widespread acceptance as an alternative to mechanical cooling, especially in light commercial and residential applications.

[0007] There remains a need for alternative cooling technologies for comfort conditioning applications, which can largely replace mechanical cooling. The growing awareness of environmental impacts, electricity consumption and increasing regulatory pressure on refrigerants are pressing challenges for current HVAC cooling equipment. There is a need for a commercially viable design which meets requirements for capital and installation costs, operating costs, performance, reliability, size/weight restrictions, etc., while avoiding the creation of any new resource utilization problems, such as excessive water or gas consumption. The design should have good cooling performance and compactness, make use of low cost materials, and avoid the use of any environmentally harmful or toxic substances. From a thermodynamic perspective, the system should operate near atmospheric pressures with low grade heat input, employ moderate temperature changes and exchange fluxes to minimize irreversibility in the system and improve second law efficiency. Comfort conditioning may only require low grade cooling, and an exergy analysis shows how wasteful it is to use precious high grade energy sources such as electricity to drive cooling equipment.

SUMMARY

[0007a] An aspect of the present disclosure provides a system for conditioning air for an enclosed space, the system comprising:

a process plenum having a plenum inlet and outlet, the process plenum configured to direct air in an air flow path from the plenum inlet to the plenum outlet, air received at the plenum inlet being hot process air and air exiting the plenum outlet being conditioned supply air for the enclosed space;

a liquid-to-air membrane energy exchanger (LAMEE) arranged inside the process plenum, the LAMEE comprising a desiccant flow path separated from the air flow path by a membrane, the LAMEE configured to circulate a desiccant through the desiccant flow path and remove water from the air in the air flow path, a moisture content of the air at a LAMEE outlet being lower than a moisture content of the air at a LAMEE inlet; and

a direct evaporative cooler (DEC) arranged inside the process plenum downstream of the LAMEE, the DEC configured to operate adiabatically and evaporatively cool the air, a temperature of the air at a DEC outlet being lower than a temperature of the air at a DEC inlet.

[0007b] Another aspect of the present disclosure provides a system for conditioning air for an enclosed space, the system comprising:

a process plenum configured to direct air from a process inlet to a process outlet, the process inlet receiving air at a first temperature and the process outlet supplying air to the space at a second temperature that is lower than the first temperature;

a first liquid-to-air membrane energy exchanger (LAMEE1) arranged inside the process plenum, the LAMEE1 configured to use a liquid desiccant flowing through the LAMEE1 to reduce the humidity of the air, a first concentration of water in the liquid desiccant at a fluid inlet of the LAMEE1 being lower than a second concentration of water in the liquid desiccant at a fluid outlet of the LAMEE1; and

a second LAMEE (LAMEE2) arranged inside the process plenum downstream of the LAMEE1, the LAMEE2 configured to operate adiabatically and use water flowing there through to evaporatively cool the air, a temperature of the air at an air outlet of the LAMEE2 being lower than a temperature of the air at an air inlet of the LAMEE2.

[0007c] Another aspect of the present disclosure provides a method of conditioning air for an enclosed space, the method comprising:

directing air through a process plenum having a plenum inlet and outlet, the air entering the plenum inlet at a first temperature;

directing the air through a liquid-to-air energy exchanger (LAMEE) arranged inside the plenum, a first moisture content of the air being higher at a LAMEE inlet compared to a second moisture content of the air at a LAMEE outlet;

directing a desiccant through the LAMEE, the desiccant and air separated by a membrane of the LAMEE, the LAMEE configured to remove water from the air using the desiccant, a first concentration of water in the desiccant being lower at a LAMEE inlet compared to a second concentration of water in the desiccant at a LAMEE outlet, the desiccant at the LAMEE outlet being a dilute desiccant;

directing the air through a direct evaporative cooler (DEC) arranged inside the process plenum downstream of the LAMEE, the DEC operating adiabatically to cool the air; and

delivering the air to the enclosed space, the air exiting the plenum outlet at a second temperature lower than the first temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components, sub-components of a larger logical or

CLAIMS

What is claimed is:

1. A system for conditioning air for an enclosed space, the system comprising:

a process plenum having a plenum inlet and outlet, the process plenum configured to direct air in an air flow path from the plenum inlet to the plenum outlet, air received at the plenum inlet being hot process air and air exiting the plenum outlet being conditioned supply air for the enclosed space;

a liquid-to-air membrane energy exchanger (LAMEE) arranged inside the process plenum, the LAMEE comprising a desiccant flow path separated from the air flow path by a membrane, the LAMEE configured to circulate a desiccant through the desiccant flow path and remove water from the air in the air flow path, a moisture content of the air at a LAMEE outlet being lower than a moisture content of the air at a LAMEE inlet; and

a direct evaporative cooler (DEC) arranged inside the process plenum downstream of the LAMEE, the DEC configured to operate adiabatically and evaporatively cool the air, a temperature of the air at a DEC outlet being lower than a temperature of the air at a DEC inlet.

2. The system of claim 1 wherein the LAMEE is a first liquid-to-air membrane energy exchanger (LAMEE1) and the DEC is a second liquid-to-air membrane energy exchanger (LAMEE2).

3. The system of claim 2 wherein water removed from the air by the desiccant in the LAMEE1 is transported to the LAMEE2 and used to supply at least a portion of the make up water required for operation of the LAMEE2.

4. The system of claim 1 wherein the DEC is a direct-contact DEC.

5. The system of claim 4 wherein the direct-contact DEC includes at least one of wetted-media and a spray atomizer.

6. The system of claim 1 further comprising a heat exchanger configured to cool the desiccant prior to recirculating the desiccant through the desiccant flow path of the LAMEE.

7. The system of claim 6 wherein the heat exchanger is external to the process plenum.

8. The system of claim 6 wherein the heat exchanger is a polymer fluid cooler.

9. The system of claim 6 wherein the heat exchanger is a liquid to air heat exchanger (LAHX) that uses outdoor air to cool the desiccant.

10. The system of claim 6 wherein the heat exchanger is a liquid to liquid heat exchanger (LLHX).

11. The system of claim 1 further comprising:

a regeneration system configured to increase a concentration of at least a portion of the desiccant exiting the LAMEE.

12. The system of claim 11 wherein the regeneration system comprises a regeneration unit in fluid connection with the LAMEE, wherein the regeneration unit is configured to receive a desiccant stream and separate water from the desiccant, and wherein a first output stream of the regeneration unit is concentrated desiccant and a second output stream of the regeneration unit is distilled water.

13. The system of claim 12 wherein the second output stream is used as make up water for operation of the DEC.

14. The system of claim 12 wherein the first output stream is transported to a desiccant tank configured to receive the first output stream and the desiccant exiting the LAMEE.

15. The system of claim 14 wherein a desiccant output stream exiting the desiccant tank is transported to at least one of the regeneration unit and a heat exchanger configured to reduce a temperature of the desiccant before the desiccant circulates through the LAMEE.

16. The system of claim 15 further comprising a modulating valve configured to control a distribution of desiccant from the desiccant tank to the heat exchanger and the regeneration unit.

17. The system of claim 1 wherein the LAMEE is configured such that the desiccant circulating through the desiccant flow path removes heat from the air to reduce a temperature of the air.

18. The system of claim 1 wherein the process plenum is configured to receive hot process air from an enclosed space and condition the process air such that reduced-temperature air can be returned to the enclosed space.

19. The system of claim 1 wherein the process plenum is configured to receive outdoor air and condition the outdoor air such that reduced-temperature air can be delivered to the enclosed space.

20. The system of claim 1 wherein the process plenum is configured to receive outdoor air that mixes with process air in the air flow path, and wherein the process air is from the enclosed space.

21. The system of claim 1 further comprising a pre-cooler arranged between the LAMEE and the DEC and configured to reduce a temperature of the air passing through the pre-cooler.

22. The system of claim 1 wherein the system operates at or near atmospheric pressure.

23. A system for conditioning air for an enclosed space, the system comprising:

a process plenum configured to direct air from a process inlet to a process outlet, the process inlet receiving air at a first temperature and the process outlet supplying air to the space at a second temperature that is lower than the first temperature;

a first liquid-to-air membrane energy exchanger (LAMEE1) arranged inside the process plenum, the LAMEE1 configured to use a liquid desiccant flowing through the LAMEE1 to reduce the humidity of the air, a first concentration of water in the liquid desiccant at a fluid inlet of the LAMEE1 being lower than a second concentration of water in the liquid desiccant at a fluid outlet of the LAMEE1; and

a second LAMEE (LAMEE2) arranged inside the process plenum downstream of the LAMEE1, the LAMEE2 configured to operate adiabatically and use water flowing there through to evaporatively cool the air, a temperature of the air at an air outlet of the LAMEE2 being lower than a temperature of the air at an air inlet of the LAMEE2.

24. The system of claim 23 wherein at least a portion of the water flowing through the LAMEE2 is water removed from the air by the liquid desiccant in the LAMEE1.

25. The system of claim 24 wherein a quantity of the water removed from the air by the liquid desiccant in the LAMEE1 is sufficient as the make-up water for operation of the LAMEE2.

26. The system of claim 23 wherein the LAMEE1 is configured to use the liquid desiccant flowing through the LAMEE1 to remove heat from the air, a temperature of the desiccant at a desiccant outlet of the LAMEE1 being higher than a temperature of the desiccant at a desiccant inlet of the LAMEE1.

27. The system of claim 23 further comprising a regenerator system in fluid connection with a desiccant flow path through the LAMEE1, the regenerator system configured to increase a concentration of the liquid desiccant at the fluid inlet of the LAMEE1 relative to the fluid outlet of the LAMEE1.

28. The system of claim 27 wherein the regenerator system comprises:

a regeneration unit configured to receive a desiccant stream at an inlet of the regeneration unit and separate the desiccant and water in the desiccant stream, wherein a first outlet of the regeneration unit includes a concentrated desiccant stream and a second outlet of the regeneration unit includes a distilled water stream.

29. The system of claim 28 wherein the distilled water stream is in fluid connection with the LAMEE2.

30. The system of claim 28 wherein the concentrated desiccant stream is transported to a desiccant storage tank configured to receive the desiccant exiting the LAMEE1, and the concentrated desiccant stream mixes with the desiccant exiting the LAMEE1.

31. The system of claim 30 wherein a desiccant output stream exiting the desiccant storage tank is delivered to at least one of the LAMEE1 and the regeneration unit.

32. The system of claim 31 wherein a modulating valve in the desiccant stream controls a distribution of the desiccant in the desiccant output stream to the LAMEE1 and to the regeneration unit.

33. The system of claim 23 further comprising:

a make-up air unit configured to provide replenishment air to the enclosed space.

34. The system of claim 23 further comprising a liquid-to-air heat exchanger LAHX arranged between the LAMEE1 and the LAMEE2, the LAHX configured to reduce a temperature of the air flowing there through.

35. The system of claim 34 wherein a first portion of the air exiting the LAHX is configured to flow through the LAMEE2 and a second portion of the air exiting the LAHX is configured to flow through a third liquid-to-air membrane energy exchanger (LAMEE3) arranged inside an exhaust plenum in fluid connection with the process plenum.

36. The system of claim 35 wherein a volume of air in the second portion is less than a volume of air in the first portion.

37. The system of claim 35 wherein a cooling liquid circulating through the LAHX is in fluid connection with the LAMEE3, wherein the cooling liquid exits the LAHX and passes through the LAMEE3, and wherein the air from the exhaust plenum cools the cooling liquid in the LAMEE3 prior to recirculating the cooling liquid through the LAHX.

38. The system of claim 23 wherein the process plenum receives outdoor air at the process inlet, and the outdoor air mixes with process air from the enclosed space prior to passing through the LAMEE1.

39. The system of claim 23 further comprising:

a heat exchanger configured to cool the liquid desiccant prior to flowing the liquid desiccant through the LAMEE1, wherein the heat exchanger is a liquid-to-air heat exchanger or a liquid-to-liquid heat exchanger.

40. The system of claim 39 wherein the heat exchanger is located external to the process plenum.

41. A method of conditioning air for an enclosed space, the method comprising:

directing air through a process plenum having a plenum inlet and outlet, the air entering the plenum inlet at a first temperature;

directing the air through a liquid-to-air energy exchanger (LAMEE) arranged inside the plenum, a first moisture content of the air being higher at a LAMEE inlet compared to a second moisture content of the air at a LAMEE outlet;

directing a desiccant through the LAMEE, the desiccant and air separated by a membrane of the LAMEE, the LAMEE configured to remove water from the air using the desiccant, a first concentration of water in the desiccant being lower at a LAMEE inlet compared to a second concentration of water in the desiccant at a LAMEE outlet, the desiccant at the LAMEE outlet being a dilute desiccant;

directing the air through a direct evaporative cooler (DEC) arranged inside the process plenum downstream of the LAMEE, the DEC operating adiabatically to cool the air; and

delivering the air to the enclosed space, the air exiting the plenum outlet at a second temperature lower than the first temperature.

42. The method of claim 41 wherein the LAMEE is configured to remove heat from the air using the desiccant as the desiccant and the air are directed through the LAMEE, and wherein a temperature of the desiccant at the LAMEE outlet is higher than a temperature of the desiccant at the LAMEE inlet.

~~43. The method of claim 41 wherein directing the air through a DEC comprises:~~

~~directing the air through an evaporative cooler LAMEE configured to adiabatically cool the air.~~

~~44~~43. The method of claim 41 wherein directing the air through a DEC comprises:

directing the air through a direct-contact DEC configured to cool the air through direct contact of an evaporative fluid with the air.

~~45~~44. The method of claim 41 further comprising:

directing the air through a pre-cooler arranged inside the process plenum downstream of the LAMEE and upstream of the DEC.

~~46~~45. The method of claim ~~45~~44 wherein the pre-cooler is a cooling coil and the method further comprises:

directing a portion of the air exiting the pre-cooler into an exhaust plenum and through a second LAMEE arranged inside the exhaust plenum;

directing water exiting the cooling coil through the second LAMEE, the second LAMEE configured to cool the water using the air, the water at an outlet of the second LAMEE at a reduced temperature relative to the water at an inlet of the second LAMEE; and

recirculating the water to the cooling coil.

~~47~~46. The method of claim 41 further comprising regenerating at least a portion of the desiccant exiting the LAMEE.

~~48~~47. The method of claim 46~~47~~ wherein regenerating at least a portion of the desiccant comprises:

transporting the dilute desiccant exiting the LAMEE to a desiccant storage tank; and

transporting a portion of the desiccant from the desiccant storage tank to a regeneration unit.

~~49~~48. The method of claim ~~48~~47 further comprising:

separating at least a portion of the water from the desiccant by directing the desiccant through the regeneration unit, wherein a first output stream of the regeneration unit is concentrated desiccant and a second output stream of the regeneration unit is distilled water.

~~50~~49. The method of claim ~~49~~48 further comprising:

transporting at least a portion of the distilled water in the second output stream to the DEC to provide at least a portion of make-up water for operation of the DEC.

~~51~~50. The method of claim ~~49~~48 further comprising:

transporting a portion of the distilled water in the second output stream to a fluid circuit that includes a pre-cooler and an exhaust cooler; and

utilizing the distilled water as make-up water in the fluid circuit, wherein the pre-cooler is arranged inside the process plenum downstream of the LAMEE and upstream of the DEC, and the exhaust cooler is an evaporative cooler configured to cool increased-temperature water exiting the pre-cooler.

~~52~~51. The method of claim ~~49~~48 further comprising:

transporting the concentrated desiccant in the first output stream to the desiccant storage tank; and

mixing the concentrated desiccant with the dilute desiccant from the LAMEE , wherein a concentration of the desiccant inside the desiccant storage tank has a desiccant concentration higher than the dilute desiccant and lower than the concentrated desiccant.

~~53~~52. The method of claim ~~48~~47 further comprising:

transporting a portion of the desiccant from the desiccant storage tank to the LAMEE for recirculation of the desiccant through the LAMEE.

~~54~~53. The method of claim 52~~53~~ further comprising:

directing the desiccant through a heat exchanger upstream of the LAMEE to cool the desiccant prior to recirculation of the desiccant through the LAMEE.

~~55~~54. The method of claim 52~~53~~ further comprising:

controlling a volume distribution of desiccant transported from the desiccant storage tank to the LAMEE and to the regeneration unit.

~~56~~55. The method of claim 54~~55~~ wherein controlling the volume distribution of desiccant to the LAMEE and to the regeneration unit comprises using a modulating valve located in a desiccant output stream of the desiccant storage tank.