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(54) HEAT DISSIPATION SYSTEM WITH HYGROSCOPIC WORKING FLUID

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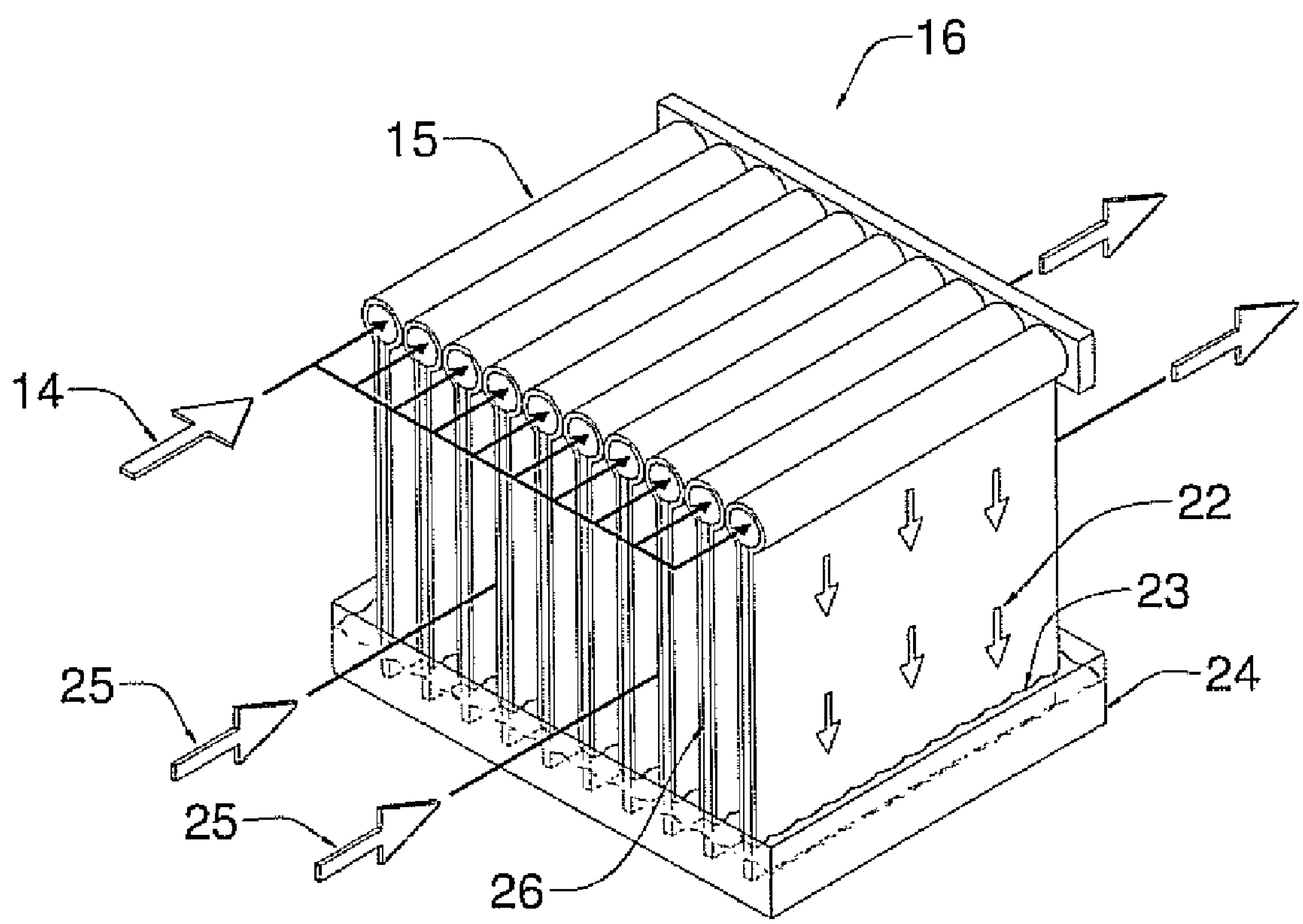
(57) ABSTRACT

A system and method for transferring heat from a process source and dissipating it to the ambient atmosphere. The system uses a low-volatility, hygroscopic working fluid to reject thermal energy directly to ambient air. Direct-contact heat exchange allows for the creation of large interfacial surface areas for effective heat transfer. Heat transfer is further enhanced by water vapor pressure gradients present between the equilibrium moisture content of the working fluid and the ambient air. Cyclic absorption and evaporation of atmospheric moisture dampens variations in cooling capacity because of ambient temperature changes. The low-volatility and hygroscopic nature of the working fluid prevents complete evaporation of the fluid and a net consumption of water.



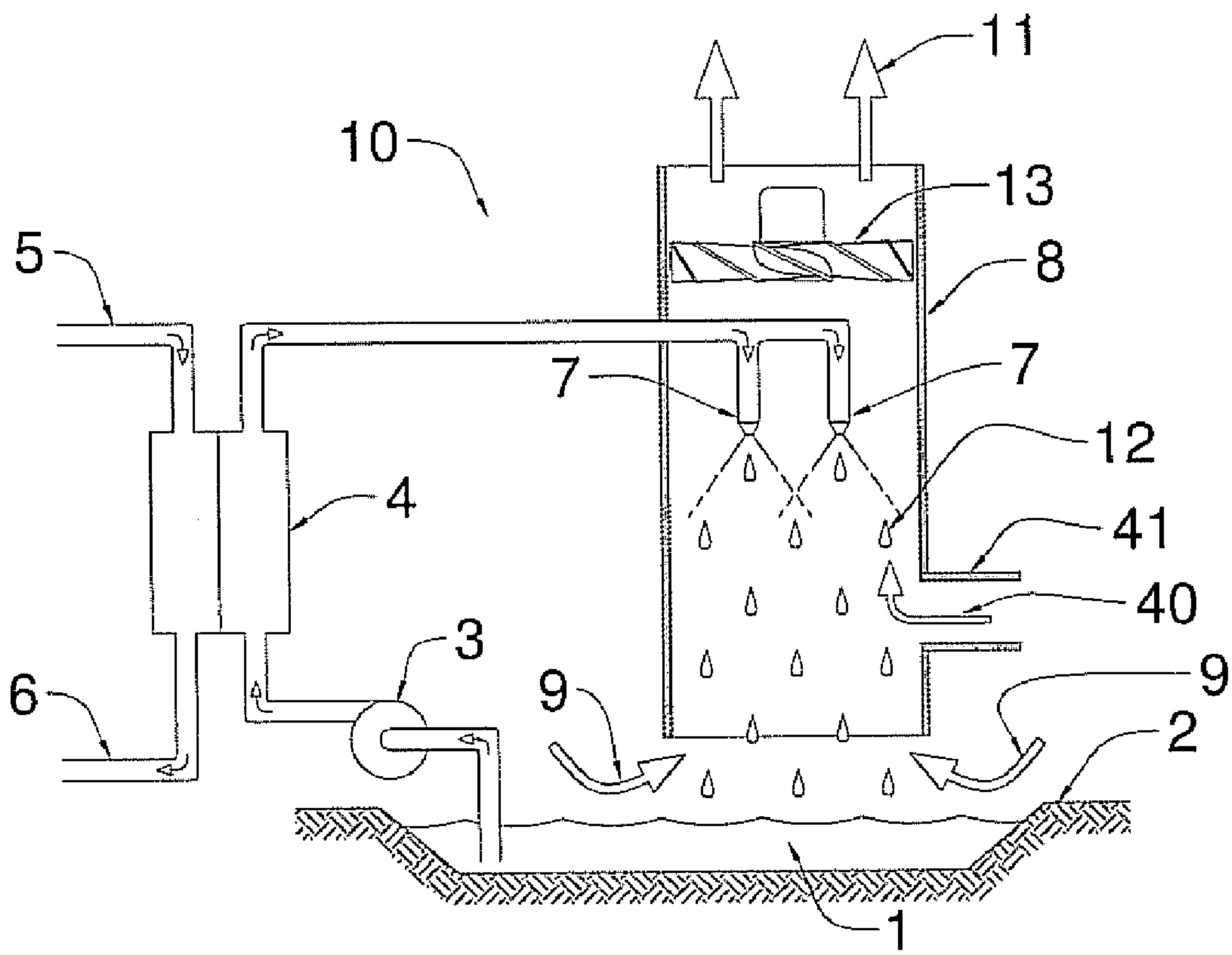
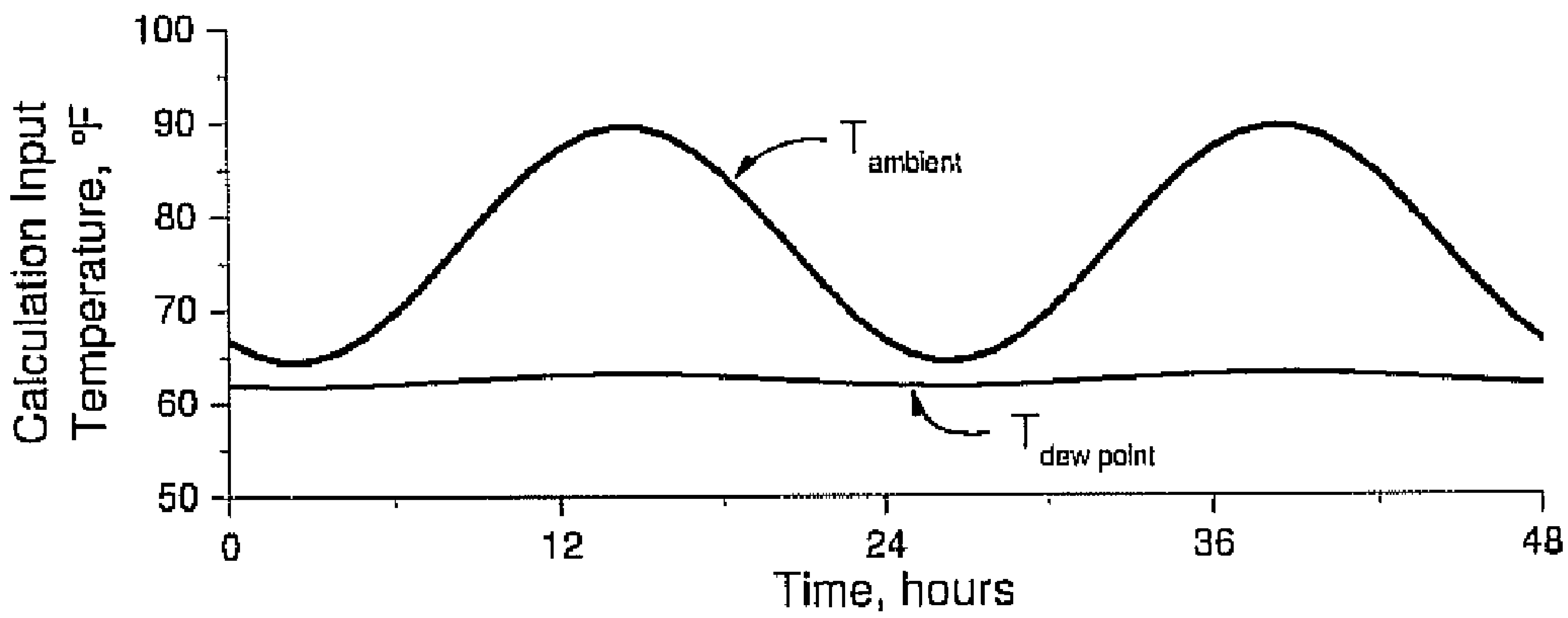
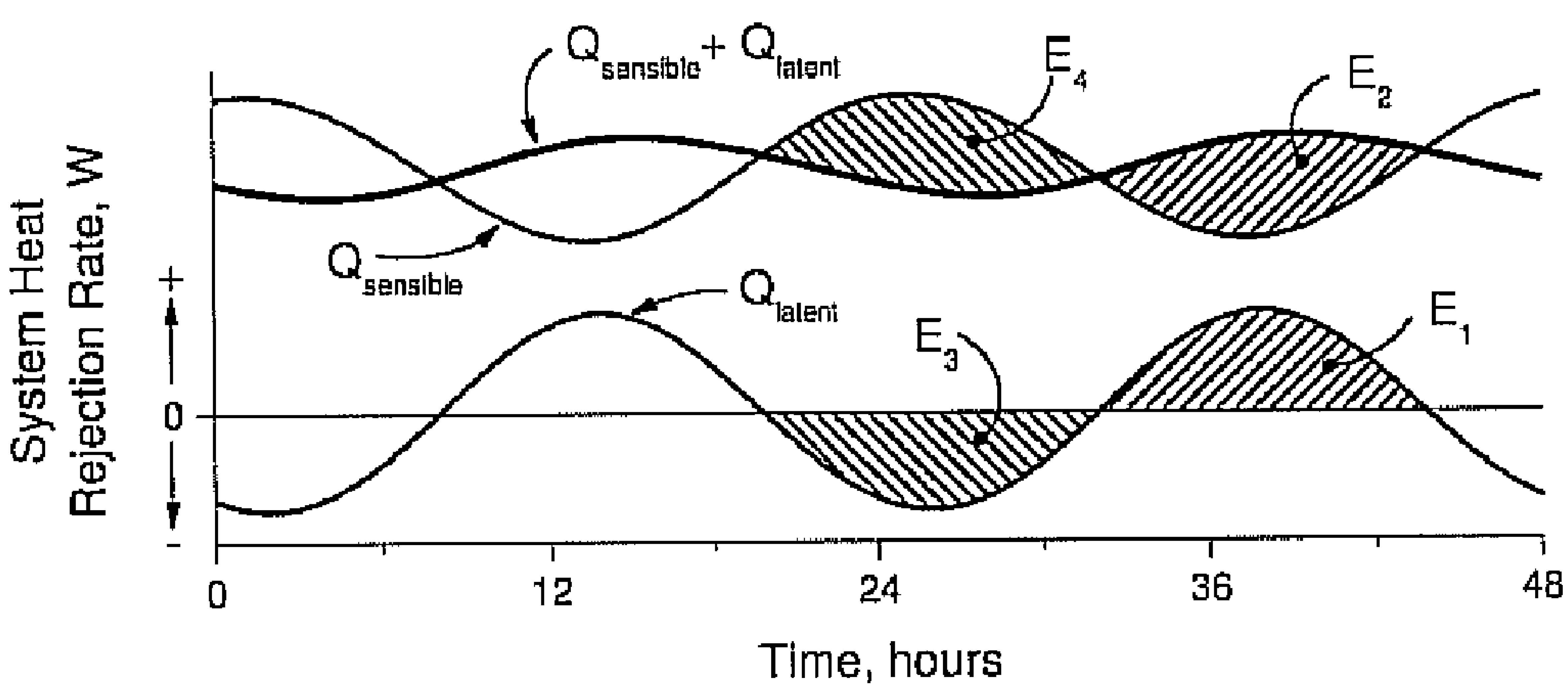


FIG. 1



Calculation Input Temperature, °F
100
90
80
70
60
50
T ambient
T dew point
0
12
24
36
48
Time, hours

FIG. 2A



System Heat Rejection Rate, W
Q sensible + Q latent
E4
E2
Q sensible
Q latent
E3
E1
+
0
-
0
12
24
36
48
Time, hours

FIG. 2B

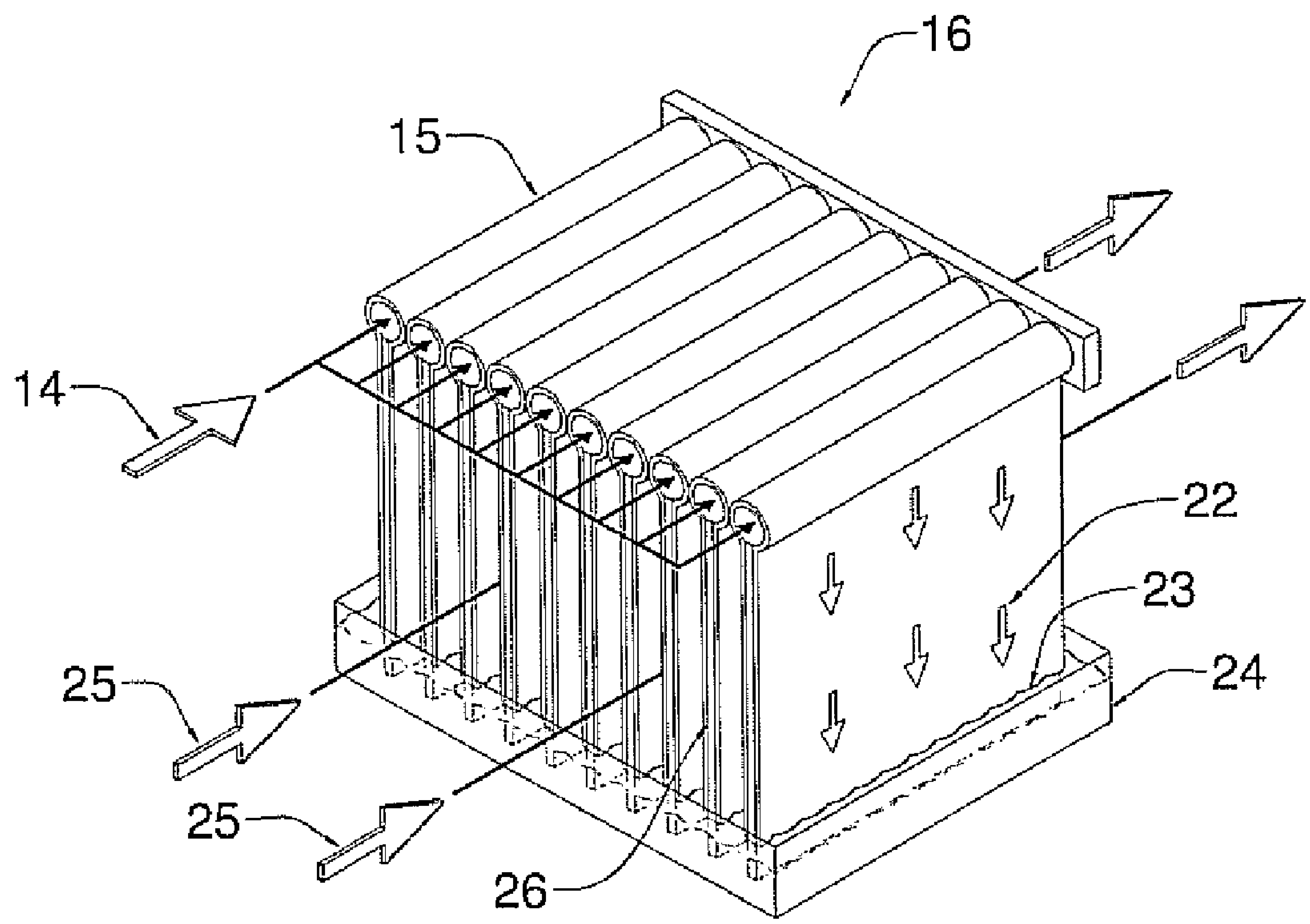


FIG. 3

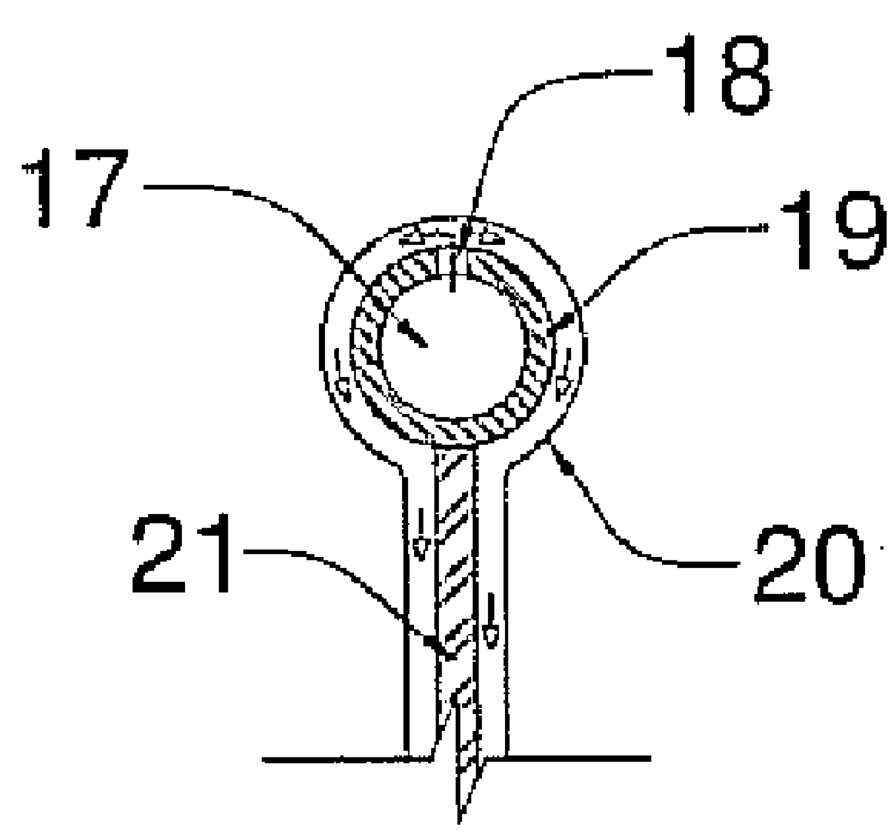


FIG. 4

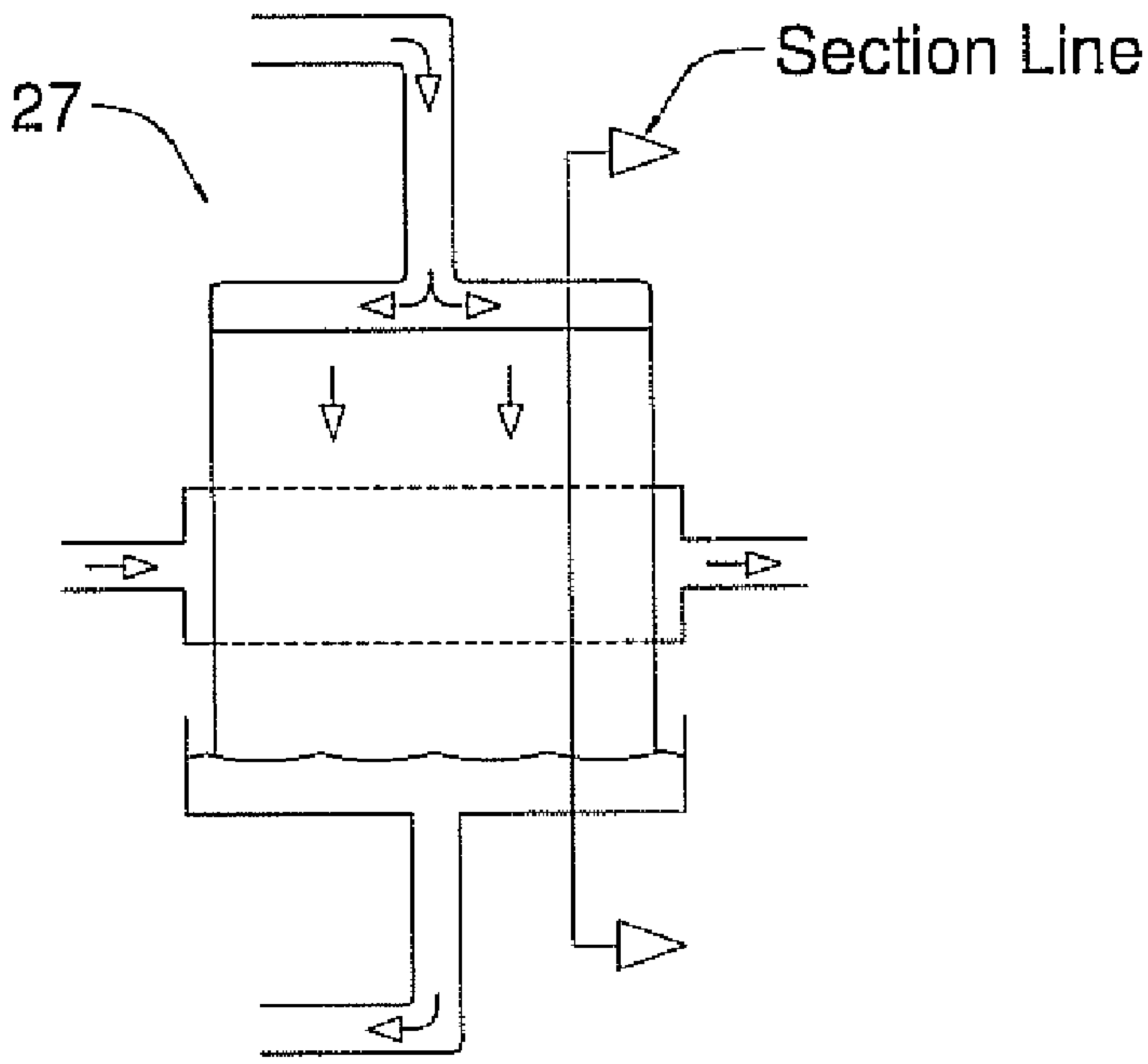


FIG. 5A

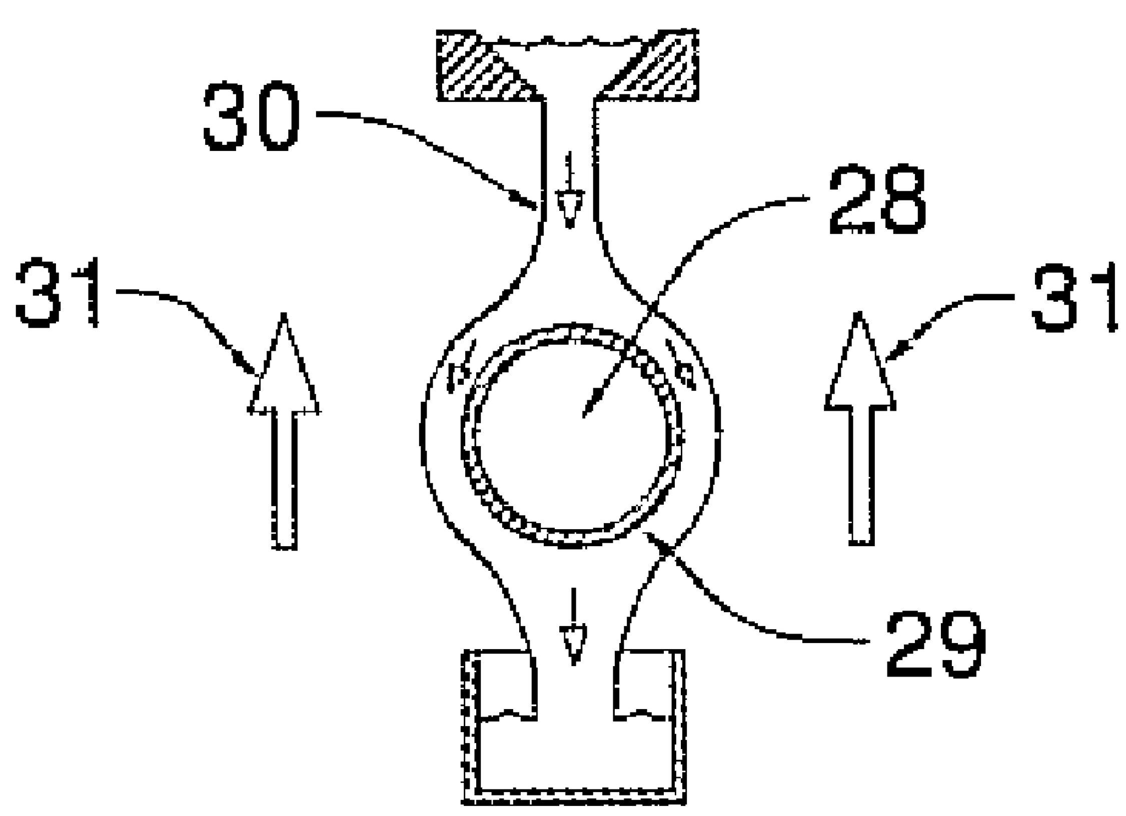


FIG. 5B

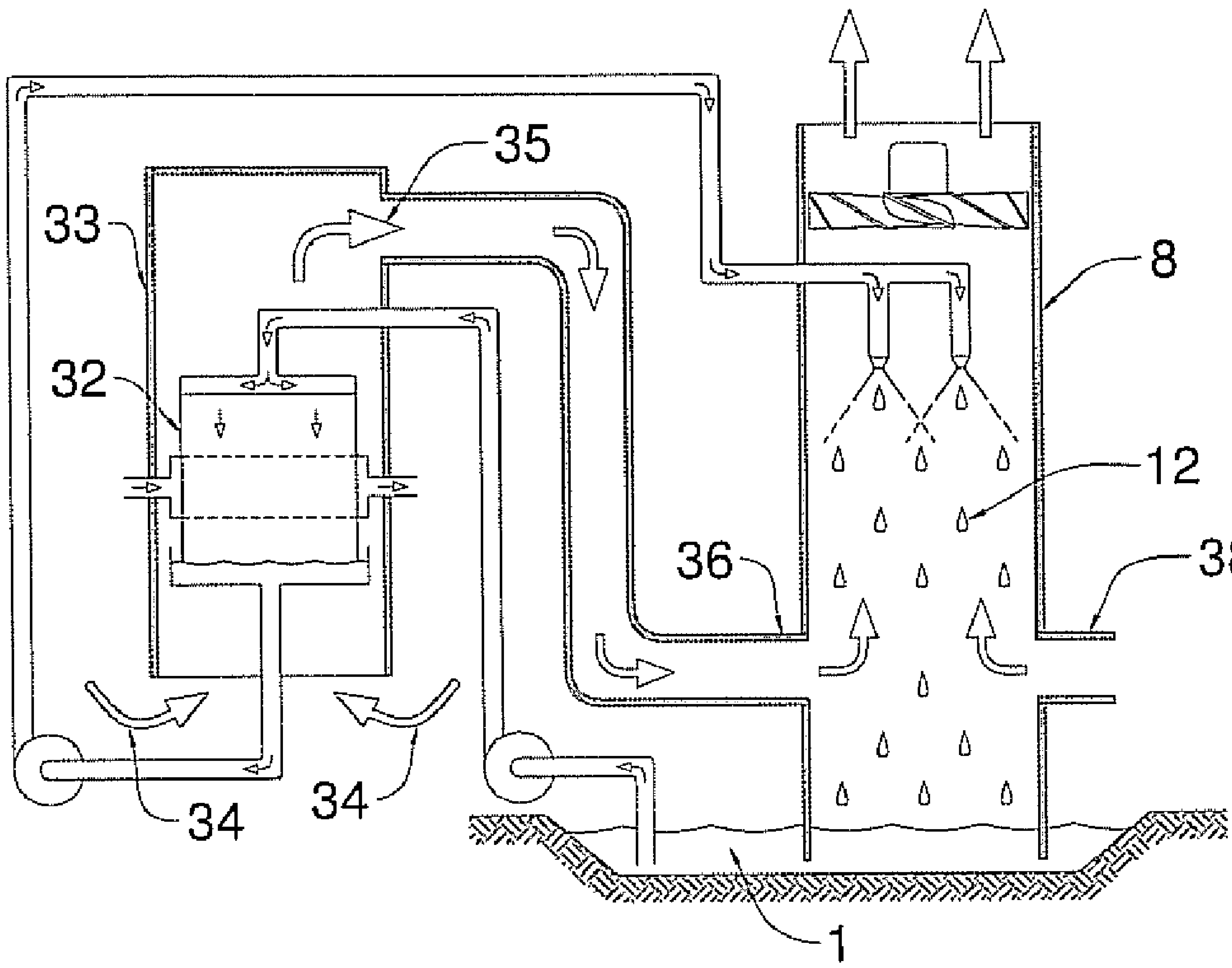


FIG. 6

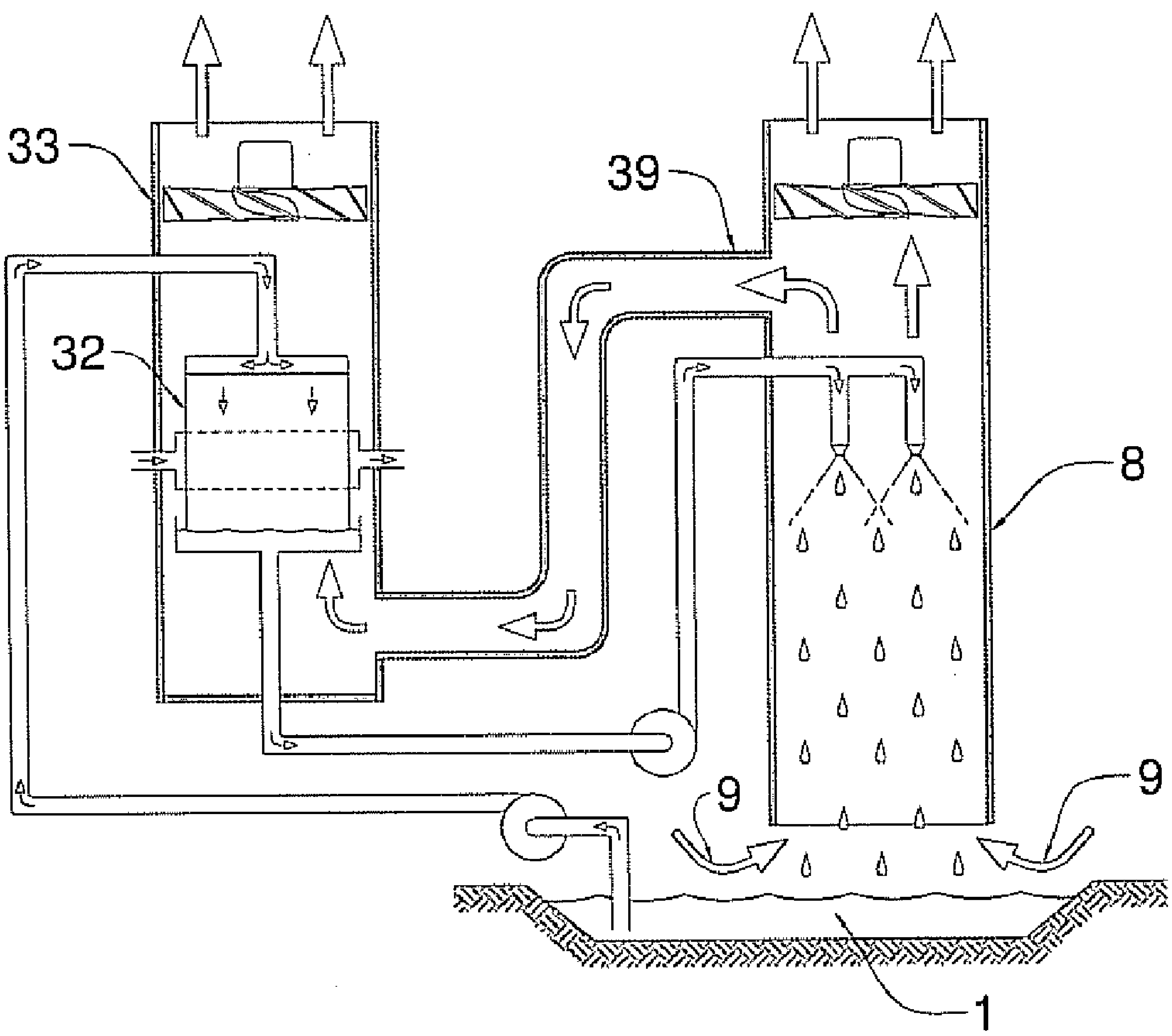


FIG. 7

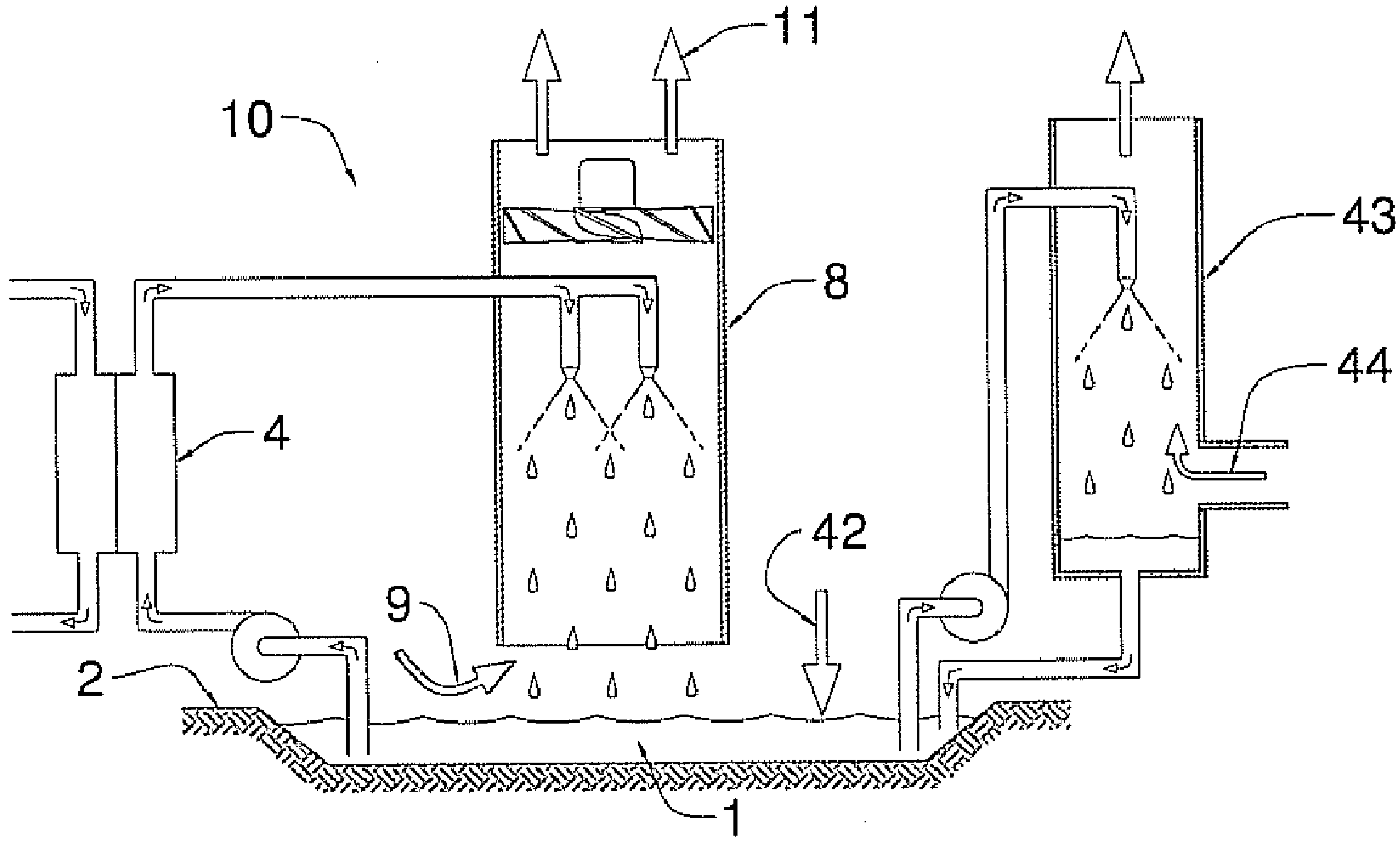


FIG. 8

HEAT DISSIPATION SYSTEM WITH HYGROSCOPIC WORKING FLUID

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of U.S. Provisional Patent Application Ser. No. 61/345,864 filed May 18, 2010, which is incorporated herein in its entirety by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under Cooperative Agreement No. DE-FC26-08NT43291 entitled "EERC-DOE Joint Program on Research and Development for Fossil Energy-Related Resources," awarded by the U.S. Department of Energy (DOE). The government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] This invention relates to the dissipation of degraded thermal energy to ambient air.

BACKGROUND OF THE INVENTION

[0004] Cooling and thermal energy dissipation are universal tasks in industry. Common heat rejection processes include steam condensation in thermoelectric power plants, refrigerant condensation in air-conditioning and refrigeration equipment, and process cooling during chemical manufacturing. In the case of power plants and refrigeration systems, it is desired to dissipate thermal energy at the lowest possible temperature and as close as possible to the operating environment for optimum energy efficiency.

[0005] Where the local environment has a suitable low-temperature sink, e.g., a river, sea, or lake, cooling water can be extracted directly. However, few of these opportunities for once-through cooling are expected to be available in the future because of competition for water sources and recognition of their impact on the environment. In the absence of a suitable coolant source, the only common thermal sink available at all locations is ambient air. Both sensible and latent heat transfer are currently used to reject heat to the air. In sensible cooling, air is used directly as the coolant, and it is used to cool one side of the process heat exchanger. For latent cooling, liquid water is used as the coolant, and it is then itself cooled by partial evaporation in a cooling tower. The thermal energy is transferred to the ambient air in the form of evaporated water vapor, with minimal temperature rise of the air.

[0006] These technologies are used routinely in industry, but each one has distinct drawbacks. In the sensible cooling case, air is an inferior coolant compared to liquids, and the resulting efficiency of air-cooled processes can be poor. The air-side heat-transfer coefficient is invariably much lower than liquid-cooled heat exchangers or condensation processes and, therefore, requires a large heat exchange surface area for good performance. In addition to larger surface area requirements, air-cooled heat exchangers approach the ambient dry-bulb temperature, which can vary 30° to 40° F. over the course of a day and can hinder cooling capacity during the hottest hours of the day. Air-cooled system design is typically a compromise between process efficiency and heat exchanger cost. Choosing the lowest initial cost option can have negative energy consumption implications for the life of the system.

[0007] With latent heat dissipation, the cooling efficiency is much higher, and the heat rejection temperature is more consistent throughout the course of a day since a wet cooling tower will approach the ambient dew point temperature instead of the oscillatory dry-bulb temperature. The key drawback of this approach is the associated water consumption, which in many areas is becoming a limiting resource. Obtaining sufficient water rights for wet cooling system operation delays plant permitting, limits site selection, and creates a highly visible vulnerability for opponents of new development.

[0008] Improvements have been proposed to these basic cooling systems. A significant effort has gone into hybrid cooling concepts that augment air-cooled condensers with evaporative cooling during the hottest parts of the day. These systems can use less water compared to complete latent cooling, but the performance benefit is directly related to the amount of water-based augmentation, so these systems do not solve the underlying issue of water consumption. Despite the fact that meeting the cooling needs of industrial processes is a fundamental engineering task, significant improvements are still desired, primarily the elimination of water consumption while simultaneously maintaining high-efficiency cooling at reasonable cost.

[0009] In summary, there is a need for improved heat dissipation technology relative to current methods. Sensible cooling with air is costly because of the vast heat exchange surface area required and because its heat-transfer performance is handicapped during the hottest ambient temperatures. Latent or evaporative cooling has preferred cooling performance, but it consumes large quantities of water which is a limited resource in some locations.

SUMMARY OF THE INVENTION

[0010] A heat dissipation system apparatus and method of operation using hygroscopic working fluid.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a schematic of the heat dissipation system according to one embodiment of the present invention.

[0012] FIG. **2**A is a chart depicting the input temperature conditions used to calculate the dynamic response of one embodiment of the present invention.

[0013] FIG. **2**B is a chart depicting the calculated components of heat transfer of the present invention in response to the cyclical input temperature profile of FIG. **2**A.

[0014] FIG. **3** is a schematic of a cross-flow air contactor depicting an alternate embodiment of the present invention.

[0015] FIG. **4** is a cross-sectional detail of one of the tube headers shown in the air contactor of FIG. **3**.

[0016] FIG. **5**A is a schematic of a falling-film process heat exchanger depicting an alternate embodiment of the present invention.

[0017] FIG. **5**B is a section view of the process heat exchanger in FIG. **5**A as viewed from the indicated section line.

[0018] FIG. **6** is a schematic of an alternate embodiment of the present invention incorporating a falling-film process heat exchanger to precondition the air contactor inlet air.

[0019] FIG. **7** is a schematic of an alternate embodiment of the present invention incorporating the air contactor to precondition a falling-film process heat exchanger.

[0020] FIG. **8** is a schematic of an alternate embodiment of the present invention incorporating alternate means to increase the moisture content of the working fluid.

DETAILED DESCRIPTION OF THE INVENTION

[0021] The heat dissipation system described herein circulates a hygroscopic working fluid to transfer heat from a process requiring cooling directly to the ambient air. The hygroscopic fluid is in liquid phase at conditions in which it is at thermal and vapor pressure equilibrium with the expected local ambient conditions. The fluid is composed of a solution of a hygroscopic substance and water. In one embodiment, the hygroscopic substance itself should have a very low vapor pressure compared to water in order to prevent significant loss of the hygroscopic component during cycle operation. The hygroscopic component can be a pure substance or a mixture of substances selected from compounds known to attract moisture vapor and form liquid solutions with water that have reduced water vapor pressures. The hygroscopic component includes all materials currently employed for desiccation operations or dehumidifying operations including hygroscopic inorganic salts, such as LiCl, LiBr, $CaCl_2$, $ZnCl_2$; hygroscopic organic compounds, such as ethylene glycol, propylene glycol, triethylene glycol; or inorganic acids, such as H_2SO_4 and the like.

[0022] Thermal energy is removed from the process in a suitable heat exchanger having one side thereof, the flow of process fluid, and on the other side thereof, the flow of hygroscopic working fluid coolant. This heat exchanger can take the form of any well-known heat exchange device, including shell-and-tube heat exchangers, plate-and-frame heat exchangers, or falling-film heat exchangers. The process fluid being cooled includes a single-phase fluid, liquid, or gas or can be a fluid undergoing phase change, e.g., condensation of a vapor into a liquid. Consequently, the thermal load presented by the process fluid can be sensible, i.e., with a temperature change, or latent which is isothermal. Flowing through the other side of the heat exchange device, the hygroscopic working fluid coolant can remove heat sensibly, such as in a sealed device with no vapor space, or it can provide a combination of sensible and latent heat removal if partial evaporation of the moisture in solution is allowed, such as in the film side of a falling-film heat exchanger.

[0023] After thermal energy has been transferred from the process fluid to the hygroscopic working fluid, the hygroscopic fluid is circulated to an air-contacting device where it is exposed directly to ambient air for heat dissipation. The contacting device is constructed in such a way as to generate a large amount of interfacial surface area between the solution and air. Any well-known method may be used to generate the interfacial area, such as by including a direct spray of the liquid into the air, a flow of solution distributed over random packing's, or a falling film of liquid solution clown a structured surface. Flow of the air and solution streams can be conducted in the most advantageous way for a particular situation, such as countercurrent where the solution may be flowing down by gravity and the air is flowing up, cross-flow where the flow of solution is in an orthogonal direction to airflow, cocurrent where the solution and air travel in the same direction, or any combination of these flow types.

[0024] Heat- and mass-transfer processes inside the air contactor are enhanced by convective movement of air through the contactor. Convective flow may be achieved by several different means or a combination of such different means. The first means for convective airflow is through natural convection mechanisms such as by the buoyancy difference between warmed air inside the contactor and the cooler and the surrounding ambient air. This effect would naturally circulate convective airflow through a suitably designed chamber in which the air is being heated by the warmed solution. Another means for convective airflow includes the forced flow of air generated by a fan or blower. A further convective airflow means includes inducing airflow using momentum transfer from a jet of solution pumped out at sufficient mass flow rate and velocity.

[0025] Inside the air contactor, an interrelated process of heat and mass transfer occurs between the hygroscopic solution and the airflow that ultimately results in the transfer of thermal energy from the solution to the air. When the air and solution are in contact, they will exchange moisture mass and thermal energy in order to approach equilibrium, which for a desiccant liquid and its surrounding atmosphere requires a match of temperature and water vapor pressure. Since the solution's vapor pressure is partially dependent on temperature, the condition is often reached where the solution has rapidly reached its equivalent dew point temperature by primarily latent heat transfer (to match the ambient vapor pressure), and then further evaporation or condensation is limited by the slower process of sensible heat transfer between the air and solution (to match the ambient temperature). The induced mass transfer required to equilibrate vapor pressure is an added gradient that enhances sensible heat transfer.

[0026] The net amount of heat and mass transfer within the air contactor is dependent on the specific design of the air contactor and the inlet conditions of the hygroscopic solution and the ambient air. However, the possible outcomes as solution passes through the contactor include situations where the solution can experience a net loss of moisture (a portion of the thermal energy contained in the solution is released as latent heat during moisture evaporation; this increases the humidity content of the airflow), the solution can experience a net gain in moisture content (such occurs when the vapor pressure in the air is higher than in the solution, and moisture is absorbed by the solution having the latent heat of absorption released into the solution and being transferred sensibly to the air), and the solution is in a steady state where no net moisture change occurs (any evaporation being counterbalanced by an equivalent amount of reabsorption, or vice versa). Even in this last instance where there is no net moisture change, the counterbalancing processes of evaporation and reabsorption still have the potential to enhance sensible heat transfer by altering the working fluid temperature and, thus, the sensible heat transfer gradient.

[0027] After passing through the air contactor, the solution has released thermal energy to the ambient air either through sensible heat transfer alone or by a combination of sensible and latent heat transfer (along with any concomitant moisture content change). The solution is then collected in a reservoir, the size of which will be selected to offer the best dynamic performance of the overall cooling system for a given environmental location and thermal load profile. It can be appreciated that the reservoir can alter the time constant of the cooling system in response to dynamic changes in environmental conditions. For example, moisture absorption in the ambient atmosphere will be most encouraged during the night and early morning hours, typically when diurnal temperatures are at a minimum, and an excess of moisture may be collected. On the other extreme, moisture evaporation in the ambient atmosphere will be most prevalent during the afternoon when diurnal temperatures have peaked, and there could be a net loss of solution moisture content. Therefore, for a continuously operating system in the ambient atmosphere, the reservoir and its method of operation can be selected so as to optimize the storage of excess moisture gained during the night so that it can be evaporated during the next afternoon, to maintain cooling capacity.

[0028] The reservoir itself can be a single mixed tank where the average properties of the solution are maintained. The reservoir also includes a stratified tank or a series of separate tanks intended to preserve the distribution of water collection throughout a diurnal cycle so collected water can be metered out to provide maximum benefit.

[0029] The present heat dissipation system includes the use of a hygroscopic working fluid to remove thermal energy from a process stream and dissipate it to the atmosphere by direct contact of the working fluid and ambient air. This enables several features that are highly beneficial for heat dissipation systems, including 1) using the working fluid to couple the concentrated heat-transfer flux in the process heat exchanger to the lower-density heat-transfer flux of ambient air heat dissipation, 2) allowing for large interfacial surface areas between the working fluid and ambient air, 3) enhancing working fluid-air heat-transfer rates with simultaneous mass transfer, and 4) moderating daily temperature fluctuations by cyclically absorbing and releasing moisture vapor from and to the air.

[0030] Referring to drawing FIG. **1**, one embodiment of heat dissipation system **10** is illustrated using a hygroscopic working fluid **1** in storage reservoir **2** drawn by pump **3** and circulated through process heat exchanger **4**. In the process heat exchanger, the hygroscopic working fluid removes thermal energy from the process fluid that enters hot-side inlet **5** and exits through hot-side outlet **6**. The process fluid can be a single phase (gas or liquid) that requires sensible cooling or it could be a two-phase fluid that undergoes a phase change in the process heat exchanger, e.g., condensation of a vapor into a liquid.

[0031] After absorbing thermal energy in process heat exchanger **4**, the hygroscopic working fluid is routed to distribution nozzles **7** where it is exposed in a countercurrent fashion to air flowing through air contactor **8**. Ambient airflow through the air contactor in drawing FIG. **1** is from bottom ambient air inlet **9** vertically to top air outlet **11** and is assisted by the buoyancy of the heated air and by powered fan **13**. Distributed working fluid **12** in the air contactor flows down, countercurrent to the airflow by the pull of gravity. At the bottom of air contactor **8**, the working fluid is separated from the inlet airflow and is returned to stored solution **1** in reservoir **2**.

[0032] In air contactor **8**, both thermal energy and moisture are exchanged between the hygroscopic working fluid and the airflow, but because of the moisture retention characteristics of the hygroscopic solution, complete evaporation of the working fluid is prevented.

[0033] If the heat dissipation system **10** is operated continuously with unchanging ambient air temperature, ambient humidity, and a constant thermal load in process heat exchanger **4**, a steady-state temperature and concentration profile will be achieved in air contactor **8**. Under these conditions, the net moisture content of stored working fluid **1** will remain unchanged. That is not to say that no moisture is exchanged between distributed working fluid **12** and the airflow in air contactor **8**, but it is an indication that any moisture evaporated from working fluid **12** is reabsorbed from the ambient airflow before the solution is returned to reservoir **2**.

[0034] However, prior to reaching the aforementioned steady-state condition and during times of changing ambient conditions, heat dissipation system **10** may operate with a net loss or gain of moisture content in working fluid **1**. When operating with a net loss of working fluid moisture, the equivalent component of latent thermal energy contributes to the overall cooling capacity of the heat dissipation system **10**. In this case, the additional cooling capacity is embodied by the increased moisture vapor content of airflow **11** exiting air contactor **8**.

[0035] Conversely, when operating with a net gain of working fluid moisture content, the equivalent component of latent thermal energy must be absorbed by the working fluid and dissipated to the airflow by sensible heat transfer. In this case, the overall cooling capacity of the system is diminished by the additional latent thermal energy released to the working fluid. Airflow **11** exiting air contactor **8** will now have a reduced moisture content compared to inlet ambient air **9**.

[0036] Another embodiment of heat dissipation system **10** illustrated in drawing FIG. **1** uses the supplementation of the relative humidity of inlet ambient air **9** with supplemental gas stream **40** entering through supplemental gas stream inlet **41**. When used, gas stream **40** can be any gas flow containing sufficient moisture vapor including ambient air into which water has been evaporated either by misting or spraying, an exhaust stream from a drying process, an exhaust stream of high-humidity air displaced during ventilation of conditioned indoor spaces, an exhaust stream from a wet evaporative cooling tower, or a flue gas stream from a combustion source and the associated flue gas treatment systems. The benefit of using supplemental gas stream **40** is to enhance the humidity level in air contactor **8** and encourage absorption of moisture into dispersed working fluid **12** in climates having low ambient humidity. It is also understood that supplemental gas stream **40** would only be active when moisture absorption is needed to provide a net benefit to cyclic cooling capacity, e.g., where the absorbed moisture would be evaporated during a subsequent time of peak cooling demand or when supplemental humidity is needed to prevent excessive moisture loss from the working fluid.

[0037] With the operation of the heat dissipation system **10** described herein and the effects of net moisture change set forth, the performance characteristics of cyclic operation can be appreciated. Illustrated in drawing FIG. **2**A is a plot of the cyclic input conditions of ambient air dry-bulb temperature and dew point temperature. The cycle has a period of 24 hours and is intended to be an idealized representation of a diurnal temperature variation. The moisture content of the air is constant for the input data of FIG. **2**A since air moisture content does not typically vary dramatically on a diurnal cycle.

[0038] Illustrated in drawing FIG. **2**B is the calculated heat-transfer response of the present invention corresponding to the input data of FIG. **2**A. The two components of heat transfer are sensible and latent, and their sum represents the total cooling capacity of the system. As shown in drawing FIG. **2**B, the sensible component of heat transfer ($Q_{sensible}$) varies out of phase with the ambient temperature since sensible heat transfer is directly proportional to the working fluid and the airflow temperature difference (all other conditions remaining equal). In practice, a conventional air-cooled heat exchanger is limited by this fact. In the case of a power plant steam condenser, this is the least desirable heat-transfer limitation since cooling capacity is at a minimum during the hottest part of the day, which frequently corresponds to periods of maximum demand for power generation.

[0039] The latent component of heat transfer illustrated in drawing FIG. **2**B (Q_{latent}) is dependent on the ambient moisture content and the moisture content and temperature of the hygroscopic working fluid. According to the sign convention used in drawing FIG. **2**B, when the latent heat-transfer component is positive, evaporation is occurring with a net loss of moisture, and the latent thermal energy is dissipated to the ambient air; when the latent component is negative, the hygroscopic solution is absorbing moisture, and the latent energy is being added to the working fluid, thereby diminishing overall cooling capacity. During the idealized diurnal cycle illustrated in drawing FIG. **2**A, the latent heat-transfer component illustrated in drawing FIG. **2**B indicates that moisture absorption and desorption occur alternately as the ambient temperature reaches the cycle minimum and maximum, respectively. However, over one complete cycle, the net water transfer with the ambient is zero, i.e., the moisture absorbed during the night equals the moisture evaporated during the next day, so there is no net water consumption.

[0040] The net cooling capacity of the heat dissipation system **10** is illustrated in drawing FIG. **2**B as the sum of the sensible and latent components of heat transfer ($Q_{sensible}$+Q_{latent}). As illustrated, the latent component of heat transfer acts as thermal damping for the entire system by supplementing daytime cooling capacity with evaporative cooling, region E_1 illustrated in drawing FIG. **2**B. This evaporative heat transfer enhances overall heat transfer by compensating for declining sensible heat transfer during the diurnal temperature maximum, region E_2. This is especially beneficial for cases like a power plant steam condenser where peak conversion efficiency is needed during the hottest parts of the day.

[0041] The cost of this boost to daytime heat transfer comes at night when the absorbed latent energy, region E_3, is released into the working fluid and must be dissipated to the airflow. During this time, the total system cooling capacity is reduced by an equal amount from its potential value, region E_4. However, this can be accommodated in practice since the nighttime ambient temperature is low and overall heat transfer is still acceptable. For a steam power plant, the demand for peak power production is also typically at a minimum at night.

[0042] Regarding air contactor configuration, direct contact of the working fluid and surrounding air allows the creation of significant surface area with fewer material and resource inputs than are typically required for vacuum-sealed air-cooled condensers or radiators. The solution-air interfacial area can be generated by any means commonly employed in industry, e.g., spray contactor, wetted packed bed (with regular or random packings), or a falling-film contactor.

[0043] Air contactor **8**, illustrated in drawing FIG. **1**, is shown to be a counterflow spray contactor. While the spray arrangement is an effective way to produce significant interfacial surface area, in practice such designs can have undesirable entrained aerosols carried out of the contactor by the airflow. An alternate embodiment of the air contactor to prevent entrainment is illustrated in drawing FIG. **3**, which is a cross-flow, falling-film contactor designed to minimize droplet formation and liquid entrainment. Particulate sampling across such an experimental device has demonstrated that there is no propensity for aerosol formation with this design.

[0044] Illustrated in drawing FIG. **3**, inlet hygroscopic working fluid **14** is pumped into distribution headers at the top of contactor **16**. Referring to drawing FIG. **4**, which is a cross section of an individual distribution header, working fluid **17** is pumped through distribution holes **18** perpendicular to the axis of tube header **19** where it wets falling-film wick **20** constructed from a suitable material such as woven fabric, plastic matting, or metal screen. Film wick support **21** is used to maintain the shape of each wick section. Illustrated in drawing FIG. **3**, distributed film **22** of the working fluid solution flows down by gravity all of the way to the surface of working fluid **23** in reservoir **24**. Inlet airflow **25** flows horizontally through the air contactor between falling-film sheets **26**. In the configuration illustrated in drawing FIG. **3**, heat and mass transfer take place between distributed film **22** of working fluid and airflow **25** between falling-film sections **26**. While drawing FIG. **3** illustrates a cross-flow configuration, it is understood that countercurrent, cocurrent, or mixed flow is also possible with this configuration.

[0045] Illustrated in drawing FIG. **1**, the process heat exchanger **4** can assume the form of any indirect heat exchanger known in the art such as a shell-and-tube or plate-type exchanger. One specific embodiment of the heat exchanger that is advantageous for this service is the falling-film type. Illustrated in drawing FIG. **5**A is a schematic of alternate embodiment process heat exchanger **27**. Illustrated in drawing FIG. **5**B is a cross-sectional view of process heat exchanger **27** viewed along the indicated section line in drawing FIG. **5**A. Referring to drawing FIG. **5**B, process fluid **28** (which is being cooled) is flowing within tube **29**. Along the top of tube **29**, cool hygroscopic working fluid **30** is distributed to form a film surface which flows down by gravity over the outside of tube **29**. Flowing past the falling-film assembly is airflow **31** which is generated either by natural convection or by forced airflow from a fan or blower.

[0046] As working fluid **30** flows over the surface of tube **29**, heat is transferred from process fluid **28** through the tube wall and into the working fluid film by conduction. As the film is heated, its moisture vapor pressure rises and may rise to the point that evaporation takes place to surrounding airflow **31**, thereby dissipating thermal energy to the airflow. Falling-film heat transfer is well known in the art as an efficient means to achieve high heat-transfer rates with low differential temperatures. One preferred application for the falling-film heat exchanger is when process fluid **28** is undergoing a phase change from vapor to liquid, as in a steam condenser, where temperatures are isothermal and heat flux can be high.

[0047] A further embodiment of the heat dissipation system **10** is illustrated in drawing FIG. **6**. The heat dissipation system **10** incorporates the film-cooled process heat exchanger to condition a portion of the airflow entering air contactor **8**. Illustrated in drawing FIG. **6**, process heat exchanger **32** is cooled by a falling film of hygroscopic working fluid inside housing **33**. Ambient air **34** is drawn into process heat exchanger housing **33** and flows past the film-cooled heat exchanger where it receives some quantity of evaporated moisture from the film. The higher-humidity airflow at **35** is conducted to inlet **36** of air contactor **8** where it flows countercurrent to the spray of hygroscopic working fluid **12**. Additional ambient air may also be introduced to the inlet of air contactor **8** through alternate opening **38**.

[0048] In the embodiment illustrated in drawing FIG. **6**, moisture vapor released from process heat exchanger **32** is added to the air contactor's inlet airstream and thereby increases the moisture content by a finite amount above ambient humidity levels. This effect will tend to inhibit moisture evaporation from working fluid **12** and will result in a finite increase to the steady-state moisture content of reservoir solution **1**. The embodiment illustrated in drawing FIG. **6** may be preferred in arid environments and during dry weather in order to counteract excessive evaporation of moisture from the working fluid.

[0049] A further embodiment of the heat dissipation system **10** is illustrated in drawing FIG. **7**. The heat dissipation system **10** incorporates the air contactor to condition the airflow passing the film-cooled process heat exchanger. As illustrated in drawing FIG. **7**, a portion of the airflow exiting air contactor **8** at outlet **39** is conducted to the inlet of process heat exchanger housing **33**. This airflow then flows past film-cooled process heat exchanger **32** where it receives moisture from film moisture evaporation.

[0050] During high-ambient-humidity conditions when the net moisture content of reservoir solution **1** is increasing, the air at outlet **39** will have a lower moisture vapor content than ambient air **9** entering air contactor **8**. Therefore, some advantage will be gained by exposing film-cooled process heat exchanger **32** to this lower-humidity airstream from outlet **39** rather than the higher-humidity ambient air. The lower-humidity air will encourage evaporation and latent heat transfer in film-cooled process heat exchanger **32**, and it will allow for lower film temperatures because of the lower dew point associated with the lower-humidity air. The embodiment illustrated in drawing FIG. **7** may be preferred for high-humidity conditions since it will enhance the latent component of heat transfer when a film-cooled process heat exchanger is used.

[0051] A further embodiment of the heat dissipation system **10** is illustrated in drawing FIG. **8**. The heat dissipation system **10** uses an alternate means for increasing the working fluid moisture content above those that could be obtained by achieving equilibrium with the ambient air. The first alternative presented in drawing FIG. **8** is to increase moisture content of working fluid **1** directly by addition of liquid water stream **42**. In the other alternative presented, working fluid **1** is circulated through absorber **43** where it is exposed to gas stream **44**. Gas stream **44** has higher moisture vapor availability compared to ambient air **9**. Therefore, the working fluid that passes through absorber **43** is returned to reservoir **2** having a higher moisture content than that achievable in air contactor **8**. The source of gas stream **44** may include ambient air into which water has been evaporated either by misting or spraying, an exhaust stream from a drying process, an exhaust stream of high-humidity air displaced during ventilation of conditioned indoor spaces, an exhaust stream from a wet evaporative cooling tower, or a flue gas stream from a combustion source and the associated flue gas treatment systems. The benefit of such alternatives illustrated in drawing FIG. **8** is to increase the moisture content of working fluid **1** during periods of low heat dissipation demand, such as at night, for the purpose of providing additional latent cooling capacity during periods when heat dissipation demand is high.

[0052] The foregoing discussion discloses and describes merely exemplary embodiments of the present invention. One skilled in the art will readily recognize from such discussion, and from the accompanying drawings and claims, that various changes, modifications, and variations can be made therein without departing from the spirit and scope of the invention as defined in the following claims.

1. A method for heat dissipation comprising:
- providing a low-volatility hygroscopic working fluid,
- removing heat from a process heat exchanger to absorb thermal energy for dissipation using the low-volatility hygroscopic working fluid,
- providing a working fluid-air contactor,
- enabling combined heat dissipation from the low-volatility hygroscopic working fluid to the air using the fluid-air contactor, and
- enabling a bidirectional moisture mass transfer between the low-volatility hygroscopic working fluid and the air using the working fluid-air contactor.

2. The method for heat dissipation according to claim **1**, wherein the hygroscopic working fluid comprises an aqueous solution including at least one of sodium chloride (NaCl), calcium chloride ($CaCl_2$), lithium chloride (LiCl), lithium bromide (LiBr), zinc chloride ($ZnCl_2$), sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), sodium sulfate (Na_2SO_4), potassium chloride (KCl), calcium nitrate ($Ca[NO_3]_2$), potassium carbonate (K_2CO_3), ammonium nitrate (NH_4NO_3), ethylene glycol, diethylene glycol, propylene glycol, triethylene glycol, dipropylene glycol, and any combination thereof.

3. The method for heat dissipation according to claim **1**, wherein the process heat exchanger comprises one of a condenser of a thermodynamic power production or a refrigeration cycle.

4. The method for heat dissipation according to claim **1**, wherein the fluid-air contactor operates in at least one relative motion including countercurrent, cocurrent, or cross-flow operation.

5. The method for heat dissipation according to claim **1**, wherein the fluid-air contactor is enhanced by at least one of the forced or induced draft of ambient air by a powered fan; the natural convection airflow generated from buoyancy differences between heated and cooled air; and the induced flow of air generated by the momentum transfer of sprayed working fluid into the air.

6. The method for heat dissipation according to claim **1**, wherein said ambient airstream is supplemented with additional humidity from at least one of:
- a spray, mist, or fog of water directly into the airstream,
- an exhaust gas stream from a drying process,
- an exhaust gas stream consisting of high-humidity rejected air displaced during the ventilation of conditioned indoor spaces,
- an exhaust airstream from a wet evaporative cooling tower, and
- an exhaust flue gas stream from a combustion source and any associated flue gas treatment equipment.

7. The method for heat dissipation according to claim **1**, wherein the overall heat-transfer performance is enhanced by addition of moisture to the hygroscopic working fluid using any one of:
- direct addition of liquid water to the hygroscopic working fluid and
- absorption of vapor-phase moisture by the working fluid from a moisture-containing gas stream outside of the process air contactor, where the moisture-containing gas stream could include ambient air into which water has been evaporated by spraying or misting, flue gas from a combustion source and its associated flue gas treatment equipment, exhaust gas from a drying process, rejected

high-humidity air displaced during ventilation of conditioned indoor air, or the exhaust airstream from a wet evaporative cooling tower.

8. The method for heat dissipation according to claim **1**, wherein the process heat exchanger is cooled by a flowing film of said hygroscopic working fluid enabling both sensible and latent heat transfer to occur during thermal energy absorption from the process fluid.

9. The method for heat dissipation according to claim **8**, wherein the process heat exchanger is placed at the inlet to said air contactor for raising inlet airflow humidity levels.

10. The method for heat dissipation according to claim **8**, wherein the process heat exchanger is placed at the outlet of said air contactor for receiving air dehumidified with respect to the ambient air atmosphere.

11. A heat dissipation method comprising:

removing heat from a process heat exchanger absorbing thermal energy using a low-volatility hygroscopic working fluid,

enabling combined heat dissipation from the low-volatility hygroscopic working fluid to the air using a fluid-air contactor, and

enabling a bidirectional moisture mass transfer between the low-volatility hygroscopic working fluid and the air using the working fluid-air contactor.

12. The method for heat dissipation according to claim **11**, wherein the hygroscopic working fluid comprises an aqueous solution including at least one of sodium chloride (NaCl), calcium chloride ($CaCl_2$), lithium chloride (LiCl), lithium bromide (LiBr), zinc chloride ($ZnCl_2$), sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), sodium sulfate (Na_2SO_4), potassium chloride (KCl), calcium nitrate ($Ca[NO_3]_2$), potassium carbonate (K_2CO_3), ammonium nitrate (NH_4NO_3), ethylene glycol, diethylene glycol, propylene glycol, triethylene glycol, dipropylene glycol, and any combination thereof.

13. The method for heat dissipation according to claim **11**, wherein the process heat exchanger comprises one of a condenser of a thermodynamic power production or a refrigeration cycle.

14. The method for heat dissipation according to claim **11**, wherein the fluid-air contactor operates in at least one relative motion including countercurrent, cocurrent, or cross-flow operation.

15. The method for heat dissipation according to claim **11**, wherein the fluid-air contactor is enhanced by at least one of the forced or induced draft of ambient air by a powered fan; the natural convection airflow generated from buoyancy differences between heated and cooled air; and the induced flow of air generated by the momentum transfer of sprayed working fluid into the air.

16. The method for heat dissipation according to claim **11**, wherein said ambient airstream is supplemented with additional humidity from at least one of a spray, mist, or fog of water directly into the airstream, an exhaust gas stream from a drying process, an exhaust gas stream consisting of high-humidity rejected air displaced during the ventilation of conditioned indoor spaces, an exhaust airstream from a wet evaporative cooling tower, and an exhaust flue gas stream from a combustion source and any associated flue gas treatment equipment.

17. The method for heat dissipation according to claim **11**, wherein the overall heat-transfer performance is enhanced by addition of moisture to the hygroscopic working fluid using at least one of direct addition of liquid water to the hygroscopic working fluid and absorption of vapor-phase moisture by the working fluid from a moisture-containing gas stream outside of the process air contactor, where the moisture-containing gas stream could include ambient air into which water has been evaporated by spraying or misting, flue gas from a combustion source and its associated flue gas treatment equipment, exhaust gas from a drying process, rejected high-humidity air displaced during ventilation of conditioned indoor air, or the exhaust airstream from a wet evaporative cooling tower.

18. The method for heat dissipation according to claim **11**, wherein the process heat exchanger is cooled by a flowing film of said hygroscopic working fluid enabling both sensible and latent heat transfer to occur during thermal energy absorption from the process fluid.

19. The method for heat dissipation according to claim **18**, wherein the process heat exchanger is placed at the inlet to said air contactor for raising inlet airflow humidity levels.

20. The method for heat dissipation according to claim **18**, wherein the process heat exchanger is placed at the outlet of said air contactor for receiving air dehumidified with respect to the ambient air atmosphere.

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