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(71) **Applicants:** UNIVERSITY OF FLORIDA RESEARCH FOUNDATION, INC. [US/US]; 223 Grinter Hall, Gainesville, FL 32611 (US). UT-BATTELLE, LLC [US/US]; One Bethel Valley Road, PO Box 2008, Oak Ridge, Tennessee 37831-6258 (US).

(72) **Inventors:** MOGHADDAM, Saeed; 4235 S.W. 96th Drive, Gainesville, FL 32608 (US). CHUGH, Devesh; 3800 S.W. 34th Street, Apt. T181, Gainesville, FL 32608 (US). NASRISFAHANI, Rasool; 23230 S.W. Williston Road, Apt. 2221, Gainesville, FL 32608-3960 (US). BIGHAM, Sajjad; 704 S.W. 16th Avenue, Apt. 211, Gainesville, FL 32601-85810 (US). FAZELI, Seyyed, A.;

3800 S.W. 34th Street, Apt. BB-381, Gainesville, FL 32608-6562 (US). YU, Dazhi; 1036 N.W. 86th Terrace, Gainesville, FL 32606 (US). MORTAZAVI, Mehdi; 301 Diamond Village, Apt. 5, Gainesville, FL 32606-2227 (US). ABDELAZIZ, Omar; 5901 Montrose Road, Apt. S604, North Bethesda, MD 20852 (US).

(74) **Agents:** BUESE, Mark, A. et al.; Saliwanchik, Lloyd & Eisenschenk, P.O. Box 142950, Gainesville, FL 32614-2950 (US).

(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, BN, 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, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, 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.

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[Continued on next page]

(54) **Title:** OPEN ABSORPTION CYCLE FOR DEHUMIDIFICATION, WATER HEATING, AND EVAPORATIVE COOLING

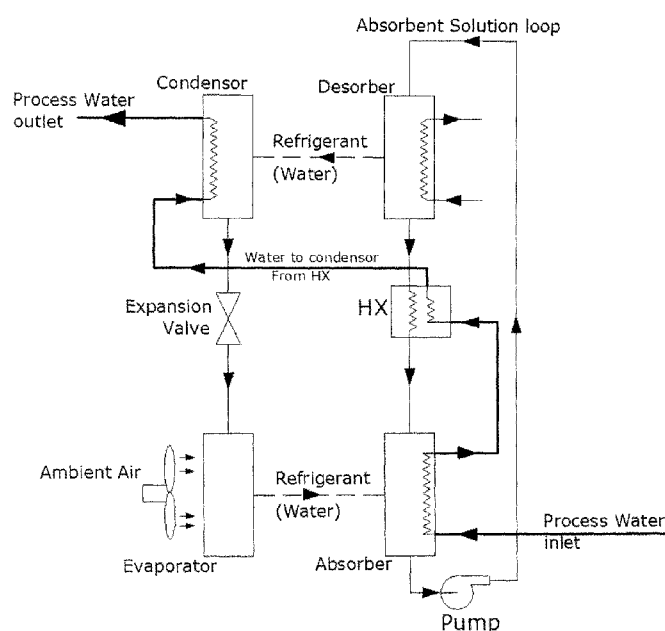


Figure 1

(57) **Abstract:** An absorption cycle system that permits water heating, dehumidifying, and/or evaporative cooling includes a desorber, absorber, heat exchanger, and, optionally, an evaporator, is constructed to heat a process water that is plumbed through the absorber, heat exchanger, and condenser. In the absence or isolation of the evaporator, the system can dehumidify ambient air to the absorber. The water vapor released by evaporative cooling at the evaporator can be provided to the absorber in a controlled manner to simultaneously maintain a desired humidity while cooling the air ambient by the evaporator. The absorption cycle system can be housed within a single unit or can be compartmentalized.



DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, **Published:**

LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE,
SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA,
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— with international search report (Art. 21(3))

DESCRIPTION

OPEN ABSORPTION CYCLE FOR DEHUMIDIFICATION, WATER HEATING, AND
EVAPORATIVE COOLING

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CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application Serial No. 61/925,435, filed January 9, 2014, the disclosure of which is hereby incorporated by reference in its entirety, including all figures, tables and drawings.

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This invention was made with government support under DE-AC08-00OR22725 awarded by the Department of Energy. The government has certain rights in the invention.

BACKGROUND OF INVENTION

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Vapor compression systems (VCSs) have helped shape modern civilization and population demographics. Increased access to electricity in the later part of the 19th century and better performance and operational characteristics of VCSs triggered the gradual replacement of absorption refrigeration systems, ARSs the cooling system of that time, with VCSs. Despite their great benefits, VCSs consume significant electrical energy and use refrigerants that are not environment friendly. As much as 72% of the U.S. electricity consumption is to buildings where a large proportion is used for space cooling/heating, dehumidification, and hot water heating. The use of these amenities is rapidly rising in developing countries. Refrigerant emission from VCSs in developing countries is also increasing. The development of more energy efficient technologies can greatly benefit the world's energy and environmental sustainability while sustaining or improving the quality of life. ARSs can use low-grade thermal energy, such as waste heat and solar-thermal energy, for cooling and heating; which can allow development of high performance, inexpensive, and robust systems.

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In attempts to build compact and inexpensive systems, alternative heat exchanger configurations and system architectures have been examined. Depending on the choice of working fluid pairs, absorption systems are classified as ammonia-water or lithium bromide-water systems. LiBr-water systems use water as the refrigerant and LiBr solution as the

absorbent. The size of heat exchangers required for absorption and desorption of water must account for the limited water mass transfer coefficient of LiBr solution. By enhancing the absorption and desorption transport processes, compact heat exchanger architectures can be developed for economical small-scale heating and cooling systems.

5 The absorbers and desorbers commonly employed in LiBr–water ARSs involve a falling film over horizontal or vertical tubes or are in a pool boiling configuration where water is boiled from a pool of LiBr solution. Falling-film desorbers are more suitable with low temperature heat sources. In a falling film desorber, LiBr solution is sprayed over a tube bundle to generate thin solution films over the tubes to facilitate a higher rate of water
10 desorption while the heating medium flows within the tubes. At low surface temperatures, water directly diffuses out of the solution film until the solution temperature is insufficient to sustain a sufficient water vapor pressure above the solution.

 To enhance the efficiency of these absorbers and desorbers, thin film systems have been investigated, recently. Although the earlier work indicated that the absorption rates
15 were only about half of that achievable with the conventional absorbers, the development of ultra-thin film absorbers, Moghaddam *et al.*, WO2013/063210; Isfahani *et al.*, *International Journal of Heat and Mass Transfer*, 2013, 63, 82-90; and Isfahani *et al.*, *International Journal of Multiphase Flow*, 2014, 58, 27-38 identifies an absorber structure using a nanofiber membrane where the absorption rate is improved to beyond that possible from
20 conventional absorbers. In like manner, an ultra-thin film absorber can function as an ultra-thin film desorber when the cooling source employed in the absorber is replaced with a heating source to drive desorption. Hence, a system employing ultra-thin film absorbers and desorbers for systems that can provide improved water heating, dehumidification and/or evaporative cooling is desirable.

BRIEF SUMMARY

Embodiments of the invention exploit an absorption technology to capture low grade heat to provide useful dehumidification and water heating. The technology involves a lithium bromide-water based absorption cycle where water cycles between absorption and desorption
30 from a lithium bromide aqueous solution. Water vapor condenses and evaporates to complete the cycle. Ambient water vapor absorbs into a lithium bromide solution, which dehumidifies the ambient air. The energy released by the absorption of the ambient water vapor in the

absorber due to the phase transition is used to heat the process fluid. The lithium bromide solution is regenerated in the desorber by providing sufficient heat to the solution. The desorbed water vapor is then condensed in the condenser where the condensation of water vapor in the condenser heats the process fluid, which is process water in embodiments of the invention. The condensed water vapor is either drained from the system to provide exclusively dehumidification at the absorber or is sprayed into an air stream to provide evaporative cooling of the air stream and the volume that the air stream services. Thus dehumidification, water heating and evaporative cooling can be achieved by a single system.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows an absorption cycle system for water heating, according to an embodiment of the invention.

Figure 2 shows a prior art heat pump based water heater.

Figure 3 shows an absorption cycle system for water heating and dehumidifying, according to an embodiment of the invention.

Figure 4 shows an absorption cycle system for water heating, dehumidifying to a controlled humidity, and evaporative cooling, according to an embodiment of the invention.

DETAILED DISCLOSURE

Embodiments of the invention are directed to an open absorption cycle system where water heating, dehumidification, and/or evaporative cooling can be implemented through a single machine. Ultra-thin film absorbers and desorbers are employed where the membrane of the absorber permits a concentrated LiBr solution to interface with the ambient air and absorb the water vapor for dehumidifying. The latent heat of absorption that is released with the generation of a weak (dilute) LiBr solution can be transferred into a process water stream used to cool the absorber. The concentrated LiBr solution regenerates by the loss of water vapor from the desorber, where it is heated by a heating fluid or other heating source. The water vapor generated in the desorber can be condensed, releasing its heat of condensation to the process water, which is employed as the coolant in the condenser. The condensed water vapor can be used for evaporative cooling in the presence of the absorber, or the condensed water vapor can simply be drained if evaporative cooling is not needed or desired, allowing the dehumidification of air in the vicinity of the absorber. In this manner, the open absorption

cycle collects heat from the ambient and transfers that heat to the process water as a source of hot water, for use in a house or other building that requires hot water. To efficiently carry out these tasks of water heating, dehumidification, and/or cooling, an improved architecture for the water heating cycle that is employed in the system is illustrated in Figure 1 for a water heating unit, according to an embodiment of the invention. This architecture recovers heat from the concentrated LiBr solution exiting the desorber at a heat exchanger using the process water. This feature of the architecture differs from a state of the art absorption heat pump based water heater, shown in Figure 2, which uses the dilute LiBr solution exiting the absorber to absorb the heat placed into the concentrated LiBr solution at the desorber by means of the heat exchanger. A 3.2 kW conventional absorption heat pump water heater of five components, as shown in Figure 2, was modeled using ABSIM software, which was developed at Oak Ridge National Laboratories, to probe the sensitivity of the coefficient of performance (COP) to changes in parameters employed. The results of this modeling are given in Table 1, below, which indicates that the effectiveness of the heat exchanger does not impact the COP of the system significantly. The insensitivity to the efficiency of the heat exchanger allows the design change of using the heat exchanger to warm process water rather than using dilute LiBr solution in an embodiment of the invention. The improved water heater increases the total amount of heat absorbed in the process water while relatively insignificantly increasing the amount of heat that must be provided from outside of the system at the desorber. Hence, the efficiency of producing hot water is significantly increased.

Table 1 Effect of parameter variation on the sensitivity of COP, where the range of the parameter and the COP sensitivity to the change is determined relative to the COP of a base case

Parameter	Range	Base value	Maximum percentage change in COP w.r.t. base case
UA-Absorber (kW/K)	0.05-0.8	0.3	1.6
UA-Condenser (kW/K)	0.05-0.6	0.25	4.3
UA-Desorber (kW/K)	0.002-0.2	0.03	16
UA-Evaporator (kW/K)	0.05-1.5	0.8	6.1
Eff-Solution heat exchanger	0.1-0.9	0.5	0.14
Process water flow rate (kg/sec)	0.005-0.1	0.02	22
Flow rate of hot air(kg/sec)	0.02-0.2	0.12	9.1
LiBr Solution flow rate (kg/sec)	0.0026-0.029	0.015	26

As an alternative to that shown in Figure 1, the process water need not proceed in sequence as a cooling medium for the absorber, subsequently as a cooling meium for the heat exchanger, and subsequently as a cooling medium to the condenser, but can be plumbed in an alternative sequence or the process water flow can be plumbed to individually address one or more of the absorber, heat exchanger, and/or condenser. As an alternative to that shown in Figure 1, the heat exchanger can have process water and dilute LiBr solution plumbed through the heat exchanger, where both fluids absorb heat from the hot concentrated LiBr solution.

As can be seen in Figure 1, a pump directly transfers the dilute LiBr solution from the low temperature outlet of the absorber to the low temperature dilute LiBr solution inlet of the desorber. Although not shown in Figure 1, in an embodiment of the invention, the dilute LiBr solution can be plumbed to act as a coolant of the pump such that at least a portion of the heat generated mechanically within the pump and/or pump motor can be transferred into the dilute LiBr solution to reduce the amount of heat that is required from a source external to the water heating system. The pump can be of any design that can resist corrosion by a dilute LiBr solution, including, but not limited to: rotary lobe pump, progressive cavity pump, rotary gear pump, piston pump, diaphragm pump, screw pump, gear pump, hydraulic pump, rotary vane pump, and flexible impeller pumps. The dilute LiBr solution exits the pump and bypasses a heat exchanger, which is used in conventional absorption heat pump based water heaters, as shown in Figure 2. Alternatively, the process water that exits either the absorber, heat exchanger, or the condenser, can be plumbed to absorb heat from the pump. In similar fashion, the fan or other device to promote an air flow to the evaporator and/or absorber, as shown in Figure 1, or a motor driving the device, can be plumbed to permit absorption of the heat from the fan motor into the process water or dilute LiBr solution.

The absorber in the system, according to an embodiment of the invention, can be used to absorb moisture from ambient air. In embodiments of the invention, the absorber is an ultra-thin film absorber, as taught in Moghaddam *et al.*, WO2013/063210, and incorporated herein by reference. Unlike liquid desiccant commercial dehumidifiers, which use a saturated aqueous solution and has direct contact of air and the saturated solution, the concentrated LiBr solution at the absorber is separated from air by the membrane. This separation allows for higher air velocities than that tolerated by direct contact systems, where desiccant can be forced from the functional site of the absorber. A schematic of a system where water heating

and dehumidification, without evaporative cooling, is shown in Figure 3. In this system, no evaporator is used and the water from the condenser is discarded rather than being returned to the absorber as water vapor.

In an embodiment of the invention, the system architecture allows water heating, dehumidification, and evaporative cooling, as shown in Figure 4. In this embodiment of the invention, the evaporator is isolated from the absorber in a manner where an evaporator provides evaporative cooling where the water removed by the condenser is either discarded or provided to the evaporator, where the water vapor therefrom can be placed in communication with the absorber in a controlled fashion, for example, via an control valve, where a humidity in the presence of the absorber can be maintained at a low level yet is sufficient humidity to drive the absorber-desorber cycle that heats the water.

Using ABSIM, an analysis of performance of the system under various conditions was calculated. The first two conditions require dehumidification and water heating, whereas the third requires that a sufficient amount of water vapor is introduced to the absorber to maintain a proper humidity to have the refrigerant water cycle between the open cycle absorber, desorber, condenser and evaporator. Table 2 gives the calculated COP normalized to the heat input to the desorber. As indicated in Figure 5 the thermal COP is 1.63 for the system carrying out water heating, cooling, and maintaining a desired 50% relative humidity.

Table 2 Performance of the machine in different ambient conditions

Environment	Ambient Temperature °C	RH %	Heat Input (kW)	Water Heating Capacity (kW)	Thermal COP
Cold humid basement	6	80	2.12	3.28	1.54
Humid Open Space	35	70	2.2	3.78	1.72
Air-conditioned closed space	23	50	1.96	3.22	1.63

Hence by the use of the absorption cycle system design, according to an embodiment of the invention, where the heat exchanger coolant differs from a conventional heat pump based water heater such that the cooling of the hot concentrated LiBr solution from the desorber is carried out by the process water rather than the dilute LiBr solution from the absorber, the efficiency of the system can be improved significantly. For example, an exemplary system, according to an embodiment of the invention, that has a 3.2 kW water heating capacity can achieve a thermal coefficient of performance (COP) of 1.6 for water heating while simultaneously performing dehumidification and cooling for a structure.

The absorption cycle system can be constructed as a single system, or can be compartmentalized as is appropriate for the space or building to be cooled and/or

dehumidified. A system, if desired, can include at least one desorber, at least one absorber, at least one heat exchanger, at least one condenser, and, optionally, at least one evaporator, and at least one pump, while employing a common process water source and a common hot water outlet. A method of water heating, dehumidifying, and/or evaporative cooling, according to an embodiment of the invention, can employ one or more absorption cycle systems that employ a common process water source or a plurality of different process water sources and can deliver heated water to a common hot water reservoir or a plurality of different hot water reservoirs.

All patent applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

CLAIMS

We claim:

1. An absorption cycle system, comprising:

at least one desorber;

at least one absorber;

at least one heat exchanger, wherein a conduit between the desorber and the absorber comprises the heat exchanger;

at least one condenser, and

optionally, at least one evaporator

wherein a process water source is plumbed to provide process water as a cooling medium to:

the at least one absorber;

the at least one heat exchanger; and

the at least one condenser, wherein the process water is outlet from the absorption cycle system as hot water, wherein the absorption cycle system has the capacity for dehumidification of air in contact with the absorber, and, optionally, evaporative cooling of air in contact with the evaporator.

2. The absorption cycle system of claim 1, wherein absorbent in the absorber is concentrated aqueous solution and the desorbent in the desorber is dilute aqueous solution.

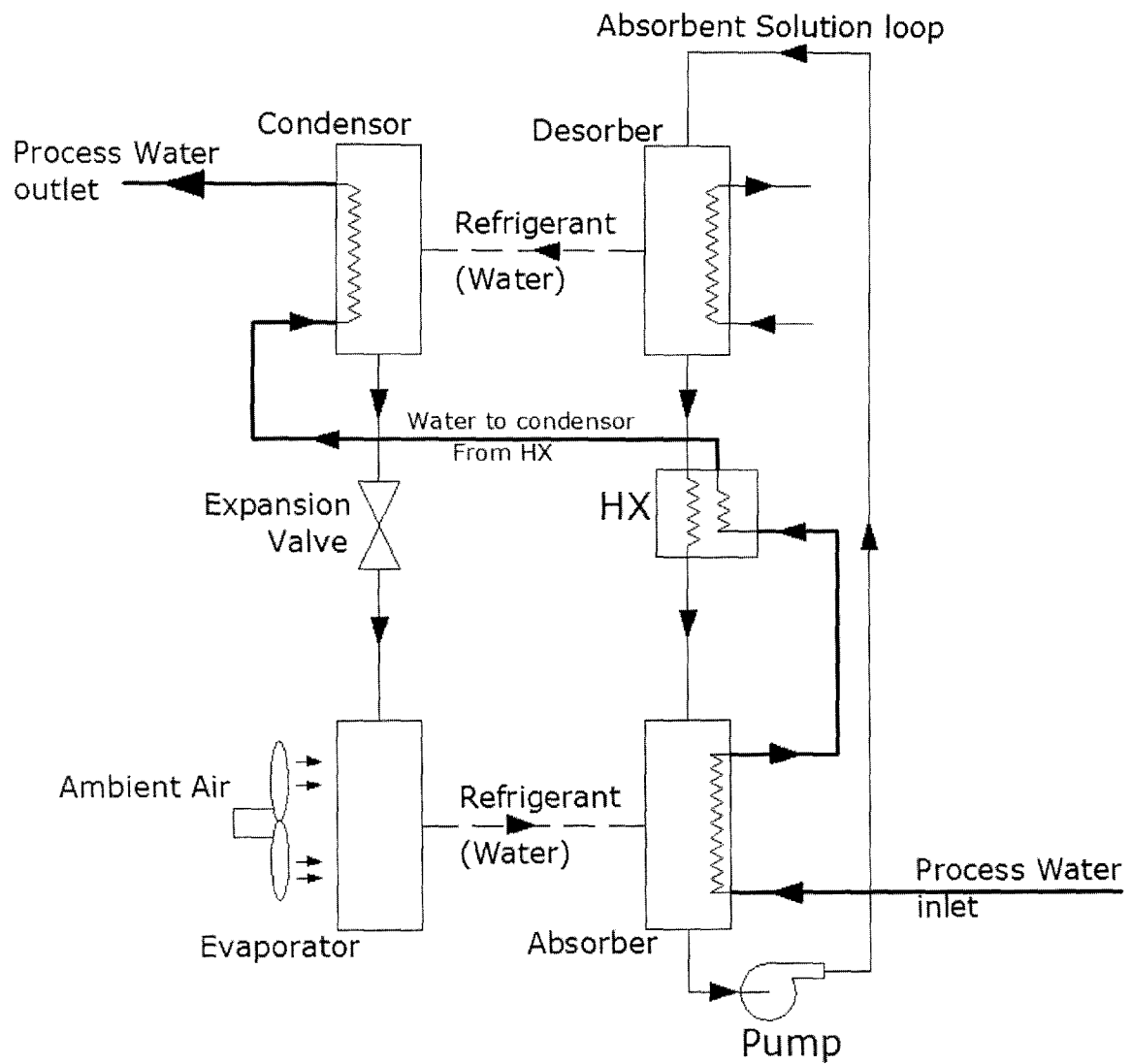
3. The absorption cycle system of claim 2, wherein absorbent in the aqueous solution is a LiBr solution.

4. The absorption cycle system of claim 1, wherein the desorber is an ultra-thin film desorber.

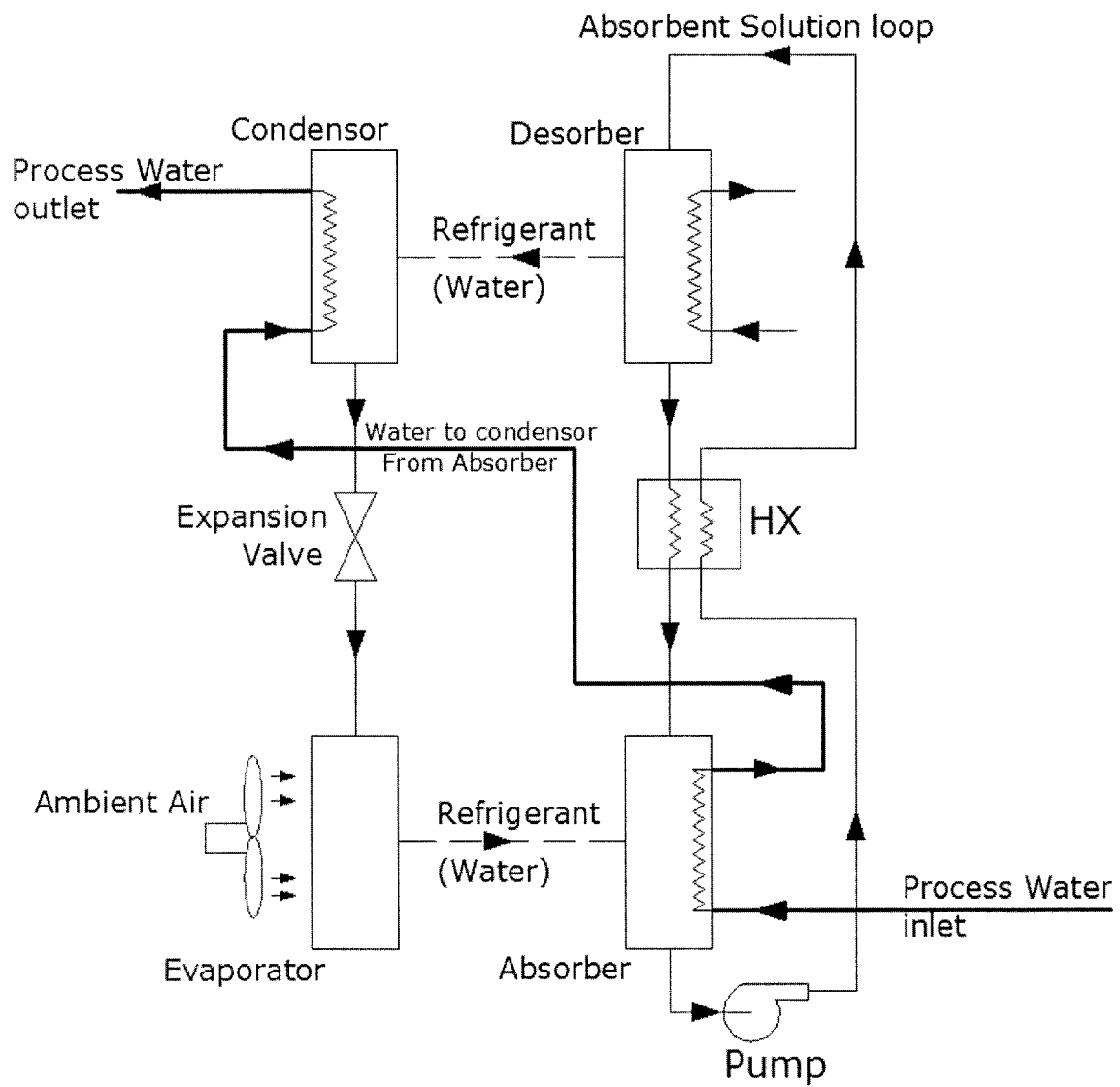
5. The absorption cycle system of claim 1, wherein the absorber is an ultra-thin film absorber.

6. The absorption cycle system of claim 1, wherein the process water flows from the absorber to the heat exchanger and from the heat exchanger to the condenser.
7. The absorption cycle system of claim 1, wherein the desorber, the absorber, the heat exchanger, and the condenser are housed as a single unit.
8. A method of water heating, comprising:
 - in-putting process water at a first temperature through an inlet to the absorption cycle system according to claim 1 having the optional evaporator;
 - heating the process water within the absorber, the heat exchanger, and the condenser;
 - and out-putting the process water from the absorption cycle system at a second temperature that is greater than the first temperature.
9. The method of water heating according to claim 7, wherein the absorption cycle system according to claim 1 includes the evaporator, wherein a controlled portion of the water vapor from the evaporator is provided to the absorber, whereby the air in a space in communication with the absorber is dehumidified and the air in a space in communication with the evaporator is cooled.
10. A method of dehumidifying, comprising:
 - in-putting process water at a first temperature through an inlet to the absorption cycle system according to claim 1 lacking the evaporator, wherein water vapor is provided to the absorber is from ambient air without any second source of water vapor, whereby the air in a space in communication with the absorber is dehumidified.
11. The method of dehumidifying according to claim 10, wherein the absorber is an ultra-thin film absorber.

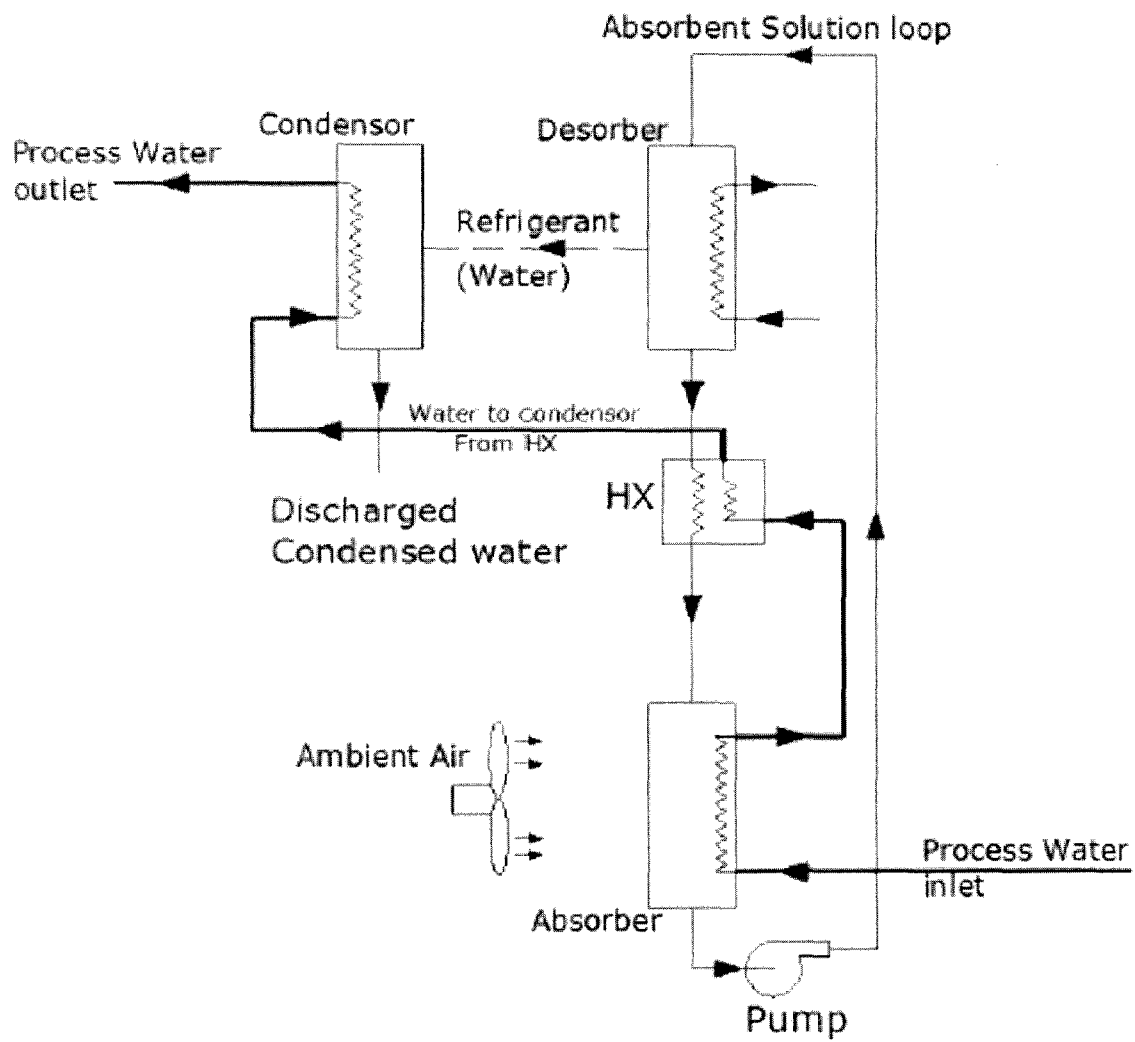
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*Figure 1*

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*Figure 2*

3/4

*Figure 3*

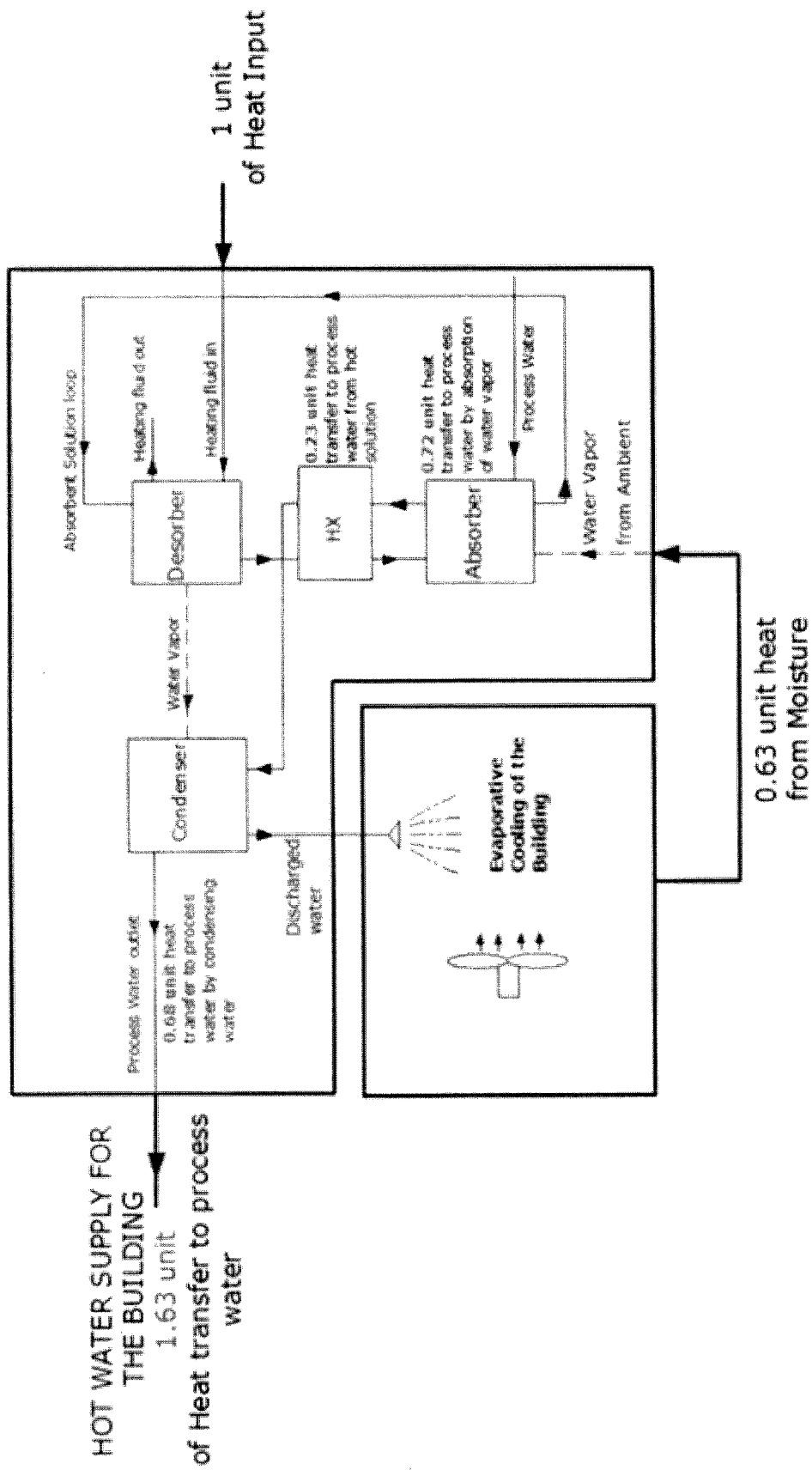


Figure 4

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US15/10757

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - F25B 15/16, 15/12, 15/06 (2015.01)

CPC - F25B 15/16, 15/12, 15/06

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)

IPC(8) - F25B 15/00, 15/06, 15/12, 15/16; F24F 3/14 (2015.01)

CPC - F25B 7/00, 15/00, 15/025, 15/06, 15/12, 15/16; USPC - 165/274, 302

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)

PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); ProQuest: IEEE; Google Scholar; absorption cycle, water heating, dehumidifying, desorber, absorber, heat exchanger, condenser

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 2012/0000221 A1 (ABDELAZIZ, O et al.) 05 January 2012; abstract; figure 2; paragraphs [0009], [0013], [0019], [0030], [0033], [0035], [0047]-[0049], [0051]-[0052], [0062], [0068]-[0069], [0071]	1, 3, 6-8 2, 4-5, 10-11
Y	US 2010/0281899 A1 (GARRABRANT, MA) 11 November 2010; paragraphs [0034]-[0035]	2,
Y	WO 2013/063210 A1 (UNIVERSITY OF FLORIDA RESEARCH FOUNDATION, INC.) 02 May 2013; abstract; page 4, lines 4-23	4-5, 11
Y	US 6,134,903 A (POTNIS, SV et al.) 24 October 2000; abstract; figure 1; column 7; lines 43-51	10-11

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

“A” document defining the general state of the art which is not considered to be of particular relevance

“E” earlier application or patent but published on or after the international filing date

“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)

“O” document referring to an oral disclosure, use, exhibition or other means

“P” document published prior to the international filing date but later than the priority date claimed

“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

“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

“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

“&” document member of the same patent family

Date of the actual completion of the international search

18 March 2015 (18.03.2015)

Date of mailing of the international search report

03 APR 2015

Name and mailing address of the ISA/

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Shane Thomas

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US15/10757

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.: 9
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 9
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.