, fig. 1		17, 18																				
☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.																							
* Special categories of cited documents: <table border="0"> <tr> <td>“A”</td> <td>document defining the general state of the art which is not considered to be of particular relevance</td> <td>“T”</td> <td>later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</td> </tr> <tr> <td>“E”</td> <td>earlier document but published on or after the international filing date</td> <td>“X”</td> <td>document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</td> </tr> <tr> <td>“L”</td> <td>document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</td> <td>“Y”</td> <td>document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</td> </tr> <tr> <td>“O”</td> <td>document referring to an oral disclosure, use, exhibition or other means</td> <td>“&”</td> <td>document member of the same patent family</td> </tr> <tr> <td>“P”</td> <td>document published prior to the international filing date but later than the priority date claimed</td> <td></td> <td></td> </tr> </table>				“A”	document defining the general state of the art which is not considered to be of particular relevance	“T”	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention	“E”	earlier document but published on or after the international filing date	“X”	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone	“L”	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	“Y”	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art	“O”	document referring to an oral disclosure, use, exhibition or other means	“&”	document member of the same patent family	“P”	document published prior to the international filing date but later than the priority date claimed		
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“E”	earlier document but published on or after the international filing date	“X”	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone																				
“L”	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	“Y”	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art																				
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“P”	document published prior to the international filing date but later than the priority date claimed																						
Date of the actual completion of the international search		Date of mailing of the international search report																					
30 May 2012 (30.05.2012)		21 June 2012 (21.06.2012)																					
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