The present invention includes an adsorbent sub-system to concentrate water vapor from an incoming pressurized air stream to a level that allows efficient water condensation with ambient air as the single cooling source. The heat released when condensing the water is transferred to the ambient air, without affecting the cooling capacity of the system.
TRADITIONAL HPWS

\[ y_{\text{ambient}} = 133 \text{ g/lb} \]
\[ y_{\text{supply}} = 45 \text{ g/lb} \]
\[ y_{\text{extracted}} = 88 \text{ g/lb} \]
\[ y_{\text{entrained}} = 93 \text{ g/lb} = 133 - y_{\text{saturation}} \]
\[ y_{\text{saturation}} = 40 \]

FIG. 1B
(PRIOR ART)
\[ \gamma_{\text{entrained}} = 93 \text{ g/lb} \]

\[ = 133 + \gamma_{\text{adsorbed}} - \gamma_{\text{saturation}} \]

\[ \gamma_{\text{saturation}} = 40 + \gamma_{\text{adsorbed}} \]

**FIG. 2B**
FIG. 3

CONDENSING PRESSURE AND TEMPERATURE AT WATER EXTRACTOR

- 80 g/lb Adsorbent, saturation curve
- 32 g/lb Adsorbent, saturation curve
- HPWS-No adsorbent, saturation curve
- HPWS application
- ADS-ECS application
- Condensing cycle application
FIG. 13
BLEED AIR
------------
RAM AIR
CABIN
47 RAMAR
76
FG.16C RECIRCULATED AIR

FIG. 16C
100 PROVIDING A COMPRESSED AIR STREAM

120 INCREASING THE MOISTURE CONTENT OF THE COMPRESSED AIR STREAM SUCH THAT A SUPER-HUMIDIFIED AIR STREAM IS PROVIDED

130 COOLING THE SUPER-HUMIDIFIED AIR STREAM SUCH THAT A MOISTURE SATURATED AIR FLOW HAVING A SUPPLY OF CONDENSED WATER IS PROVIDED

140 EXTRACTING THE SUPPLY OF CONDENSED WATER FROM THE MOISTURE SATURATED AIR FLOW SUCH THAT THE SUPPLY OF WATER AND A SATURATED FLOW ARE PROVIDED

150 DRYING THE SATURATED FLOW SUCH THAT A DRIED AIR FLOW IS PROVIDED

160 COOLING THE DRIED AIR FLOW

FIG. 17
ENVIROMENTAL CONTROL SYSTEM
WITH ADSORPTION BASED WATER REMOVAL

[0001] This application claims the benefit of U.S. Provisional Application Ser. No. 60/865,377, which was filed on Nov. 10, 2006. This application also claims the benefit of U.S. Provisional Application Ser. No. 60/865,577, which was filed on Nov. 13, 2006.

BACKGROUND OF THE INVENTION

[0002] The present invention generally relates to air conditioners and, more particularly, to aircraft environmental control systems.

[0003] All aircraft environmental control systems (ECS) designed to cool the cabin environment need to remove excessive atmospheric water. Water in excess of 30 to 50 grams of water per pound of dry air (g/lb) would freeze in the expansion process of air cycle based ECS or could result in unwanted liquid droplets entrained in the cooled air distributed to the cabin.

[0004] For a typical prior art high pressure water separation ECS 500, as depicted in FIG. 1a, the water extraction process can be simply represented by the schematics shown in FIG. 1b. The prior art high pressure water separation ECS 500 uses expansion in a single turbine 501 to provide a cold air flow 502 that causes condensation of the water in a condenser heat exchanger 503 located downstream of the turbine 501. The condenser 503 exit air (a cooled conditioned airflow 506) is supplied to the cabin to be cooled, however, its cooling capacity is reduced from that of turbine air (cold air flow 502) by all heat transfer occurring in the condenser 503 for the purpose of water condensation and removal. At a typical hot and humid design condition where an ambient airflow 504 brings moisture containing 133 grams of water per pound of dry air, if the ECS 500 has to deliver a cooled conditioned airflow 506 containing 45 g/lb, 88 g/lb has to be removed. If the system 500 includes a water extractor 505 with 95% extraction efficiency, an amount of 93 g/lb of entrained liquid water has to be provided to the water extractor 505. Simple equations establish that the saturation humidity of the air entering the extractor 505 has to be 40 g/lb. Saturation humidity (in this example 40 g/lb) is defined as the maximum amount of water vapor that can be held by the air at a given temperature and pressure. Condensation may occur at any moisture above the saturation humidity level. Saturation humidity varies with temperature (as temperature increases, the ability of the air to hold water vapor may increase). Saturation humidity also varies inversely with pressure (as pressure increases, the ability of the air to hold water vapor may decrease). Lowering the saturation humidity to permit condensation of liquid water can be achieved in this type of prior art system by a combination of relatively high pressure and cold turbine-induced temperature. The heat of condensation given off by the water upon changing phase from vapor to liquid adds to the temperature of the cooled conditioned air flow 506 supplied by the ECS 500 to the cabin (not shown), requiring the ECS turbine 501 to operate that much colder or its flow to be increased. The ECS therefore has to be oversized or require higher inlet pressure to cool the cabin load. Other prior art systems may include a second turbine (not shown) downstream of the condenser 503 that feeds the cabin directly. The second turbine recovers part, but not all of the heat energy incurred in the condensing step. That type of system is inherently more complex and may be heavier than the system 500 described above. Both types of cooling systems devote a substantial portion of turbine cooling capacity to the task of condensing the water. Turbine inlet energy is acquired in the form of pressurized airflow by compression of ambient air in a propulsion engine, auxiliary power unit or a number of mechanically driven compressors, all of which require an expensive source of power.

[0005] Aircraft air conditioners are disclosed in U.S. Pat. Nos. 6,655,168 and 6,666,839 to Mitani et al. In the described systems, air extracted from the engine is fed through a main air flow path into the cabin after being cooled by a cooling device. Extracted air is also fed into the cabin through an auxiliary air flow path. A plurality of adsorption sections are constituted by an adsorption agent that adsorbs molecules (e.g. water) contained in the air and releases adsorbed molecules by being raised in temperature in a desorption step. By control of an airflow changeover mechanism, each adsorption section is changed over between a condition connected with the auxiliary air flow path and a condition connected with an outflow air flow path. In the described process, the adsorption agent absorbs cabin moisture contained in recirculated cabin air and releases it by desorption to a fraction of the compressed fresh air extracted from the engine or APU that bypasses the air conditioning pack (ECS). The thus humidified air is then returned to the cabin to maintain the humidity level (in cruise or climb operation), or dumped overboard to prevent excess moisture in the cabin (in ground operation).

[0006] The Mitani et al. systems use hot air that bypasses the ECS to desorb the moisture from the adsorbent devices. That hot air is not subject to the normal ECS cooling and is delivered to the cabin at a temperature higher than that supplied by the ECS pack. In conditions when maximum cooling capacity is required (such as hot day Climb), this will constitute a capacity penalty, only overcome by the use of additional bleed pressure, motor power, ram air flow, or increased size of the ECS pack, all undesirable for operating economy.

[0007] As can be seen, there is a need for a system that can avoid adding the heat of condensation, or part of it, to the heat load that an ECS has to be designed to overcome. Another need is to avoid the use of turbine expansion to cause water to condense, instead using a source of cooling with lower energy cost. Another need is to avoid adding heat to the cabin by partially avoiding the cooling apparatus. There is also a need to avoid dumping overboard air to which mechanical energy has been added in the process of water removal. The energy expenditure in the form of cooling capacity or mechanical power needed for condensation of water vapor for the purpose of removal represents a sizeable penalty that has not been totally avoided by current ECS systems.

SUMMARY OF THE INVENTION

[0008] In one aspect of the present invention, a method of removing a supply of water from an air stream comprises the steps of providing a compressed air stream; increasing the moisture content of the compressed air stream such that a super-humidified air stream is provided; positioning the super-humidified air stream in thermal contact with a cooling airflow such that a moisture saturated air flow having a supply of condensed water is provided; and extracting the supply of condensed water from the moisture saturated air flow such that the supply of water and a saturated flow are provided.
In a further aspect of this invention, the method for increasing the moisture content of the compressed air is through the use of an adsorbing subsystem having an adsorbing portion and a desorbing portion, with moisture transferred from the adsorbing portion to the desorbing portion and to the compressed stream.

In another aspect of the present invention, a system comprises a compressor; and an adsorbent sub-system having a desorbing portion and an adsorbing portion, the desorbing portion in flow communication with the compressor that provides a source of heat for desorption of water.

In another aspect of the present invention, a system comprises an air supply sub-system; an air cycle machine having a compressor and a turbine, the compressor in flow communication with the air supply sub-system; an adsorbent sub-system having a desorbing portion and an absorbing portion, the adsorbing portion in flow communication with the turbine so it provides a source of dried air to the turbine; a secondary heat exchanger in flow communication with the desorbing portion; and a water extractor in flow communication with the secondary heat exchanger so the cooled desorbed fluids condense and are extracted.

In another aspect of this invention, the water is performed at ambient temperature such that a low energy water flow air can be used instead of colder turbine air.

These other aspects, features, and advantages of the present invention will become better understood with reference to the following drawings, description and claims.

**BRIEF DESCRIPTION OF THE DRAWINGS**

**FIG. 1a** is a schematic of a prior art ECS based on high pressure water separation;

**FIG. 1b** is a schematic of a water extraction process of FIG. 1a;

**FIG. 2a** is a schematic of an ECS with adsorption based water removal according to one embodiment of the present invention;

**FIG. 2b** is a schematic of a water extraction process of FIG. 2a;

**FIG. 3** is a plot of the saturation curves of water for a prior art no adsorbent ECS and for two embodiments of the present invention;

**FIG. 4** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 5** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 6** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 7** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 8** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 9** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 10** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 11** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 12** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 13** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 14** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 15** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 16a** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 16b** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 16c** is a schematic of an ECS with adsorption based water removal according to another embodiment of the present invention;

**FIG. 17** is a flow chart of a method of removing water from an air stream according to an embodiment of the present invention.

**DETAILED DESCRIPTION OF THE INVENTION**

The following detailed description is of the best currently contemplated modes of carrying out the invention. The description is not to be taken in a limiting sense, but is made merely for the purpose of illustrating the general principles of the invention, since the scope of the invention is best defined by the appended claims.

Broadly, the present invention provides air conditioning systems with adsorption based water removal and methods for removing water from an air stream. Embodiments of the present invention may find beneficial use in industries such as aerospace, automobile and water production. Embodiments of the present invention may be useful in applications including environmental control systems and refrigeration systems. Embodiments of the present invention may be useful in applications including, but not limited to water concentrating and processing (such as concentration of atmospheric water for purification and human use), and process fluid dehydration. Embodiments of the present invention may be used in any air conditioning application including, but not limited to, environmental control systems for aircraft.

In one embodiment, the present invention provides an air cycle ECS that includes an adsorbent medium to concentrate water vapor from the incoming pressurized air stream to a level that allows efficient condensation with ambient air as the single cooling source. Unlike the prior art conventional air cycle systems, the present invention avoids the need for cooling by an expansion turbine and thus adds no heat of condensation to the supply temperature, so the system requires less energy than conventional air cycle systems for the same delivered cooling capacity. Ambient (or ram air in flight) may be one of the lowest energy sources of cooling and may impose a minimal fuel penalty on the airplane. This is not the case for prior art systems, which must rely on expansion through the cooling turbine of compressed air obtained from high-energy sources (engine or motorized compressors).
Also, as at least one cooling turbine of the prior art systems has to be followed by a condenser heat exchanger, the air normally sent to the cabin is burdened with an additional heat load corresponding to all or part of the heat of water condensation. Additionally, the present invention is relatively simpler than prior art systems as several heat exchangers and possibly multiple turbine wheels may be deleted. The present invention is therefore of relatively lower cost than the prior art systems as it can replace the traditional condenser and reheater by a relatively low cost adsorbent system (e.g. adsorbent wheel).

Unlike the prior art that does not concentrate the water vapor, the present invention can use an adsorbent desorbent device (for example, a set of two or more separate adsorbent beds, each bed including an adsorbent medium) for water vapor concentration to facilitate water extraction at a more favorable combination of pressure and temperature. For embodiments of the present invention, water adsorbed at relatively low temperature can be released to the ECS stream in the desorbing step, so that the water concentration at the inlet of the water extractor is increased by the water adsorption capacity of the adsorbent/desorbent device.

In the example used for the prior art system, it then can be established that to remove the same overall amount of water with an adsorbent-based ECS, the saturation humidity ($\gamma$-saturation) of the air entering the water extractor becomes 40 g/lb plus the adsorbed quantity ($\gamma$-adsorbed). This is illustrated in FIG. 25. The saturation humidity ($\gamma$-saturation) is defined as the maximum amount of water vapor that can be held by the air at a given temperature and pressure. The adsorbed quantity ($\gamma$-adsorbed) is defined as the amount of water per unit of dry air adsorbed by the adsorbent medium. For a system designed with equal adsorbing and desorbing mass flows, $\gamma$-saturation = $40 + \gamma$-adsorbed. The saturation humidity at the point of water extraction required to meet the design requirement is therefore higher with an adsorbent-based ECS, where the water extraction is followed by an additional reduction of moisture content by adsorption. This establishes a more favorable combination of pressure and temperature at the point of water extraction, illustrated in FIG. 3. For the chosen example, it is possible to provide the same amount of condensed water with an adsorbent-based ECS operating at a pressure 5 psi lower and a temperature 33° F. warmer than with a conventional system. Unlike the prior art systems that have to expand turbine energy to provide a cooling stream at below ambient temperatures to affect water condensation, embodiments of the present invention can then use ambient air directly as the cooling medium (in the example, hot ambient air at 120° F. instead of subfreezing turbine air at −31° F. to cool compressed air in a condenser to 87° F.). The energy penalty for water condensation is reduced both by operating at a lower pressure and by using ambient air requiring minimal power to draw.

Unlike the prior art systems that make use of adsorbent devices but depend on hot air by-passing the ECS pack to desorb the moisture from the adsorbent devices, the present invention does not rely on a separate hot air stream for desorption. Unlike the prior art, the present invention can use for desorption warm compressed air that is part of the normal ECS airflow cycle and by doing so can avoid the system cooling capacity penalty associated with the prior art use of hot by-pass air.

An embodiment of the present invention is depicted in FIG. 2a. The present invention can comprise a system having an adsorbent sub-system 41. As a general overview of the present invention, an adsorbing portion (ADS) 42 of the adsorbent sub-system 41 may adsorb water from an ADS inlet flow 65 at near ambient temperature. The ADS inlet flow 65 may comprise a compressed moist air stream. The system 40 then may deliver an ADS outlet flow 66 to a turbine 43. The ADS outlet flow 66 may constitute a relatively dry air flow matching the system’s design requirements for supply humidity. The turbine 43 may expand the ADS outlet flow 66 and may deliver a turbine outlet flow 68 to an enclosure 44 to be supplied with cool, relatively dry air (e.g. a cabin). The turbine outlet flow 68 may constitute a cold air flow matching the system’s cooling capacity requirements.

A desorbing portion (DES) 45 of the adsorbent sub-system 41 may desorb the water that was adsorbed by the ADS 42. A DES inlet flow 60 may flow over the DES 45 to desorb the captured water vapor. The DES inlet flow 60 may comprise a compressed air flow, such as hot compressed air that is part of the normal ECS airflow cycle. For example, as depicted in FIG. 2a, the DES inlet flow 60 may comprise air flow from cabin air compressors that has been temperature controlled by a heat exchanger and further compressed and heated by an ECS compressor. The DES 45 provides a DES outlet flow 46. In situations where it is desirable to reclaim the water in its liquid form, as depicted in FIG. 2a, the DES outlet flow 46 may be cooled by a cooling air flow 47 (consisting of a ram air stream or ambient air or recirculated enclosure air) in a condenser heat exchanger (a secondary heat exchanger 48) and then a water extractor 49 may extract the liquid water. A water extractor outlet flow 64, consisting of a flow of cooled, water saturated compressed air then may be directed to the ADS 42. Alternatively, as depicted in FIG. 15, the present invention also may apply to situations where it is not desirable to reclaim the water. In that case, the DES outlet flow 46 may be discharged back to ambient.

The system 40, as depicted in FIG. 2a, can comprise an ECS with adsorption based water removal. The system 40 may include an air supply sub-system 50, a primary heat exchanger (PHX) 51, an air conditioning compressor 52, the adsorbent sub-system 41 (comprising the DES 45 and the ADS 42), the secondary heat exchanger (SHX) 48, the water extractor 49 and the turbine 43.

The air supply sub-system 50, as depicted in FIG. 2a, may receive a supply of outside air 88. Although, the air supply sub-system 50 is depicted as a cabin air compressor, other configurations of air supply sub-systems 50 may be useful with embodiments of the present invention, for example engine bleed air subsystems. Useful air supply subsystems 50 may include, but are not limited to, bleed ports on a propulsion engine, an auxiliary power unit (APU), ground carts, and any other compression source using the supply of outside air 88, such as electric, shaft or hydraulically driven compressors. The air supply sub-system 50 may compress and heat the supply of outside air 88 and provide an air supply sub-system outlet flow 53. The air supply sub-system outlet flow 53 may therefore comprise a compressed outside air flow. The air supply sub-system outlet flow 53 may comprise a humid, compressed and heated airflow and may be directed towards the PHX 51. In that case, the air supply sub-system outlet flow 53 may comprise a PHX inlet flow 54.

The PHX 51, as depicted in FIG. 2a, may receive the PHX inlet flow 54. The PHX 51 may be in fluid communication with the air supply sub-system 50 and in thermal contact with the cooling air flow 47. The PHX 51 may comprise a ram
heat exchanger positioned within a ram duct 55. The PHX 51 may cool the PHX inlet flow 54 to provide a PHX outlet flow 56. Ambient air or ram air (cooling air flow 47) may have the lowest energy cost of all potential cooling sources available for the system 40. The energy cost associated with ambient, or ram air, (cooling air flow 47) is the energy needed to drive a fan 57 that pulls the cooling air flow 47 on the ground, as well as that resulting for the airplane having to overcome the drag associated with the amount of additional ambient airflow captured (momentum loss). This energy amount can be much lower than that required by a propulsion engine or electrical compressors to capture and compress ambient air to a level suitable for expansion in the turbine 43. After cooling by the ambient air medium, the PHX outlet flow 56 may constitute a cooled, compressed humid airflow. The PHX outlet flow 56 may be directed towards the air conditioning compressor 52 as part of a compressor inlet flow 58.

[0046] The air conditioning compressor 52, as depicted in FIG. 2a, may be in flow communication with the PHX 51 and the air conditioning compressor 52 and may receive the compressor inlet flow 58. The air conditioning compressor 52 may comprise a compressor, such as an ECS compressor (e.g. air cycle machine compressor). As used herein, “compressor” may be a generic term and may comprise the air conditioning compressor 52, an enclosure flow compressor 81 (discussed below, see FIGS. 11, 12, 13 and 16) or a motorized compressor 79 (discussed below, see FIG. 9). The air conditioning compressor 52 may further compress and heat the compressor inlet flow 58 and provide a compressor outlet flow 59, constituting a heated and compressed flow. The air conditioning compressor 52 may be in flow communication with the DES 45. The compressor outlet flow 59 may be directed towards the DES 45 of the adsorbent sub-system 41, so that the compressor outlet flow 59 may comprise the DES inlet flow 60.

[0047] The adsorbent sub-system 41, as depicted in FIG. 2a, may comprise the DES 45 and the ADS 42. The adsorbent sub-system 41 may comprise a set of two or more separate adsorbent beds (DES 45 and ADS 42). The ADS 42 and the DES 45 each can comprise one or more adsorbent beds. The adsorbent beds can be used in an alternating manner to regenerate the beds and maintain a continuous adsorption capacity. For example, a first bed can be used for desorption (DES 45) while a second bed can be used for adsorption (ADS 42) and then the second bed can be used for desorption (DES 45) while the first bed is used for adsorption (ADS 42). For some embodiments, a purge or cooling portion (not shown) may be included for optimization of the thermal cycle as the adsorbent sub-system 41 transitions from the relatively cool ADS 42 to the hotter DES 45. Each bed may be cycled through the phases of adsorption, desorption and purging to regenerate the adsorbent sub-system 41. In other words, the adsorbent beds may be regenerated in a desorbing step, and then recycled in an adsorbing step by continuously or periodically exchanging the functions of the beds (ADS 42 and DES 45). In lieu of separate beds, the adsorbent sub-system 41 may comprise at least one adsorbent wheel. An adsorbent wheel may comprise a slowly rotating adsorbent wheel with adsorbing and desorbing sectors (ADS 42 and DES 45). Useful adsorbent wheels may include the adsorbent wheels described in U.S. Pat. No. 5,667,560, which is incorporated herein by reference.

[0048] The adsorbent sub-system 41 may be loaded with adsorbent material (not shown). Useful adsorbent materials may include, but are not limited to, activated carbon, silica gel, activated alumina, and zeolites. Zeolites may be commercially available crystalline aluminosilicates with complex three-dimensional infinite lattices. Useful zeolites may include, but are not limited to, DDR-70, which is a rare earth exchanged form of FAU available from UOP LLC, Des Plaines, Ill.

[0049] The DES 45 of the adsorbent sub-system 41, as depicted in FIG. 2a, may receive the DES inlet flow 60. The DES 45 may comprise a compressed air flow. Although, the embodiment of FIG. 2a depicts the system 40 as including the air supply sub-system 50 (cab-in-air compressors), the primary heat exchanger 51 and the air conditioning compressor 52 (part of the air cycle machine) to provide the DES inlet flow 60, embodiments of the present invention, described below, can include other combinations of compressors or heat exchangers to provide the DES inlet flow 60 as long as the DES inlet flow 60 comprises a compressed air flow. The compressed air flow can comprise compressed outside air, as described for the embodiment of FIG. 2a, recirculated air (an enclosure outlet flow 75) as described below for FIG. 11, or a combination of both outside air and recirculated air as described below for FIG. 8. The DES 45 may be in flow communication with the air supply sub-system 50 and may receive the compressed outside air flow. The DES inlet flow 60 may heat the adsorbent material (not shown) of the DES 45 and may cause water (not shown) previously adsorbed by the adsorbent material to desorb. For some aircraft applications, the temperature of the DES inlet flow 60 may be less than about 400°F. The DES inlet flow 60 may be loaded with this additional desorbed water vapor. At the same time, the DES inlet flow 60 progressing further through the DES 45 may also be cooled by the endothermic desorption process and by heat transfer with the cooler adsorbent material. The DES 60 may provide the DES outlet flow 46, constituting a super-humidified and cooled compressed airflow. For some aircraft applications, the temperature of the DES outlet flow 46 may be between about 170°F and about 220°F. The DES outlet flow 46 may be directed towards the SHX 48, comprising a SHX inlet flow 61.

[0050] The water content in the DES outlet flow 46 may be higher than the water content of the DES inlet flow 60 due to the addition of the desorbed moisture. The DES outlet flow 46 will exceed the saturated amount of water that it can carry in vapor form when cooled in a subsequent condensation step, but because of higher moisture content, that condensation step may occur at a higher temperature or lower pressure, or combination of both, than can the ambient supply flow (supply of outside air 88). In particular, it may become possible to affect condensation of undesired water amounts at temperatures that can be achieved by simply cooling the DES outlet flow 46 by heat transfer with ambient air or equivalent (cooling air flow 47), and with an elevated pressure lower than required by non-adsorbent assisted prior art systems.

[0051] The saturation curves of water that would allow removal of 88 g/lb of liquid water from an original stream containing 133 g/l of moisture per pound of dry air in an extractor with an efficiency of 95% are shown in FIG. 3 for a non-adsorbent assisted prior art system and for two embodiments of the present invention. In FIG. 3, adsorbent devices (adsorbent sub-system 41) with capacity to adsorb, transfer and desorb the equivalent of 80 g/lb and 32 g/lb respectively are compared to the prior art non-adsorbent high pressure water separation ECS. The saturation curve of water for the embodiment having a capacity of 80 g/lb is indicated by
number 90, the saturation curve of water for the embodiment having a capacity of 32 g/lb is indicated by number 91 and the saturation curve of water for the prior art ECS is indicated by the number 92. The saturation curves of water show that the same water extraction potential can be achieved at higher temperatures with both embodiments of the present invention when compared to the prior art system. The embodiment having a capacity of 90 g/lb was found to require 7 psia lower inlet pressure than the prior art system, while conditioning with hot ambient air 33° F. above the prior art turbine-cooled condensers.

[0052] The SHX 48, as depicted in FIG. 2a may receive the SHX inlet flow 61. The SHX 48 may be in flow communication with the DES 45. The SHX 48 may comprise a heat exchanger adapted to receive and cool the DES outlet flow 46 to provide a cooled SHX outlet flow 62. The SHX 48 may comprise a ram heat exchanger disposed within the ram duct 55 at a position upstream of the PHX 51. Upstream may be defined with reference to the cooling air flow 47. Due to the highly concentrated amount of water vapor loaded in the SHX inlet flow 61, by reducing its temperature a substantial amount of liquid water may be condensed, releasing its heat of condensation to the cooling air flow 47. Embodiments of the present invention can use ambient air (e.g. cooling air flow 47) for conditioning water and can avoid the need for cooling by the turbine 43 for conditioning water as normally used in prior art ECS. As a result, the heat of condensation of the atmospheric water may not affect the output of the ECS packs, which depend on the turbine 43 for supplying sub-ambient air temperatures to the enclosure 44, as no condenser heat exchanger may be required between the turbine 43 and the enclosure 44 to be conditioned (e.g. cabin). The SHX 48 may cool the SHX inlet flow 61 to provide the SHX outlet flow 62. The SHX outlet flow 62 may comprise an air flow at ambient or near ambient air temperature (ex. 110-120°F. on a hot design day). The SHX outlet flow 62 may comprise a ram-cooled, compressed humid air flow containing a substantial amount of liquid water. The SHX outlet flow 62 may be directed towards the water extractor 49, constituting a water extractor inlet flow 63.

[0053] The water extractor 49, as depicted in FIG. 2a, may receive the water extractor inlet flow 63. The water extractor 49 may be in flow communication with the SHX 48. The water extractor 49 may comprise a conventional water extractor, such as a passive centrifuge-action water extractor, which is a high pressure water extractor. The water extractor 49 may strip at least some, and desirably most or all, of the condensed water from the water extractor inlet flow 63 to provide the water extractor outlet flow 64. The water extractor outlet flow 64 emerging from the water extractor 49, and consisting in a cooled and still pressurized stream may then be released in an essentially saturated state. The water extractor outlet flow 64 may be directed towards the ADS 42 of the adsorbent sub-system 41 comprising the ADS inlet flow 65.

[0054] The ADS 42 of the adsorbent sub-system 41, as depicted in FIG. 2a, may receive the ADS inlet flow 65. Depending on the adsorbent sub-system design capacity and operating conditions, the ADS 42 may absorb at least some, and desirably most or all, of the water vapor moisture from the ADS inlet flow 65 and provide the ADS outlet flow 66. The ADS outlet flow 66 may comprise a dried, compressed stream that has been reheated at the adsorption process as well as by heat transfer with the hotter adsorbent material. For some aircraft applications, the temperature of the ADS outlet flow may be between about 190° F. and about 200° F. and its moisture content may be between about 30 and about 50 grain/lb, although lower moisture levels may be selected by design of the adsorbent capacity and operating pressure. The transition from a free vapor state to that bonded to the adsorbent material may be considered the equivalent of a phase change and requires exchange of a heat of adsorption/desorption. Embodiments of the present invention can make use of this energy transfer without penalizing the cooling capacity. The adsorbent material handles the water in vapor phase, so there may be no heat of condensation to be overcome by the system 40 beyond that released to the cooling air flow 47 in the SHX 48. After adsorption, the ADS outlet flow 66 then may be directed to the turbine 43, constituting a turbine inlet flow 67.

[0055] The turbine 43, as depicted in FIG. 2a, may comprise the air cycle machine turbine and may receive the turbine inlet flow 67. The turbine 43 may expand and cool the turbine inlet flow 67 to below ambient temperature and provide the turbine outlet flow 68. The turbine outlet flow 68 may be designed to be suitable for delivery to the enclosure 44 to be cooled and conditioned (e.g. cabin), having both a cold temperature and reduced humidity content.

[0056] Embodiments of the system 40 also may include means of by-passing the air supply sub-system flow compressor 52, the turbine 43 and the adsorbent sub-system 41 when expansion cooling and water removal are not required, such as high altitude cruise when the ambient air is cold enough to cool by heat transfer alone and no significant moisture is present in the air. For these embodiments, the system 40 may include a temperature control valve 69 and a compressor by-pass check valve 70. The temperature control valve 69 may be positioned between and in flow communication with the water extractor inlet or outlet flow 64 and the turbine outlet flow 68. The compressor by-pass check valve 70 may be positioned between and in flow communication with the PHX outlet flow 56 and the DES outlet flow 46.

[0057] In another embodiment of the present invention, as depicted in FIG. 4, the system 40 further may include an additional heat exchanger (AHX) 71. The AHX 71 may comprise a ram heat exchanger disposed within the ram duct 55 at a position upstream of the PHX 51 and in flow communication with the air supply sub-system flow compressor 52. The AHX 71 may be set in a parallel configuration with the COND 48 on the ram air side so together the AHX and CONDHX take the place of the SHX 48 of FIG. 2a. In this embodiment, the compressor outlet flow 59 may be split such that compressor 52 may provide a first portion of compressor outlet flow.
The first portion of compressor outlet flow 59a may be directed towards the DES 45 and the second portion of compressor outlet flow 59b may be directed towards the ADS 42. The first portion of compressor outlet flow 59a directed towards the DES 45 may comprise the DES inlet flow 60 and may be processed as described above. The second portion of compressor outlet flow 59b may be directed towards the AHX 71 and comprise an AHX inlet flow 72.

The embodiment of FIG. 4 may have the advantage of creating a very high water concentration in the water extractor inlet flow 63, as moisture from the combined compressor streams (AHX outlet flow 73 and water extractor outlet flow 64) may be removed by the ADS 42 and transferred back to the lower DES outlet flow 46. This arrangement may favor high water extraction efficiency, in particular for conditions when the inlet air (supply of outside air 88 to the air supply sub-system 50) is not very highly loaded with moisture. This may be specifically advantageous if the purpose of the system 40 is to gather liquid water in relatively dry conditions. For example, on a dry 70°F day with only 20% relative humidity, a system with a 3:1 adsorbing-to-desorbing flow ratio and 3:1 compression ratio could extract more than one third of the atmospheric water available in the process stream. However, for typical aircraft ECS applications, where the objective may be to remove excess water, the design cases are generally at relatively high moisture levels (133 g/lb of dry air), and may not require such flow concentration factor. Instead, simplicity and low weight may be favored, as provided by the embodiment of FIG. 2a.

Another embodiment of the present invention, as depicted in FIG. 5, illustrates a second version of the design of FIG. 4. In this embodiment, the AHX outlet flow 73 may be split such that a first portion of AHX outlet flow 73a and a second portion of AHX outlet flow 73b are formed. The first portion of AHX outlet flow 73a may be directed towards the turbine 43 and may comprise a portion of the turbine inlet flow 67. Said first portion of AHX outlet flow 73a may mix with the ADS outlet flow 66 to provide the turbine inlet flow 67. The second portion of AHX outlet flow 73b may be directed towards the ADS 42 and may comprise a portion of the ADS inlet flow 65. Said second portion of AHX outlet flow 73b may mix with the water extractor outlet flow 64 to provide the ADS inlet flow 65. For these embodiments, the size and weight of the ADS 42 may be reduced because the first portion of AHX outlet flow 73a may by-pass the ADS 42. For embodiments including adsorbent wheels, the wheel may be operated at higher RPH and the system 40 may provide a drier and warmer output. Although not depicted, this same ADS by-pass concept also may apply to the embodiment of FIG. 2a.

Another embodiment of the present invention, as depicted in FIG. 6, illustrates a third version of the design of FIG. 4. In this embodiment, the system 40 further may include a recuperator 74, the enclosure outlet flow 75, and a mixer 76. The enclosure outlet flow 75 may be provided out of the enclosure 44 and may consist of recirculated enclosure air. The recuperator 74 may be in thermal contact with the COND outlet flow 62 and may be positioned between the COND 48 and the water extractor 49. The recuperator 74 also may be in thermal contact with the enclosure outlet flow 75 (recirculated air). The embodiment depicted in FIG. 6 may take advantage of the colder temperature of the enclosure outlet flow 75 to assist the condensing process by providing additional cooling to the COND outlet flow 62. After passing through the recuperator 74, the recirculated air (enclosure outlet flow 75 and the turbine outlet flow 68 may be mixed by the mixer 76 and a mixer outlet flow 77 may be returned to the enclosure 44. For some applications, this embodiment may reduce the size of the adsorbent sub-system components as more water can be removed mechanically, but it may require a subfreezing turbine outlet flow 68 to compensate for the higher temperature of the recirculated air (enclosure outlet flow 75) returned to the enclosure 44.
air supply sub-system outlet flow 53 comprises at least a portion of the compressor inlet flow 58. In this embodiment, the DES inlet flow 60 may comprise a combination of both outside air and recirculated air from the compressor outlet flow 59. For this embodiment the compressor outlet flow 59 may be directed towards the DES 45 (inlet flow 60) and then may be processed as described above for FIG. 2a. The embodiment depicted in FIG. 8 may presuppose that the air supply sub-system 50 pressure is essentially matching or lower than that of the enclosure 44 and therefore may require a relatively low expenditure of energy. To balance that low pressure, the air conditioning compressor 52 may operate at higher pressure ratios. In the embodiment depicted in FIG. 8, the system 40 further may include an electric motor 78 operationally connected to the compressor 52 to augment the energy provided by the turbine 43. For this embodiment, the air supply sub-system 50 also may be in flow communication with the SHX 48 such that another portion of the air supply sub-system outlet flow 53 may be directed to the SHX 48 to provide a by pass mode for cruise operation. In cruise, a by-pass flow 86 may avoid the water extractor 49, the ADS 42 and the turbine 43. The by-pass on cruise flow 86, together with the turbine outlet flow 68, may constitute an enclosure inlet flow 87.

[0064] Another embodiment of the present invention, as depicted in FIG. 9, illustrates a second version of the design of FIG. 8. In this embodiment the recirculated air (enclosure outlet flow 75) may enter the system 40 at a position upstream of the ADS 42. In this embodiment, the ADS inlet flow 65 may therefore comprise a mixture of the enclosure outlet flow 75 and the water extractor outlet flow 64. The system 40 may include the motorized compressor wheel 79 providing additional energy to the recirculated enclosure outlet flow 75. The motorized compressor 79 may be required to match the higher pressure of the ADS inlet flow 64 coming from the compressed air supply as water separator outlet flow. The enclosure outlet flow 75 may lower the relative humidity of the mixed flow (ADS inlet flow 65) entering the adsorbent, but may bring an additional quantity of moisture for adsorption. Unlike the embodiment depicted in FIG. 8, the air supply pressure may be independent of cabin pressure, which may make the embodiment of FIG. 9 equally compatible with bleedless aircraft and airplane applications.

[0065] Another embodiment of the present invention, as depicted in FIG. 10 illustrates a version of the design of FIG. 2a with chilled recirculation air. The embodiment depicted in FIG. 10 may not process the recirculated air (enclosure outlet flow 75) within the fresh air cycle; instead the system 40 may provide separate cooling of the enclosure outlet flow 75 via a ram air/liquid transport loop 80. The air cycle machine (compressor and turbine) can include the electric motor 78, which may allow for an optimization of power and operating conditions for both the air cycle machine and the air supply sub-system 50 (e.g. cabin air compressors for a bleedless engine application). In this embodiment of the system 40, the air supply sub-system outlet flow 53 may be processed as described for FIG. 2a above to provide the turbine outlet flow 68. After being cooled by the ram air/liquid transport loop 80, the enclosure outlet flow 75 may be mixed with the turbine outlet flow 68 by the mixer 76. The mixer outlet flow 77 (see FIG. 6) then may be directed to the cabin.

[0066] Another embodiment of the present invention, as depicted in FIG. 11, illustrates a concept where both fresh compressed air (air supply sub-system outlet flow 53) and recirculated air (enclosure outlet flow 75) are combined in the adsorption/desorption process. On hot, humid day conditions typical for ECS design, the enclosure outlet flow 75 may be cooler than ambient air and therefore may represent a desirable source of cooling. The enclosure outlet flow 75 also may contain a level of moisture (some of this moisture generated by the cabin occupants) generally lower than the most humid ambient conditions. Capturing some of that moisture may be equally valuable to control the humidity level delivered to the enclosure 44 as removing fresh air moisture. The enclosure flow compressor 81 (as an additional compressor wheel) may be included in the air cycle machine to boost the recirculated air pressure to the level of the fresh compressed air at the inlet of the adsorbent unit (ADS 42). The enclosure flow compressor 81 may be in flow communication with the DES 45. After passing through the recuperator 74 (optional—may be included to reduce the size of COND 48), the enclosure outlet flow 75 (recirculated air) may be compressed by the enclosure flow compressor 81 to provide a compressed enclosure air flow 82. The compressed enclosure air flow 82 may constitute the DES inlet flow 60 as it is directed towards the DES 45. In this embodiment, the DES inlet flow 60 may be constituted exclusively of recirculated air. The DES outlet flow 46 then can be processed as described above for FIG. 6 to provide at least a portion of the ADS inlet flow 65. The air supply sub-system outlet flow 53 (fresh air stream) can pass through the PHX 51, the air conditioning compressor 52 and the AHX 71 to provide the AHX outlet flow 73. The AHX outlet flow 73 may comprise at least a portion of the ADS inlet flow 65. The ADS 42 can collect water from both fresh and recirculated streams as for this embodiment the ADS inlet flow 65 comprises a mixture of the AHX outlet flow 73 and the water extractor outlet flow 64. For some aircraft applications, it may be expected that desorbing capacity of the system 40 may be increased by approximately 8% by use of the colder, drier recirculation stream as the single desorbing fluid (DES inlet flow 60). The optional recuperator heat exchanger 74 may assist in the final cooling and condensing of the stream (COND outlet flow 62) by heat transfer with the colder recirculation air (enclosure outlet flow 75). An additional advantage of this concept may be that, due to the increase of delivered mass flow from the turbine (turbine outlet flow 68 comprising both fresh and recirculated air mass), it may not be necessary to supply sub freezing air temperatures to cool the loads in the enclosure 44. A non-freezing turbine can use simplified systems and can be more reliable than conventional sub-freezing designs. Also, the pressure and energy required from the air supply may be reduced when the turbine expansion pressure is lower, which may be the case when operating at higher mass flow and higher supply temperatures.

[0067] Another embodiment of the present invention, as depicted in FIG. 12, illustrates a second version of the design of FIG. 11. FIG. 12 illustrates the same principle as FIG. 11, but with a single secondary-condensing heat exchanger (AHX 71 not included in embodiment of FIG. 12). Moisture-loaded desorbing recirculation stream (DES outlet flow 46) and compressed fresh air at ambient humidity (compressor outlet flow 59) merge at the inlet of the SHX 48. In other words, the SHX inlet flow 61 may comprise a mixture of the compressor outlet flow 59 (fresh stream) and the DES outlet flow 46 (recirculation stream). The omission of the AHX 71 may simplify the system 40, but may somewhat dilute the moisture concentration of the stream (water extractor inlet...
flow 63) prior to water condensation. To counter that effect, the recirculation air recuperator (recuperator 74) may be used to lower the condensing temperature. The embodiment depicted in FIG. 12 also may include the electric motor 78 (optional) to power the air cycle machine and balance the power required by the two compressors (air conditioning compressor 52 and enclosure flow compressor 81) with that provided by the turbine 43.

Another embodiment of the present invention, as depicted in FIG. 13 illustrates a third version of the design of FIG. 11. In this embodiment the fresh air compressor wheel (air conditioning compressor 52) is not included. The single ACM compressor (enclosure flow compressor 81) may only handle the recirculated air (enclosure outlet flow 75), while the fresh air pressure may be the pressure supplied by the supply sub-system 50 with no further compression. The enclosure flow compressor 81 may compress the enclosure recirculated air outlet flow 75 and provide the compressed enclosure air flow 82 (recirculation stream). The compressed enclosure air flow 82 may result in the DES inlet flow 60. The DES outlet flow 46 then can be processed as described above for FIG. 6 to provide at least a portion of the ADS inlet flow 65. In this application, the air supply sub-system 50 is assumed to provide a pressure sufficient and greater than that of the enclosure 44 for the fresh air flow to proceed directly without further compression through the cooling and water removal circuit. The air supply sub-system outlet flow 53 (fresh air stream) can pass through and can be cooled by the PHX 51 and the AHX 71 to provide the AHX outlet flow 73. The AHX outlet flow 73 may constitute at least a portion of the ADS inlet flow 65. This embodiment may therefore adsorb water from both fresh and recirculated air. The optional recuperator heat exchanger (recuperator 74) may be in thermal contact with the colder recirculation air (enclosure outlet flow 75) to improve condensation. As depicted, the air cycle machine may incorporate the fan 57 as a third wheel, which may provide a cost and weight reduction compared to a separate electric fan. It is one intent of this invention to teach that the incorporation of the fan 57 into the air cycle machine may be equally applicable to most other embodiments shown as claims for aircraft ECS applications.

Another embodiment of the present invention, as depicted in FIG. 14, may also use the recirculated air (enclosure outlet flow 75) as the sole desorbing stream (DES inlet flow 60). The system 40 may include a recirculation compressor 83 as the driving element for the enclosure outlet recirculation flow 75. The recirculation compressor 83 may be operationally in contact with the enclosure outlet flow 75. The recirculation compressor 83 may be motorized and may be positioned between and in flow communication with the DES 45 and the enclosure 44. The enclosure outlet flow 75a may be a compressed air flow that may be directed towards the DES 45, so at least a portion of the enclosure outlet flow 75 may comprise the DES inlet flow 60. The compressed enclosure outlet flow 60 may remain at low pressure relative to the compressed fresh air (compressor outlet flow 59). Alternatively, compressed enclosure outlet flow 60 may be controlled to the same pressure at the face of the desorbing element DES 45 as that exiting the adsorbing element (adsorbent outlet stream 65). The compressed enclosure outlet flow 60 may pass through the DES 45, the condenser 48 and the water extractor 49 and then may be expanded and cooled in a turbine 85 and directed back to the enclosure 44 (providing a supply of cooled recirculated air 84 to the enclosure 44). The air supply sub-system outlet flow 53 (fresh air) may be passed through the PHX 51, the air conditioning compressor 52, the recuperator 74 (optional), the AHX 71 and the ADS 42 before being expanded by the turbine 43. The turbine outlet flow 68 may be directed to the enclosure 44 to provide fresh air to the enclosure 44. This embodiment may present a benefit to the desorption cycle and may lead to smaller adsorb/desorb components. This system is capable of delivering fresh air only to one cabin zone (such as the flight deck) to meet some customer requirements, and may operate at relatively low input pressure. For applications that include a rotating adsorbent wheel, the compressor 83 may be controlled so that pressure differential across the face seals of the wheel is minimized so as to reduce or eliminate leakage. Turbine 85 may be integrated as part of the air cycle machine with compressor 43 and turbine 52, or preferably with the motorized recirculation compressor 83.

Another embodiment of the present invention, as depicted in FIG. 15, illustrates a system 40 wherein the DES outlet flow 46, in this case originating from a portion of the dried compressor flow (ADS outlet flow 66), may be discarded along with the water vapor it contains. Another portion of the ADS outlet flow 66 may be directed to a high pressure water separation sub-system 85. This embodiment, and its variants, may have the potential for very dry output, but at the expense of input power, as a portion of the pressurized fluid (ADS outlet flow 66) may not be recovered. It may be most suitable as a desiccant process.

Other embodiments of the present invention, as depicted in FIGS. 16a-c, illustrate a system 40 wherein the ADS 41 can facilitate the collection of water from both the fresh (air supply sub-system outlet flow 53) and the recirculated streams (enclosure outlet flow 75). In these embodiments, the enclosure flow compressor 81 may be included. The enclosure flow compressor 81 may enable the pressure of the DES inlet flow 60 to be matched to the pressure of the ADS outlet flow 66, which in turn may reduce or eliminate seal leakage of the adsorbent sub-system 41. The recuperator 74 may be included to further reduce the temperature of the COND outlet flow 62, which may improve water condensing (allowing more water to be removed by the water extractor 49). The fan 57 may be separate from or, as depicted, integral to the air cycle machine. In these embodiments, recirculated enclosure air collects water adsorbed from the fresh air stream, and moisture from both fresh and recirculated streams are desorbed and removed in the water extractor. The resulting moist, compressed recirculated air may be then expanded in turbine 43 jointly with fresh air 82, or in a separate turbine 83, and delivered to the enclosure. Turbine 83 may be part of the combined air cycle machine including compressors 52, 81 and turbine 43, or integrated with compressor 81 in a second motorized air cycle machine (not shown).

The embodiments described above represent examples of the system 40, from which can be derived additional variants. Most embodiments depicted show a set of motorized “cabin air” compressors (air supply sub-system 50) as the source of compressed air for the ECS proper. As indicated above, the cabin air compressors represent only one of the possible types of air supply sub-systems 50. Other useful air supply sub-systems 50 can include an engine bleed system, an APU bleed, or any other source of compressed air.

Also, some schematics depict a two-wheel (compressor and turbine) air cycle machine and a separate motor-driven ground fan 57. It should be understood that, although
the cabin air compressors and separate ground fan may represent a desirable configuration for a bleedless “More Electric Airplane” architecture, the present invention may include other types of air cycle machines, such as 3-wheel (fan, compressor, and turbine). Embodiments of the present invention can include air cycle machines having a compressor (e.g. air conditioning compressor 52), a turbine 43, and a separate motorized fan 57 to draw outside cooling air. Embodiments of the present invention can include air cycle machines having a compressor, a turbine 43, and an electric motor 78. Embodiments of the present invention can include air cycle machines having a fresh air compressor (e.g. air conditioning compressor 52), an enclosure recirculated air compressor (e.g. additional compressor wheel 82) and a turbine 43. Embodiments of the present invention can include air cycle machines having a fresh air compressor, an enclosure recirculated air compressor, a turbine 43 and an electric motor 78. Embodiments of the present invention can include air cycle machines having a fresh air compressor, and two turbines 43. Embodiments of the present invention can include air cycle machines having a fresh air compressor, an electric motor 78 and two turbines 43. As used herein, air cycle machines may include, but are not limited to, the air cycle machine configurations described above.

The embodiments described above may be directed towards an ECS with an air cycle configuration. In alternate embodiments (not shown), the ECS may have a vapor cycle configuration. For ECS having a vapor cycle configuration, the system 40 may include an evaporator heat exchanger (not shown) in lieu of the turbine 43 for cooling the dried flow. For some embodiments, the evaporator heat exchanger may receive the ADS outlet flow 66 and provide the enclosure inlet flow 87 so that the dried air (e.g. the ADS outlet flow 66) may be cooled by the refrigerant loop of the vapor cycle pack. ECS configurations that may be useful with some embodiments of the present invention may include the air cycle pack configurations described in U.S. Pat. No. 5,887,445 and the vapor cycle pack configurations described in U.S. Pat. No. 6,629,428, both of which are incorporated herein by reference. The present invention may be useful with any ECS configuration.

The configuration of the ECS, particularly the air cycle machine (ACM) and various heat exchangers may be modified within the spirit of this invention as long as the adsorbent medium may be used to affect water concentration for the purpose of subsequent liquid water removal. In particular, a 2-wheel “bootstrap” air cycle machine, a 3-wheel, a 4-wheel or several machines using any appropriate number of compressors and turbines, with or without an electric motor may be used. Embodiments of the system 40 may include the air supply sub-system 50 that provides a cooled compressed outside air flow to the adsorbent sub-system 41.

Similarly, the concepts of the present invention may be equally valid if a single rotating wheel provides the adsorbing and desorbing functions or if separate adsorbing and desorbing components are used, along with appropriate switchover valves to affect the alternating adsorbing and desorbing functions of these components. Further, embodiments of the present invention may include additional cooling and/or heating stages inserted before and/or after the adsorbent component ADS 42 and the desorbent component DES 45 to optimize the thermodynamic process.

Moreover, embodiments of the present invention may not be limited to the use of adsorbent sub-systems 41 in a temperature swing mode, as described above. Embodiments of the present invention may use pressure swing, where a lowering of pressure may cause the adsorbed water vapor to be desorbed. Some embodiments of the present invention may use combinations of temperature and pressure swing.

Further, embodiments of the present invention may incorporate recirculated cabin air (enclosure outlet flow 75, compressed enclosure air flow 82) in the adsorb/desorb cycle in place of or in addition to some of the compressed outside air. This option may be illustrated, in part, in the embodiments depicted in FIGS. 8, 9, and 11-14. In FIG. 8, the enclosure outlet flow 75 may constitute at least a portion of the compressor inlet flow 58. In FIG. 9, the enclosure outlet flow 75 may constitute at least a portion of the ADS inlet flow 65. In FIGS. 11, 12 and 13, the compressed enclosure air flow 82 may constitute at least a portion of the DES inlet flow 60. In FIG. 14, at least a portion of the enclosure outlet flow 75 may constitute at least a portion of the DES inlet flow 60.

Additionally, embodiments of the present invention may include other sources of cooling in lieu of or in addition to the ambient air (cooling air flow 47). In particular, recirculated cabin air (enclosure outlet flow 75) may be used to advantage to cool and condense the concentrated moisture. Cabin air may be maintained colder than ambient air in most ECS hot day design conditions from sea level to approximately 12,000 feet where the challenge to remove the highest quantity of moisture also occurs. This option may be illustrated, in part, in FIGS. 6, 11-13 and 16. In FIGS. 6, 11-13 and 16, the enclosure outlet flow 75 may be in thermal contact with the water extractor inlet flow 63 via the recuperator 74. In FIG. 14, the enclosure outlet flow 75 may be in thermal contact with the compressor outlet flow 59 via the recuperator 74 both for increasing the temperature of the desorbing flow and to lower that of the adsorbing flow.

A method 100 of removing a supply of water from an air stream is depicted in FIG. 17. The method 100 may comprise a step 110 of providing a compressed air stream; a step 120 of increasing the moisture content of the compressed air stream such that a super-humidified air stream is provided; a step 130 of cooling the super-humidified air stream such that a moisture saturated air stream having a supply of condensed water is provided; and a step 140 of extracting the supply of condensed water from the moisture saturated air stream such that the supply of water and a saturated flow are provided. The method 100 further may include a step 150 of drying the saturated flow such that a dried air flow is provided. The method 100 further may include a step 160 of cooling the dried air flow.

The step 110 of providing a compressed air stream can comprise in general passing a supply of fresh outside air through an air supply sub-system, followed by sub steps of cooling and compression. Also, the step 110 can comprise a supply of recirculated enclosure air itself subjected to heat transfer and compression separately or together with the fresh air. More specifically, in one embodiment, the step 110 of providing a compressed air stream can comprise passing a supply of air through an air supply sub-system 50. In a second embodiment, the step 110 of providing a compressed air stream can comprise passing a supply of air through an air supply sub-system 50 and a primary heat exchanger PHX 51. In a third embodiment, the step 110 of providing a compressed air stream can comprise passing a supply of air through an air supply sub-system 50, a primary heat exchanger PHX 51 and an air supply sub-system flow compressor 52 such that a compressor outlet flow 59 is produced.
(see FIGS. 2a, 4-6, 9 and 10). Figures listed in this text are intended as illustrative examples only of the principle of the invention without limiting its application to these examples only. In a fourth embodiment, the step 110 of providing a compressed air stream can comprise passing the enclosure outlet flow 75 through a recuperator 74 and a compressor 81 such that a compressed enclosure air flow 82 is produced (see FIGS. 11, 12, 13 and 16). In a fifth alternate embodiment, the step 110 of providing a compressed air stream can comprise using a recirculation compressor 83 to provide a first portion of the enclosure outlet flow 75a (see FIG. 14). In a sixth alternate embodiment, the step 110 of providing a compressed air stream can comprise passing a mixture of an air supply sub-system outlet flow 53 and an enclosure outlet flow 75 through an air supply sub-system flow compressor 52 such that a compressor outlet flow 59 is produced (see FIG. 8).

[0082] The step 120 of increasing the moisture content of the compressed air stream such that a super-humidified air stream is provided can comprise passing the compressed air stream through the desorbing element 45 of an adsorbent sub-system 41 such that the super-humidified air stream (DES outlet flow 46) is provided. During the step 120, the compressed air stream may cause water vapor to be released from the desorbing element (DES 45) and by doing so may provide the super-humidified air stream (DES outlet flow 46). The step 120 may comprise passing the compressed air stream through a DES 45 wherein the DES 45 includes an adsorbent material having a supply of previously adsorbed water vapor.

[0083] The step 130 of cooling the super-humidified air stream such that a moisture saturated air flow having a supply of condensed water is provided can comprise positionizing the super-humidified air stream in thermal contact with a cooling air flow 47. The step 130 of cooling the super-humidified air stream such that a moisture saturated air flow having a supply of condensed water is provided can comprise passing the super-humidified air stream through a cooler (e.g. SHX 48) (see FIGS. 2a, 4, 5, 7-10 and 14). Alternatively, the step 130 of cooling the super-humidified air stream such that a moisture saturated air flow having a supply of condensed water is provided can comprise passing the super-humidified air stream through a cooler (e.g. SHX 48) and through a second cooler (e.g. recuperator 74) (see FIGS. 6, 11-13, and 16).

[0084] The step 140 of extracting the supply of condensed water from the moisture saturated air flow such that the supply of water and a saturated flow are provided can comprise passing the moisture saturated air flow through a water extractor 49 such that a saturated flow (e.g. water extractor outlet flow 64) is provided and liquid water is removed from that stream.

[0085] The step 150 of drying the saturated flow such that a dried air flow is provided can comprise passing the saturated flow through an adsorbent element 42 such that the dried air flow (e.g. ADS outlet flow 66) is produced.

[0086] The step 160 of cooling the dried air flow can comprise expanding the dried air flow with a turbine 43 to provide a cooled dried flow (e.g. turbine outlet flow 68). Alternatively, the step 160 can comprise any other means of cooling, such as passing the dried air flow through a cooler heat exchanger where it is cooled by heat transfer with another colder fluid. For example, the step 160 of cooling the dried air flow can comprise passing the dried air flow through an evaporator heat exchanger of a vapor cycle system wherein the dried air flow is in thermal contact with a cooling fluid (e.g. a refrigerant) of the evaporator heat exchanger.

EXAMPLE 1

[0087] For an aircraft ECS with ambient inlet moisture of 133 g/lb and a 103°F ambient temperature, an adsorbent sub-system 41 comprising an adsorbent wheel can deliver a water content of 213 g/lb to a high pressure water extractor (high pressure water separation sub-system 85), 80 g/lb above that of a traditional state-of-the-art system. At a temperature of 119°F achieved by cooling the moist stream in air heat exchange with ambient air and at a pressure of 62.8 psia, the extractor can extract 91 g/lb of the entrained condenser water.

The adsorbent wheel captures 80 g/lb out of the remaining water vapor, leaving 41 g/lb, an acceptable supply level, to the turbine 43 and the enclosure 44. The turbine 43 at 60.8 psia and 193.5°F from the adsorbent wheel delivers 24.3°F DB/9.1°F DAR at 41 g/lb, representing a cooling capacity of 44.5 kW to a 75°F enclosure based on DAR temperature and a system air flow of 100 lb/min. The air supply system (air supply sub-system 50) for that condition has to supply 32.3 psia to the system 40, representing an overall input power of 190 kW. For the same cooling capacity, the best state-of-the-art condensing cycle system would require operating at 70.7 psia cycle pressure and 88°F at the water extractor, requiring an input pressure of 37.5 psia from the air supply system. That represents an overall system input power requirement of 226 kW.

[0088] As can be appreciated by those skilled in the art, embodiments of the present invention provide improved ECS with adsorption based water removal. Embodiments of the present invention can achieve sufficient water condensation at much higher temperatures than the prior art systems, to the point where ambient air can be used as an effective cooling sink. Embodiments of the present invention can move the condensing task from the turbine to the ram air heat exchanger. Embodiments of the present invention can therefore transfer the heat of condensation to the ambient cooling air without affecting the cooling capacity of the system. Embodiments of the present invention may demand less power than existing air cycle solutions, resulting in lower fuel consumption and smaller APU or ECS components. Embodiments of the present invention may be of relatively lower cost than prior art systems because the prior art condenser and reheater heat exchangers can be replaced by a lower cost adsorbent wheel.

[0089] It should be understood, of course, that the foregoing relates to exemplary embodiments of the invention and that modifications may be made without departing from the spirit and scope of the invention as set forth in the following claims.

We claim:
1. A system comprising:
a compressor; and
an adsorbent sub-system having a desorbing portion and an adsorbing portion, said desorbing portion in flow communication with said compressor.
2. The system of claim 1, wherein said compressor provides a compressor outlet flow, said compressor outlet flow comprises a desorbing portion inlet flow.
3. The system of claim 1, further comprising a turbine operationally connected to said compressor, and wherein said
adsorbing portion provides an adsorbing portion outlet flow, said adsorbing portion outlet flow comprises a turbine inlet flow.

4. The system of claim 1, further comprising an air supply sub-system in flow communication with said compressor, said air supply sub-system receiving a supply of outside air; said compressor positioned between and in flow communication with said air supply sub-system and said desorbing portion.

5. The system of claim 1, further comprising:
an air supply sub-system in flow communication with said compressor, said air supply sub-system receiving a supply of outside air and providing an air supply sub-system outlet flow; and
an enclosure in flow communication with said compressor, said enclosure providing an enclosure outlet flow, said compressor receiving said air supply sub-system outlet flow and said enclosure outlet flow, said compressor providing a compressor outlet flow, said compressor outlet flow comprising a desorbing portion inlet flow.

6. The system of claim 1, further comprising:
an air supply sub-system in flow communication with said compressor, said air supply sub-system receiving a supply of outside air and providing an air supply sub-system outlet flow; and
a primary heat exchanger positioned between and in flow communication with said air supply sub-system and said compressor, said primary heat exchanger receiving said air supply sub-system outlet flow and providing a primary heat exchanger outlet flow, said compressor receiving said primary heat exchanger outlet flow and providing a compressor outlet flow, said compressor outlet flow comprising a desorbing portion inlet flow.

7. The system of claim 1, further comprising:
an air supply sub-system in flow communication with said compressor,
an enclosure in flow communication with said adsorbing portion, said enclosure providing an enclosure outlet flow; and
an additional compressor wheel positioned between and in flow communication with said adsorbing portion and said enclosure, said additional compressor wheel receiving said enclosure outlet flow and providing a compressed enclosure air flow, said compressed enclosure air flow comprising an adsorbing portion inlet flow.

8. The system of claim 1, further comprising:
a secondary heat exchanger in flow communication with said desorbing portion, said secondary heat exchanger providing a secondary heat exchanger outlet flow; and
a water cooler positioned between and in flow communication with said secondary heat exchanger and said desorbing portion, said water cooler receiving said secondary heat exchanger outlet flow and providing a water cooler outlet flow, said water cooler outlet flow comprising an adsorbing portion inlet flow.

9. The system of claim 1, further comprising:
a turbine operationally connected to said compressor; and
an enclosure in flow communication with said turbine, said enclosure comprising an aircraft cabin.

10. A system comprising:
an air supply sub-system;
an air cycle machine having a compressor and a turbine, said compressor in flow communication with said air supply sub-system;
an adsorbent sub-system having a desorbing portion and an absorbing portion, said adsorbing portion in flow communication with said turbine;
a secondary heat exchanger in flow communication with said desorbing portion; and
a water extractor in flow communication with said secondary heat exchanger.

11. The system of claim 10, further comprising:
an enclosure in flow communication with said desorbing portion, said enclosure providing an enclosure outlet flow; and
a motorized recirculation compressor positioned between and in flow communication with said desorbing portion and said enclosure such that at least a portion of said enclosure outlet flow comprises a desorbing portion inlet flow.

12. The system of claim 10, wherein said compressor provides a compressor outlet flow, said compressor outlet flow comprises a desorbing portion inlet flow.

13. The system of claim 10, further comprising an additional heat exchanger positioned between and in flow communication with said compressor and said adsorbing portion, said additional heat exchanger providing an additional heat exchanger outlet flow; and wherein said compressor provides a first portion of compressor outlet flow and a second portion of compressor outlet flow, said first portion of compressor outlet flow comprising a desorbing portion inlet flow, said second portion of compressor outlet flow comprising an additional heat exchanger inlet flow, at least a portion of said additional heat exchanger outlet flow directed towards said adsorbing portion.

14. The system of claim 13, wherein another portion of said additional heat exchanger outlet flow is directed towards said turbine.

15. A system comprising:
an air supply sub-system;
an air cycle machine having a compressor and a turbine, said compressor in flow communication with said air supply sub-system;
an adsorbent sub-system having a desorbing portion and an absorbing portion, said adsorbing portion in flow communication with said turbine;
a primary heat exchanger positioned between and in flow communication with said air supply sub-system and said desorbing portion, wherein said primary heat exchanger provides a desorbing portion inlet flow and said desorbing portion provides a compressor inlet flow;
a secondary heat exchanger in flow communication with said compressor; and
a water extractor in flow communication with said secondary heat exchanger and said desorbing section.

16. The system of claim 10, further comprising a primary heat exchanger positioned between and in flow communication with said air supply sub-system and said compressor; wherein said primary heat exchanger provides a compressor inlet flow and said compressor provides a desorbing portion inlet flow.

17. The system of claim 10, further comprising:
an enclosure in flow communication with said desorbing portion, said enclosure providing an enclosure outlet flow;
an additional compressor wheel positioned between and in flow communication with said enclosure and said desorbing portion; and
a recuperator positioned between and in flow communication with said enclosure and said additional compressor wheel, said secondary heat exchanger providing a secondary heat exchanger outlet flow, said recuperator in thermal contact with said secondary heat exchanger outlet flow.

18. The system of claim 10, further comprising:
an enclosure in flow communication with said desorbing portion, said enclosure providing an enclosure outlet flow;
a second compressor operationally in contact with said enclosure outlet flow;
a recuperator heat exchanger in flow communication with said compressor and with said second compressor outlet flow; said recuperator in flow communication with said desorbing portion;
an additional heat exchanger positioned between and in flow communication with said recuperator and said adsorbing portion; and
a second turbine in flow communication between said water extractor and said enclosure.

19. The system of claim 10, further comprising:
an enclosure in flow communication with said desorbing portion, said enclosure providing an enclosure outlet flow;
an additional heat exchanger positioned between and in flow communication with said desorbing section and said water separator;
a second compressor in flow communication with said desorbing portion;
a recuperator heat exchanger in flow communication with said enclosure and in with said second compressor inlet flow, said recuperator in flow communication with said second heat exchanger and said water separator; and
a second turbine in flow communication between said water extractor and said enclosure.

20. The system of claim 10, wherein said adsorbent sub-system comprises at least one adsorbent wheel.

21. A method of removing a supply of water from an air stream comprising the steps of:
providing a compressed air stream;
increasing the moisture content of said compressed air stream such that a super-humidified air stream is provided;
positioning said super-humidified air stream in thermal contact with a cooling air flow such that a moisture saturated air flow having a supply of condensed water is provided; and
extracting said supply of condensed water from said moisture saturated air flow such that said supply of water and a saturated flow are provided.

22. The method of claim 21, further comprising a step of passing said saturated flow through an adsorbing portion of an adsorbent sub-system such that a dried flow is provided.

23. The method of claim 21, further comprising the steps of:
passing said moist flow through an adsorbing portion of an adsorbent sub-system such that a dried flow is provided; and
expanding said dried flow with a turbine.

24. The method of claim 21, further comprising the steps of:
passing said moist flow through an adsorbing portion of an adsorbent sub-system such that a dried flow is provided; and
cooling said dried flow by heat exchange with a cooling fluid.

25. The method of claim 21, wherein said step of increasing the moisture content of said compressed air stream such that a super-humidified air stream is provided comprises passing said compressed air stream through a desorbing portion of an adsorbent sub-system.

26. The method of claim 21, wherein said step of increasing the moisture content of said compressed air stream such that a super-humidified air stream is provided comprises passing said compressed air stream through a desorbing portion of an adsorbent sub-system wherein said desorbing portion includes an adsorbent material having a supply of adsorbed water vapor.

27. The method of claim 21, wherein said step of increasing the moisture content of the compressed air stream comprises passing the compressed air stream through an adsorbent sub-system, said adsorbent sub-system including at least one adsorbing portion, at least one desorbing portion and at least one switchover valve.

28. The method of claim 21, wherein said step of increasing the moisture content of the compressed air stream comprises passing the compressed air stream through at least one adsorbent wheel comprising adsorbing and desorbing sections and capable of rotation so the adsorbing and desorbing sections can be alternatively exchanged and regenerated.

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