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(54) **Title**: A HEAT EXCHANGE SYSTEM

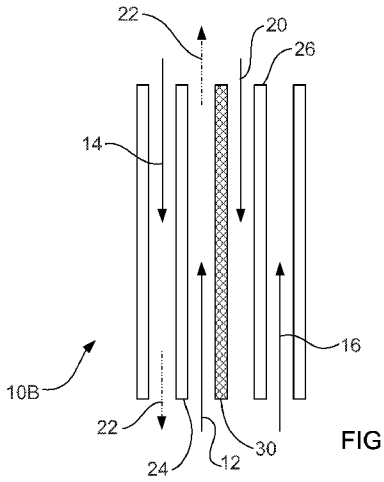


FIG 3

(57) **Abstract**: A heat exchanger (10) including a hot process stream (14) fluidly connected to an industrial process, a cold process stream (16) fluidly connected to an industrial process, and a membrane distillation system (18). The membrane distillation system (18) includes a vapourising stream (12) comprising a mixture of components, a condensing stream (20), and a membrane (30) located between the vapourising stream (12) and the condensing stream (20). The vapourising stream (12) and condensing stream (20) are in fluid communication through the membrane (30). The membrane (30) facilitates transfer of at least one volatised component of the vapourising stream (12) into the condensing stream (20). The membrane distillation system (18) also includes a first heat transfer area (24) between the hot process stream (14) and the vapourising stream (12). In use, the first heat transfer area (24) facilitates the transfer of a quantity of heat energy from the hot process stream (14) to the vapourising stream (12) to heat the vapourising stream (12). Additionally, the membrane distillation system (18) includes a second heat transfer area (26) between the condensing stream (20) and the cold process stream (16). In use, the second heat transfer area (26) facilitates transfer of a quantity of heat energy from the condensing stream (20) to the cold process stream (16).

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A HEAT EXCHANGE SYSTEM

Field of the Invention

[0001] The present invention generally relates to a heat exchange system, and more particularly a membrane distillation heat exchanger system and apparatus. The invention is particularly applicable for use in water treatment applications and it will be convenient to hereinafter disclose the invention in relation to that exemplary application. However, it is to be appreciated that the invention is not limited to that application and could be used in any process system, process train or plant that include both heat exchange and fluid treatment process steps.

Background of the Invention

[0002] The following discussion of the background to the invention is intended to facilitate an understanding of the invention. However, it should be appreciated that the discussion is not an acknowledgement or admission that any of the material referred to was published, known or part of the common general knowledge as at the priority date of the application.

[0003] Heat exchange technology is a ubiquitous part of many chemical and industrial processes. Process streams generally need heat adjustment to meet requirements for a unit process, transport, discharge or the like. Utilisation of the different temperatures of process streams within industrial processes using, for example pinch analysis methodology, can assist in minimising energy consumption of chemical processes. In many cases, excess heat from one or more process streams can be transferred to a cooler process stream through a heat exchanger.

[0004] Purified process water and/or other liquids can also be required in a large number of chemical and industrial processes. Purified water can be produced using a number of unit operations, such as distillation, osmosis, membrane

filtration or the like. All these processes require a significant amount of energy to operate.

[0005] One process that can be used to produce purified process water is membrane distillation. Membrane distillation is a separation method in which a porous membrane is used to separate a vapour phase from a hot vapourising liquid feed (or retentant) on one side of the membrane and feed that vapour to a cold condensing, permeate fluid, or in some cases a cold surface, on the other side. A vapour pressure temperature difference is established across the membranes sides to create a vapour pressure difference between the membrane sides which is the driving force for the diffusion. Temperature difference across the membrane can conveniently create the vapour pressure difference, but vapour can also be drawn away from the membrane by other means. Separation is achieved utilising the relative volatility of various components in the vapourising fluid enabling vapour from components in the vapourising fluid of higher volatility to passes through the membrane pores by a convective or diffusive mechanism. In the case of membranes with smaller pores, the membrane can also act selectively by molecular sieving and/or adsorption based separation. This is more commonly referred to as pervaporation. In any case, the vapour penetrates through the porous membrane, and condenses in the cooler fluid or surface on the condensing permeate side or in an externally mounted condenser unit. The condensed vapour is therefore removed from the retentant and thus is beneficial in its effect to separate the vapour from the retentant. An example of such benefit is the desalination of salty water.

[0006] There are four broad types of membrane distillation systems:

1. Direct contact membrane distillation (DCMD), where both the warm, vaporising vapourising stream and the cold condensing stream (distillate stream) are in direct contact with the membrane.
2. Air gap membrane distillation (AGMD), where a condenser surface contacting the condensing stream is separated from the membrane by an air gap.

3. Sweeping gas membrane distillation (SGMD), where the vaporised portion of the vapourising stream is removed in vapour form by an inert gas.
4. Vacuum membrane distillation (VMD), where the vaporised portion of the vapourising stream is removed in vapour form by vacuum.

[0007] Each of these membrane distillation systems require an external heat source and sink to heat the vapourising fluid and cool the condensing fluid. The vapourising fluid is typically heated using waste or fuel derived (combustion) sources. The condensing fluid is typically cooled using a cooling vent, such as a convective air cooler.

[0008] Energy optimisation of membrane distillation systems have generally concentrated on the use of cheap or waste heat sources, for example solar and waste process heat, to heat and vapourise the liquid feed of these systems.

[0009] For example, Japanese patent publication JP62057611A describes an air gap membrane distillation system for desalinating seawater using diesel engine waste heat from a cooling fluid of that engine. This desalination system comprises two non-permeable condensing heat-transfer plates provided on the outside of two permeable membranes, forming a liquid condensate passage therebetween, and two non-permeable heating heat-transfer plates located between both permeable membranes, forming a heat source fluid passage therebetween. Furthermore, a raw liquid passage is formed between the heating heat-transfer plate and the permeable membrane. Cooling fluid from a diesel engine is passed through the heat source fluid passage as the heat source fluid. Seawater is fed into a cooling liquid passage to cool the heat-transfer plate and the resulting heated seawater is sent into the raw liquid passage for distillation through the membrane distillation system. Energy efficiency in this system is obtained by capturing lost heat from the membrane distillation process in the incoming seawater prior to being fed into to the membrane distillation membrane.

[0010] United States patent publication US2010/0072135A1 describes a membrane distillation in which a distillate is created by passing the heat of

condensation (latent heat) towards a condenser surface which is contact with the feed stream of the membrane distillation system, enabling at least part of the latent heat to be transferred to that feed stream. Energy efficiency in this system is again obtained by capturing lost heat from the membrane distillation process in the incoming feed stream prior to being fed into to the membrane distillation membrane.

[0011] Furthermore, the paper "Membrane distillation and applications for water purification in thermal cogeneration plants" by Alaa Kullab and Andrew Martin, Separation and Purification Technology 76 (2011) 231–237 ("Kullab and Martin"), describes a cogeneration type membrane distillation (MD) process which uses waste heat produced from a first industry process (district heating supply) to supply heat to an unrelated industrial process (municipal water, used as cooling water for the MD process). The test unit produces 1 to 2 m^3/day of purified water. In this case, the MD unit is being utilised in a cogeneration configuration, where waste heat from a first industrial process is useful elsewhere in another industrial process. Internal process energy efficiency is therefore not achieved in each individual industrial process.

[0012] None of these prior membrane systems assist in heat optimisation of process streams within a proximate and related chemical process in that plant, and more particularly utilise internal heat recycling for an industrial process or plant. Energy optimisation of the systems focuses on energy efficiency of the membrane distillation process in isolation to the overall chemical process in which that membrane distillation system is a part of.

[0013] It would therefore be desirable to provide a membrane distillation system which can provide a more energy efficient means of heating and cooling the process streams of a co-located chemical or industrial process in an industrial plant, and more particularly heating and cooling the process streams utilising internal heat recycling for a plant.

Summary of the Invention

[0014] A first aspect of the present invention provides a heat exchanger including a hot process stream fluidly connected to an industrial process, a cold process stream fluidly connected to an industrial process, and a membrane distillation system. The membrane distillation system includes a vapourising stream comprising a mixture of components, a condensing stream, and a membrane located between the vapourising stream and the condensing stream. The vapourising stream and condensing stream are in fluid communication through the membrane. The membrane facilitates transfer of at least one volatised component of the vapourising stream into the condensing stream. The membrane distillation system also includes a first heat transfer area between the hot process stream and the vapourising stream. In use, the first heat transfer area facilitates the transfer of a quantity of heat energy from the hot process stream to the vapourising stream to heat the vapourising stream. Additionally, the membrane distillation system includes a second heat transfer area between the condensing stream and the cold process stream. In use, the second heat transfer area facilitates transfer of a quantity of heat energy from the condensing stream to the cold process stream.

[0015] A second aspect of the present invention provides a membrane distillation apparatus that includes a vapourising stream comprising a mixture of components, a condensing stream, and a membrane located between the vapourising stream and the condensing stream. The vapourising stream and condensing stream are in fluid communication through the membrane. The membrane facilitates transfer of at least one volatised component of the vapourising stream into the condensing stream. The system also includes a hot process stream. A first heat transfer area is also provided between the hot process stream and the vapourising stream. In use, the first heat transfer area facilitates transfer of a quantity of heat energy from the hot process stream to the vapourising stream to heat the vapourising stream. The system also includes a cold process stream. The hot and cold process streams can be part of or fluidly linked to a co-located or generally proximate industrial process, and in some cases part of the same co-located or generally proximate industrial

process. More preferably, the hot and cold process streams are internal process streams of an industrial process or plant which are utilised for internal heat recycling for in that process or plant. A second heat transfer area is provided between the condensing stream and the cold process stream. In use, the second heat transfer area facilitates transfer of a quantity of heat energy from the condensing stream to the cold process stream to produce a heated cold process stream. Furthermore, the hot process stream and cold process stream are fluidly separate to the vapourising stream and the condensing stream.

[0016] The present invention results from the realisation that membrane distillation processes can be coupled with heat exchange functionality to provide a duel energy saving benefit for a chemical/industrial process. The system and apparatus of the present invention form a heat exchanger which transfers energy from the hot process stream to the cold process stream of a co-located or generally proximate industrial process, and more preferably heating and cooling the hot and cold process streams utilising internal heat recycling for a plant. The system and apparatus also utilizes energy in hot process streams of a co-located or generally proximate industrial process to heat the vapourising fluid of a membrane distillation apparatus. The energy transferred between these streams can be significant compared to heat exhausted from the process (waste heat), which can become a substantial energy source for membrane distillation.

[0017] In a preferred embodiment, the system and apparatus utilizes energy in hot process streams of a single industrial plant or process to heat the vapourising fluid of a membrane distillation apparatus, preferably hot and cold process streams utilising internal heat recycling for a plant. In this respect, the process of the present application can be utilised in industrial plants and process in which cogeneration is not possible. The present invention can be installed between any process streams of different heat value, where it is apparent this heat is of value within the process as opposed to simply needing to get rid of it to a sink of little concern to the operation of the plant or process. The applicability of the present invention spans to many more industries than

just simply 'thermal' plants, such as is for example is covered by the MD arrangement discussed in Kullab and Martin.

[0018] This is a different view to conventional energy efficiency considerations for membrane distillation which focuses on membrane distillation sourcing heat from waste sources or from combusted fuels reduce and in some forms substantially avoid the use of additional heat in the plant's overall operations and thus can reduce the overall energy burden in that process and plant.

[0019] The present invention also increases the benefit of internal fluid treatment within an industrial process. Process streams within a co-located or generally proximate industrial process can be treated using membrane distillation to improve their value in applications such as water reuse or product refinement.

[0020] It should be understood that hot process stream refers to a process stream that has a temperature differential relative to the vapourising stream and the condensing stream, where the hot process stream is at a higher temperature than the vapourising stream and the condensing stream. Similarly, the cold process stream refers to a process stream that has a temperature differential relative to the vapourising stream and the condensing stream, where the cold process stream is at a lower temperature than the vapourising stream and the condensing stream. In those embodiments that have a hot stream and a cold stream, it should be understood that the hot stream is at a higher temperature than the cold stream. The exact temperatures and temperature differential is dependent on the vaporisation temperature desirable for the vapourising stream and the condensation temperature of the condensing stream. It should be appreciated that a large number of temperature differentials are therefore possible within the scope of the present invention.

[0021] The system and apparatus of the present invention acts as a heat exchanger and heat a cold process stream using energy from the hot process stream. The membrane distillation apparatus harnesses work as it internally transfers energy from the hot process stream (heat source) to the cold process

stream (heat sink). In use, a quantity of heat energy can be transferred from the hot process stream to the cold process stream to heat the cold process stream. This quantity of heat energy is preferably transferred through the first heat transfer area, through the membrane and through the second heat transfer area. It should be appreciated that the membrane transfers latent and sensible heat from the vapourising stream to the condensing stream.

[0022] This form of the membrane distillation system can be conceptually viewed as a heat exchanger which includes a membrane distillation apparatus in which the vapourising stream, the condensing stream and the membrane are located. The hot process stream and cold process stream form the two process flows flowing into the heat exchanger across which latent and sensible heat is transferred.

[0023] The present invention can incorporate any conventional Membrane Distillation apparatus or system including (but not limited to) Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweep Gas Membrane Distillation (SGMD) or Vacuum Membrane Distillation (VMD). These systems all require a heat source and sink.

[0024] The membrane in the system and apparatus of the present invention acts as a physical barrier between the vapourising and condensing streams which only allows the transport of vapour from the heat vapourising stream to the cooled condensing stream. The membrane is preferably substantially hydrophobic, and more preferably nonwetting and microporous. Suitable membranes include ethylene chlorotrifluoroethylene (Halar), polytetrafluoroethylene (PTFE), polypropylene (PP), polyethylene (PE), or poly(vinylidene fluoride) (PVDF) based membranes. The membranes can have any suitable configuration including hollow fibre membranes, sheet, tubular, plate, mat types or the like. The system also extends to inorganic (including ceramic) membranes, as well as those inorganic and polymeric membranes with a selective ability (i.e. pervaporation membranes).

[0025] The heat exchanger system and membrane distillation apparatus may also include a heat recovery system which facilitates transfer of a quantity of heat energy from the heated cold process stream to the vapourising stream. In some embodiments, the heat recovery system is a preheater which precedes the first heat transfer area.

[0026] The first heat transfer area and/or second heat transfer area may comprise a heat exchanger. Various heat exchangers are possible, including but not limited to a shell and tube heat exchanger, plate heat exchanger, adiabatic heat exchanger, plate heat exchanger, fin heat exchanger, pillow plate heat exchanger, fluid heat exchangers, waste heat recovery units, dynamic scraped surface heat exchanger, phase-change heat exchangers, direct contact heat exchangers, HVAC air coils, or spiral heat exchangers. In preferred forms, at least one or each of the first heat transfer area or second heat transfer area comprises a plate heat exchanger.

[0027] The first and second heat transfer areas may be housed in a separate process vessel or apparatus to a process vessel that includes the membrane. For example, the first and second heat transfer areas may be housed in a separate heat exchanger. In other embodiments, the first and second heat transfer area may be housed in the same process vessel or apparatus which includes the membrane. Preferably, the first heat transfer area is located generally proximate the membrane. Similarly, the second heat transfer area is preferably located generally proximate the membrane. Typically each of the first and second heat transfer areas would be co-located with the membrane in a process vessel. In these embodiments, heat is transferred between the hot process stream and the vapourising stream and/or between the condensing stream and the cold process stream substantially simultaneously when the vapourising stream and condensing stream contacts the membrane.

[0028] The heat exchanger system and membrane distillation apparatus of the present invention preferably utilises waste heat sources in a co-located or generally proximate process (as opposed to valuable sources) to heat the vapourising stream to drive separation of the components in the vapourising

stream. For example, in one embodiment the hot process stream and/or cold process stream are process streams of a dairy processing plant. For example, the hot process stream may be a whey process stream. Furthermore, the vapourising stream may be a water stream, a waste water stream which is treated, and in some cases substantially purified, when the vaporised water component of that waste water stream passes through the membrane. In some embodiments, the vapourising stream may be a water or liquid stream which undergoes concentration through the vaporization of a component.

[0029] The hot process stream and cold process stream are preferably process streams which are respectively cooled and heated in the co-located or generally proximate process. The desired temperature of each of these streams would typically be utilised in a heat exchanger to obtain the desired temperature. The membrane system of the present invention could be used in this heat exchanger to provide additional fluid treatment benefits to process fluids, for example process water, in that process. Preferably, the hot process stream and cold process streams of the heat exchanger system are fluidly separate to the vapourising stream and the condensing stream.

[0030] The membrane distillation apparatus of the present invention is preferably constructed as a module.

Brief Description of the Drawings

[0031] The present invention will now be described with reference to the figures of the accompanying drawings, which illustrate particular preferred embodiments of the present invention, wherein:

[0032] Figure 1 is a broad schematic representation of a heat exchanger system according to one embodiment of the present invention.

[0033] Figure 2 is a process flow diagram illustrating a heat exchanger system according to one embodiment of the present invention which includes a Direct Contact Membrane Distillation system.

[0034] Figure 3 shows the general configuration of a modified Direct Contact Membrane Distillation system including a direct heat exchange system according to one embodiment of the present invention.

[0035] Figure 4 shows a prototype membrane distillation heat exchanger (MDHX) constructed in accordance with one embodiment of the present invention.

[0036] Figure 5 provides experimental data from the prototype membrane distillation heat exchange system (MDHX) module shown in Figure 4 compared to experimental data from a conventional Membrane Distillation system.

[0037] Figure 6 shows a conventional (prior art) MD system in direct contact mode.

[0038] Figure 7 shows the general configuration of a membrane distillation heat exchange system according to one embodiment of the present invention in a process configuration to reduce pump electricity requirements

Detailed Description

[0039] Figures 1 to 3 illustrate a new process system 10, hereinafter referred to as a membrane distillation heat exchanger (MDHX) that operates as a heat exchanger in the process industry, and utilizes the exchange of heat to treat a separate process stream (vapourising stream 12 in Figures 1 to 3) to improve the value of that stream for other uses. For example, that stream 12 could be a process water stream which is purified for reuse or product development or could be a process stream which is purified or concentrated for reuse or product development.

[0040] As best shown in Figure 1, the membrane distillation heat exchanger 10 includes a hot process stream 14 fluidly connected to an industrial process (not shown), a cold process stream 16 fluidly connected to an industrial process (not shown), preferably the same industrial process as the hot process stream 14,

and a membrane distillation system 18. The membrane distillation system 18 includes a vapourising stream 12, in this case used process water, a condensing stream 20 that comprises purified water, a reject stream 22 that comprises concentrated contaminated water, and a membrane (not shown in Figure 1, but component 30 in Figures 2 and 3) located between the vapourising stream 12, reject stream 22 and the condensing stream 20. The hot process stream 14 and cold process stream 16 are fluidly separate to the vapourising stream 12 and the condensing stream 20.

[0041] The vapourising stream 12, and reject stream 22 are located on one side of the membrane 30 and the condensing stream 20 is on the other side of the membrane. The vapourising stream 12 and condensing stream 20 are in fluid communication through the membrane 30. The membrane 30 facilitates transfer of volatised water of the vapourising stream 12 into the condensing stream 20, thereby purifying that water. The remaining water in the vapourising stream 12 which is not evaporated in the membrane distillation system 18 and transported through the membrane 30 exits the membrane distillation system 18 via the reject stream 22 a concentrated contaminated water product.

[0042] It should be appreciated that the membrane distillation heat exchanger 10 can also concentrating a vapourising stream 12, for example a product stream such as producing a protein-concentrate of high value. In this embodiment, the reject stream 22 would comprise the concentrated high value product.

[0043] The membrane distillation heat exchanger 10 also includes a first heat transfer area 24 between the hot process stream 14 and the vapourising stream 12. In use, the first heat transfer area 24 facilitates the transfer of a quantity of heat energy from the hot process stream 14 to the vapourising stream 12 to heat the vapourising stream 12 to a temperature in which the partial pressure of volatised water is sufficient in the vapourising stream 12 to pass through the membrane. The membrane distillation heat exchanger 10 also includes a second heat transfer area 26 between the condensing stream 20 and the cold process stream 16. In use, the second heat transfer area 26 facilitates transfer

of a quantity of heat energy from the condensing stream 20 to the cold process stream 16. This cools the condensing stream 20, which is heated through latent and sensible heat transfer from the vapourising stream 12 through the membrane 30, and also heats the cold process stream 16.

[0044] The hot process stream 14 and cold process stream 16 preferably comprise process streams which are respectively cooled and heated in the co-located or generally proximate industrial process. In alternative embodiments (not illustrated), the cold process stream 16 could be replaced with a coolant stream or other heat sink without departing from the scope of the present invention. Nevertheless, it should be appreciated that optimal energy utilisation for an industrial process would be gained by using a cold process stream 16 from that industrial process.

[0045] The membrane 30 used in the membrane distillation system 18 is a nonwetting and microporous membrane. One or more membranes can be used to perform the separation function described above. Suitable membranes 30 include ethylene chlorotrifluoroethylene (Halar), polytetrafluoroethylene (PTFE), polypropylene (PP), polyethylene (PE), or poly(vinylidene fluoride) (PVDF) based membranes. The membrane or membranes 30 can have any suitable configuration including hollow fibre membranes, sheet, tubular, plate, mat types or the like.

[0046] The first heat transfer area 24 and second heat transfer area 26 are configured to transfer heat between the respective process streams 12, 14, 16, 20. In some embodiments, for example as shown in Figure 2, each of the first heat transfer area 24 and second heat transfer area 26 is a heat exchanger. Various heat exchangers are possible such as shell and tube heat exchangers, plate heat exchangers or the like.

[0047] Figure 2 shows one form of the membrane distillation heat exchanger 10A according to the present invention which includes a separate membrane distillation apparatus module 18 in which the vapourising stream 12, the condensing stream 20, reject stream 22 and the membrane 30 are housed.

The hot process stream 14 (inlet), 14A (exit) and cold process stream 16 (exit), 16A (inlet) are linked to the vapourising stream 12 and condensing streams 20 of that module 18 through individual heat exchangers 24, 26. A feed stream 12A, such as water to be purified or the like, is feed into the system, and a treated water stream 20A is discharged.

[0048] This membrane distillation system 10A also includes a heat recovery system in the form of a preheater 32 (shown split into two components either side of the membrane module) which facilitates transfer of quantity of heat energy from the heated cold process stream 20 to the vapourising stream 12 via the heat path 36.

[0049] The heat exchanger 26 includes a heat sink which typically comprises the cool process stream which flows through the heat exchanger 26 (via inlet stream 16A and exits as a heated stream 16) but can in some embodiments include an additional heat sink source.

[0050] The membrane module 18 for the MDHX system 10A shown in Figure 2 can be any of the conventional membrane distillation modules currently available on the market. The present invention can incorporate any conventional membrane distillation apparatus or system including (but not limited to) Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweep Gas Membrane Distillation (SGMD) or Vacuum Membrane Distillation (VMD).

[0051] Figure 3 shows a further embodiment of the membrane distillation system 10B according to the present invention in which the design of conventional membrane distillation system has been modified to increase the heat transfer efficiency of the membrane distillation heat exchanger 10B. Here, the first and second heat transfer areas 24 and 26 are proximate and parallel to the membrane 30 co-locating each of these heat transfer areas 24, 26 with the membrane in the module. Heat is transferred between the hot process stream 14 and the vapourising stream 12 and between the condensing stream 20 and the cold process stream 16 when the vapourising stream 12 and condensing

stream 20 contacts the membrane 30. It should be appreciated that the various process streams may flow in counter current, co current or cross flow configuration to achieve this heat transfer.

[0052] While not wishing to be limited to any one theory, the Applicant considers that the performance of a membrane distillation process substantially depends on the distribution of heat over the surface area of the entire membrane. In the conventional membrane distillation module designs, heat is added to the vapourising stream prior to entering the module. The Membrane Distillation Effect (evaporation on the hot side, condensation on the cold side and sensible heat conduction) inside the module thus has declining temperature profile over the length of the membrane and a reduced efficiency. This is because the hot cycle temperature drops while passing along the membrane, likewise the cold side temperature increases. The result is a reduction in the driving force across the membrane. As shown in the membrane distillation system 10B illustrated in Figure 3, adding the heat directly to the vapourising stream 12 within the module 10B adjacent the membrane 30, and likewise removing heat from the condensing stream 20 within the module 10B adjacent the membrane 30 can reduce this problem in a way that temperature decline along the membrane in the vapourising stream 12 and condensing stream 20 is reduced or substantially eliminated, thereby increasing the membrane's total area driving force.

[0053] The membrane distillation system 10B in Figure 3 includes a DCMD configuration. It is to be understood that this modification would equally apply in AGMD configurations and may be incorporated into SGMD and VMD configurations. It should be appreciated that SGMD and VMD designs would need to accommodate a condensing unit needed for these systems.

Examples

Example 1 – Dairy Process Integration

[0054] In a dairy process, whey is routinely cooled from 45ºC to around 30ºC by a heat exchanger coupled to the incoming milk stream which heats this stream up from 6 ºC to about 27 ºC. In this example, the heat transferred is about 2300 kW.

[0055] The heat transferred in this operation can be passed through a MDHX system according to the present invention. Assuming an energy demand of Membrane Distillation (MD) of 100 kWh per m^3 of water recovered, the dairy example transferring 2300 kW of heat translates to a water recovery capacity by a MDHX system according to the present invention of 23 m^3/hour. In the same plant, this treatment capacity is enough to treat all the water required for cleaning in place procedures. Alternatively, this energy could also be used for concentration purposes instead of or additionally to water recovery.

Example 2 – Bench Scale Results

[0056] A MDHX module prototype was constructed, and is illustrated in Figure 4. The hot heat exchange (HE) ports (Hot_{in} and Hot_{out}) and feed membrane distillation (MD) ports ($Feed_{in}$ and $Feed_{out}$) are indicated in Figure 4. It should be appreciated that the cold heat exchange and membrane distillation permeate ports are located on a side of the module that is not visible in Figure 4. There are a total of eight ports on this prototype MDHX.

[0057] An experiment was set up using the prototype MDHX shown in Figure 4. In the experiment, the prototype MDHX was operated as a normal membrane distillation module, without the use of the heat exchange section and heat exchange ports. The same conditions were then used running the prototype MDHX with the heat exchange section operating. The flow rate fed to the MD feed and permeate sides were varied for both a normal MD and the MDHX setup.

[0058] Figure 5 provides experimental data from a prototype MDHX module compared to conventional Membrane Distillation system. Performance expressed as single pass recovery linked to MD channel flow rates.

[0059] The effect to the flux, expressed in terms of single pass recovery (or the ratio of the permeate flow over the feed flow) is shown in Figure 5. HX channel conditions were kept at 55 ˚C on the hot side (Hot_{in} and Hot_{out}), 5 ˚C into the cold side ($Cold_{in}$ and $Cold_{out}$) and flow was kept at 800 ml/min (0.13 m/s linear velocity). Here, for this prototype MDHX, flow rates higher than 200 mL/min

yield similar performance to the MD-only system, but as the flow rate decreases, there is a great increase in the single pass recovery (at least 7-fold measured experimentally) because lost temperature in the MD hot channel is topped up by the HX hot channel. Likewise, the heat is removed from the MD permeate side by the HX cold channel ensuring effective temperature drop (i.e. driving force) across the membrane at low feed flows. The advantage of increased single pass recovery translates to lower recirculation to achieve full recovery (i.e. reduced multiple passes) which leads to less pumping requirement, thus less electricity for the same amount of treated water.

[0060] Figure 5 also shows that the temperature conditions in the channels labelled on the MD channel insert diagrams. Under normal MD mode, the 45°C $Feed_{in}$ stream drops to 39°C ($Feed_{out}$). This drop is due to sensible heat transfer from conduction as well as latent heat transfer from membrane flux. This heat is transferred to the MD permeate stream causing it to rise to 33°C from 10°C. There is an improvement by the MDHX system in the same temperature profiles where the MD feed stream now only drops to 39°C, and likewise the MD permeate stream rises only to 24°C. This is because of the HX hot and cold sides adding and removing heat from the MD feed and permeate sides respectively. Thus, for the same flow rate, there is a greater driving force across the membrane, leading to higher flux and thus higher single pass recovery.

Example 3 - Reduction in electrical energy required

[0061] A conventional membrane distillation (MD) system shown in Figure 6 was operated as a comparison to a membrane distillation heat exchange (HXMD) system according to the present invention shown in Figure 7.

[0062] In operating the MD system shown in Figure 6, raw solution to be treated by MD enters at 'MD feed' 100, then enters a warm recirculation loop 102 pumped by pump 'P01'. The solution in the cycle 102 is heated by heat exchanger 'HX01' where heat energy is added via $Q_{EXTHX,in}$ 104, in this case an external heat source, such as a heating coil. The solution then passes into the MD module 110 where some treated permeate is removed from the cycle 102 via the membrane 112 in a single pass after which it then exits the module 110.

A portion of retentate is drawn from module exit stream 106 into a reject stream 108, while the remaining majority returns to the entrance of P01 via recycle stream 109. The permeate that was treated via the membrane is now in the cooler permeate loop 120 where it is drawn by pump P02 through exit stream 122, then flows to the heat exchanger HX02 which cools the loop according to heat removed $Q_{EXTHX,out}$ 124. A portion of clean permeate is removed from stream 126, in discharge stream 128 which becomes product water, while the rest is returned to the module 110 via feed stream 129 to continue the permeate loop 120.

[0063] It is typically found that due to thermodynamic restrictions, a single pass in a normal MD module can take no more than ~2% of the flow entering the module (Figure 6). This is highly unfavourable for a typical desalination process which aims to recover 50% to 90% (and more) of the water feed to the system. In order to achieve this via MD, the water must be recirculated by more than 30 times to achieve a practical recovery of feed water. This leads to sufficiently large pumps P01 and P02 which consume electricity thus defeating the potential for MD as a low-energy process.

[0064] The Applicant has found that a HXMD module according to the present invention can be set up to reduce pumping requirements, as shown in Figure 7.

[0065] This setup has the same general configuration as the MD system in Figure 6 with the inclusion of non-fluid connected heating feed source 130 and cooling feed source 132 connected directly to the HXMD module 110A. It should be noted that similar features in Figure 7 to the MD module in Figure 6 have been given the same reference numeral plus an “A” reference. The inclusion of non-fluid connected heating feed source 130 and cooling feed source 132 transfers the heating duty from HX01A and HX02A to the external heating/cooling fluids. It is feasible that HX01A and HX02A be removed completely.

[0066] Using the experimental data from Figure 5 where 14% single pass recovery was achieved, the results in Table 1 demonstrate that an 86% reduction in the electricity required for pumps P01A and P02A for the HXMD

system shown in Figure 7 can be achieved in comparison to a conventional MD system shown in Figure 6. The key assumption in this example is the use of an identical flux for both MD and HXMD to ensure the same overall process is compared. It was assumed that the pump works against the heat exchangers and module channels to a pressure drop of 20 kPa, which is typical in the Applicant's experience with MD modules. It was assumed both pumps circulate at the same rate.

Table 1: input parameters and performance results of MD and HXMD systems

Parameter	Units	MD	HXMD
Flux	mL/min	2.8	2.8
Feed flow	mL/min	140	20
Pump pressure	kPa	20	20
Pump efficiency	%	80	80
Pump shaft power	mW	56	8.1
Total pump electricity	mW	113	16
Specific electric requirement	kWh/m^3	0.67	0.096
Electricity reduction	%	----	86

[0067] We see in Table 1, that the specific electric requirement of MD is lower (0.67 kWh/m^3), but still relatively high compared to state of the art desalination plants which use around 3 kWh of electricity for every cubic meter of fresh water produced (i.e. 3 kWh/m^3). HXMD improves the conventional MD specific electric requirement to <0.1 kWh/m^3. This example alone demonstrates a viable means for HXMD to harness heat, for example from waste industry sources or in conventional process heat exchange, to produce a treated process water with minimal electricity requirement. A reduced electric requirement means, for example, less greenhouse gas emissions associated with the electricity production.

[0068] Those skilled in the art will appreciate that the invention described herein is susceptible to variations and modifications other than those specifically described. It is understood that the invention includes all such variations and modifications which fall within the spirit and scope of the present invention.

[0069] Where the terms "comprise", "comprises", "comprised" or "comprising" are used in this specification (including the claims) they are to be interpreted as specifying the presence of the stated features, integers, steps or components,

but not precluding the presence of one or more other feature, integer, step, component or group thereof.

Claims:

1. A heat exchanger including:

a hot process stream fluidly connected to an industrial process;

a cold process stream fluidly connected to an industrial process; and

a membrane distillation system including:

a vapourising stream comprising a mixture of components;

a condensing stream;

a membrane located between the vapourising stream and the condensing stream, the vapourising stream and condensing stream being in fluid communication through the membrane, the membrane facilitating transfer of at least one volatised component of the vapourising stream into the condensing stream;

a first heat transfer area between the hot process stream and the vapourising stream which, in use, facilitates the transfer of a quantity of heat energy from the hot process stream to the vapourising stream to heat the vapourising stream; and

a second heat transfer area between the condensing stream and the cold process stream which, in use, facilitates transfer of a quantity of heat energy from the condensing stream to the cold process stream.

2. A heat exchanger according to claim 1, wherein in use, a quantity of heat energy is transferred from the hot process stream to the cold process stream to heat the cold process stream.

3. A heat exchanger according to claim 2, wherein said quantity of heat energy is transferred through the first heat transfer area, the membrane and the second heat transfer area.

4. A heat exchanger according to any preceding claim, wherein the hot process stream and cold process stream are fluidly separate to the vapourising stream and the condensing stream.

5. A heat exchanger according to any preceding claim, wherein the membrane distillation system includes at least one of a Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweep Gas Membrane Distillation (SGMD) or Vacuum Membrane Distillation (VMD) system.

6. A heat exchanger according to any preceding claim, further including a heat recovery system which facilitates transfer of a quantity of heat energy from the heated cold process stream to the vapourising stream.

7. A heat exchanger according to claim 6, wherein the heat recovery system is a preheater.

8. A heat exchanger according to any preceding claim, wherein at least one of the first heat transfer area or second heat transfer area comprises a heat exchanger.

9. A heat exchanger according to claim 8, wherein at least one of the first heat transfer area or second heat transfer area comprises a plate heat exchanger.

10. A heat exchanger according to any preceding claim, wherein the first heat transfer area is generally proximate the membrane such than in use, heat is transferred between the hot process stream and the vapourising stream when the vapourising stream contacts the membrane.

11. A heat exchanger according to any preceding claim, wherein the second heat transfer area is generally proximate the membrane such than in use, heat is transferred between the condensing stream and the cold process stream when the condensing stream contacts the membrane.

12. A heat exchanger according to any preceding claim, wherein the membrane is a nonwetting microporous membrane.

13. A heat exchanger according to any preceding claim, wherein the hot process stream and cold process stream are process streams which are respectively cooled and heated in the co-located or generally proximate process.

14. A heat exchanger according to any preceding claim, wherein the hot and cold process streams are internal process streams of an industrial process or plant which are utilised for internal heat recycling for in that process or plant.

15. A heat exchanger according to any preceding claim, wherein the hot process stream is a waste heat source in the co-located or generally proximate process.

16. A heat exchanger according to any preceding claim, wherein at least one of the hot process stream or cold process stream is a process stream of a dairy processing plant.

17. A heat exchanger according to claim 16, wherein the hot process stream comprises a whey process stream.

18. A heat exchanger according to any preceding claim, wherein the vapourising stream comprises a water stream, preferably a waste water stream which is treated, preferably substantially purified, when passed through the membrane.

19. A membrane distillation apparatus including:

a vapourising stream comprising a mixture of components;

a condensing stream;

a membrane located between the vapourising stream and the condensing stream, the vapourising stream and condensing stream being in fluid communication through the membrane, the membrane facilitating transfer of at least one volatised component of the vapourising stream into the condensing stream;

a hot process stream;

a first heat transfer area between the hot process stream and the vapourising stream which in use facilitates the transfer of a quantity of heat energy from the hot process stream to the vapourising stream to heat the vapourising stream;

a cold process stream; and

a second heat transfer area between the condensing stream and the cold process stream which in use, facilitates transfer of a quantity of heat energy from the condensing stream to the cold process stream to produce a heated cold process stream,

wherein the hot process stream and cold process stream are fluidly separate to the vapourising stream and the condensing stream.

20. A membrane distillation apparatus according to claim 19, wherein in use, a quantity of heat energy is transferred from the hot process stream to the cold process stream to heat the cold process stream.

21. A membrane distillation apparatus according to claim 20, wherein said quantity of heat energy is transferred through the first heat transfer area, the membrane and the second heat transfer area.

22. A membrane distillation apparatus according to any one of claims 20 or 21, which includes at least one of a Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweep Gas Membrane Distillation (SGMD) or Vacuum Membrane Distillation (VMD) system.

23. A membrane distillation apparatus according to any one of claims 20 to 22, further including a heat recovery system which facilitates transfer of a quantity of heat energy from the heated cold process stream to the vapourising stream.

24. A membrane distillation apparatus according to claim 23, wherein the heat recovery system is a preheater.

25. A membrane distillation apparatus according to any one of claims 20 to 24, wherein at least one of the first heat transfer area or second heat transfer area comprises a heat exchanger.

26. A membrane distillation apparatus according to claim 25, wherein at least one of the first heat transfer area or second heat transfer area comprises a plate heat exchanger.

27. A membrane distillation apparatus according to any one of claims 20 to 26, wherein the first heat transfer area is generally proximate the membrane such than in use, heat is transferred between the hot process stream and the vapourising stream when the vapourising stream contacts the membrane.

28. A membrane distillation apparatus according to any one of claims 20 to 27, wherein the second heat transfer area is generally proximate the membrane such than in use, heat is transferred between the condensing stream and the cold process stream when the condensing stream contacts the membrane.

29. A membrane distillation apparatus according to any one of claims 20 to 28, wherein the membrane is a nonwetting microporous membrane.

30. A membrane distillation apparatus according to any one of claims 20 to 29, wherein the hot process stream and cold process stream are process streams which are respectively cooled and heated in a co-located or generally proximate process.

31. A membrane distillation apparatus according to any one of claims 20 to 30, wherein the hot process stream is a waste heat source in a co-located or generally proximate process.

32. A membrane distillation apparatus according to any one of claims 20 to 30, wherein the hot and cold process streams are internal process streams of an industrial process or plant which are utilised for internal heat recycling for in that process or plant.

33. A membrane distillation apparatus according to any one of claims 20 to 32, wherein at least one of the hot process stream or cold process stream is a process stream of a dairy processing plant.

34. A membrane distillation apparatus according to claim 33, wherein the hot process stream comprises a whey process stream.

35. A membrane distillation apparatus according to any one of claims 20 to 34, wherein the vapourising stream comprises a water stream, preferably a waste water stream which is treated, preferably substantially purified, when passed through the membrane.

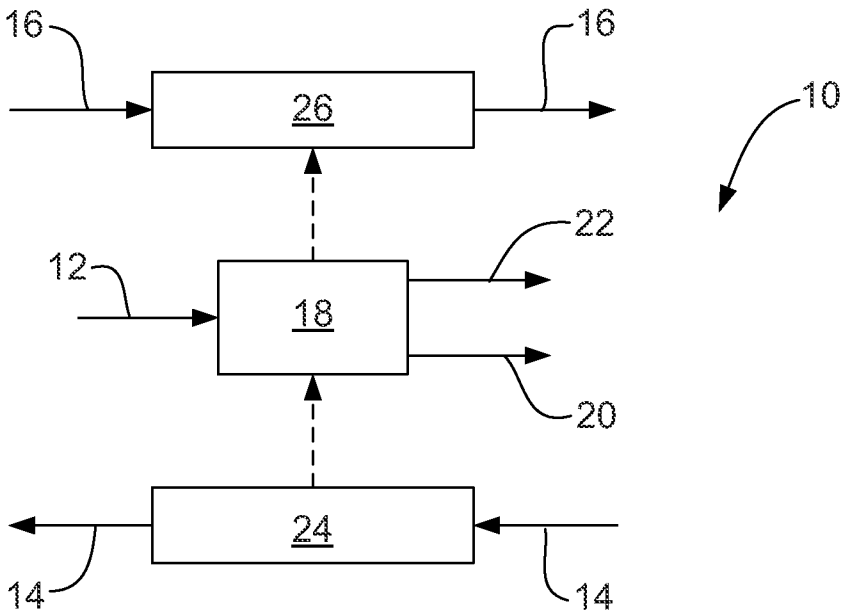


FIG 1

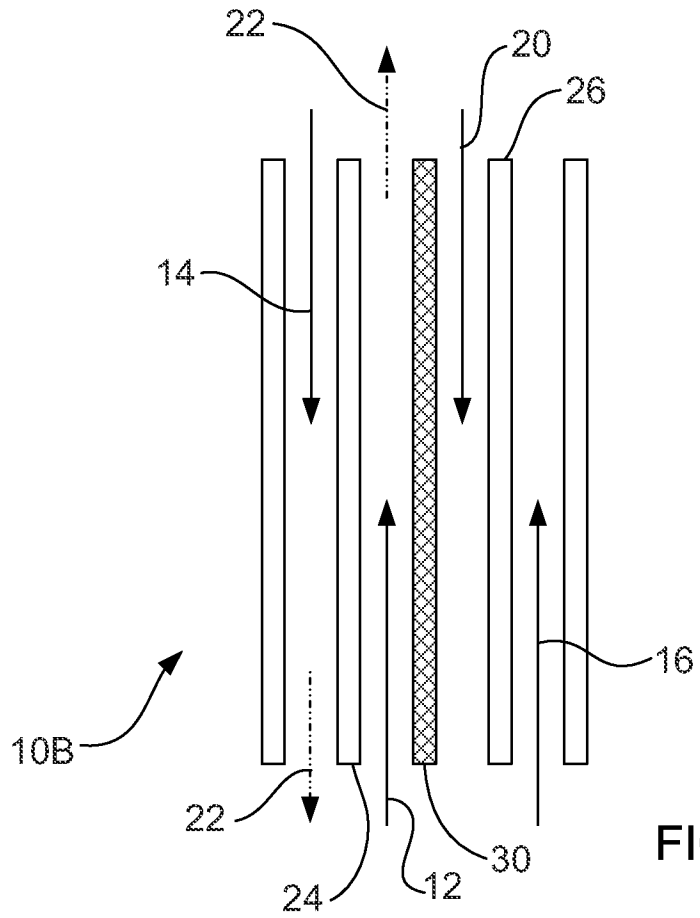
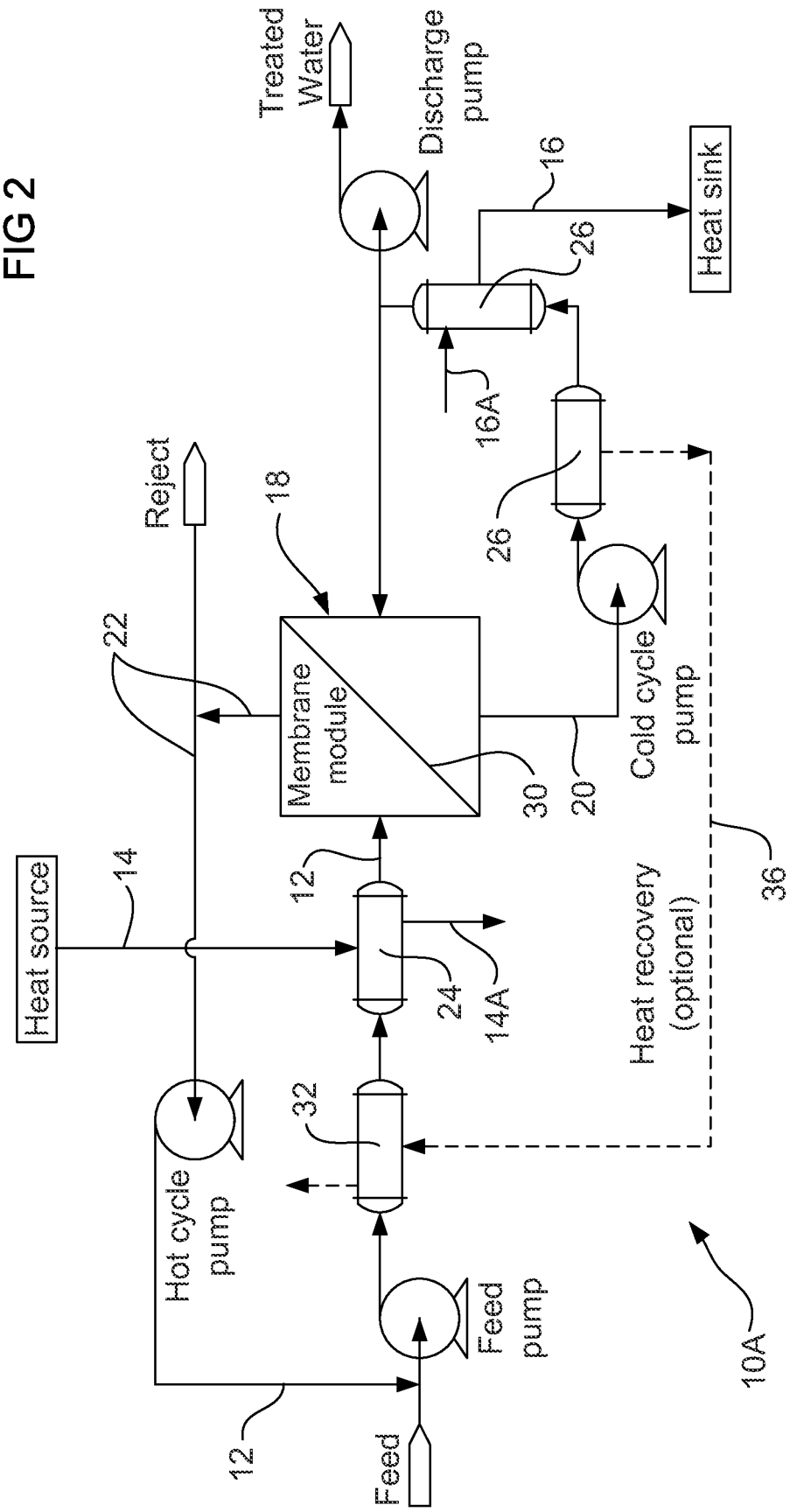
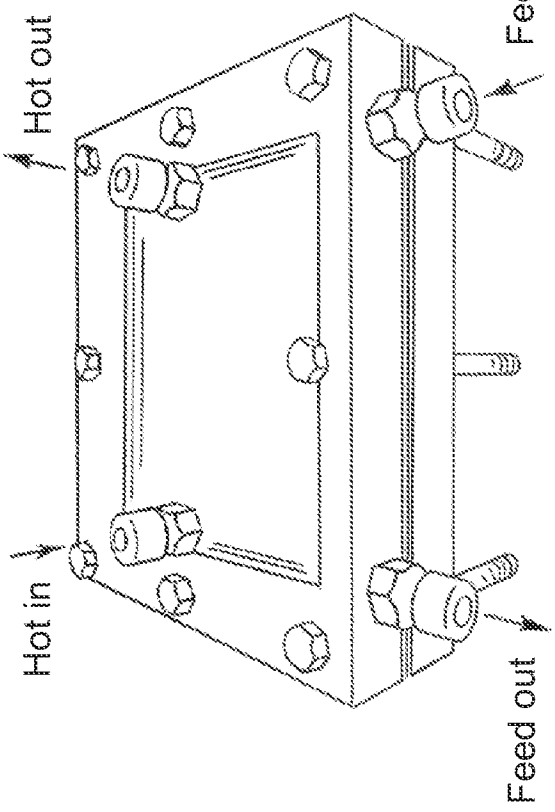
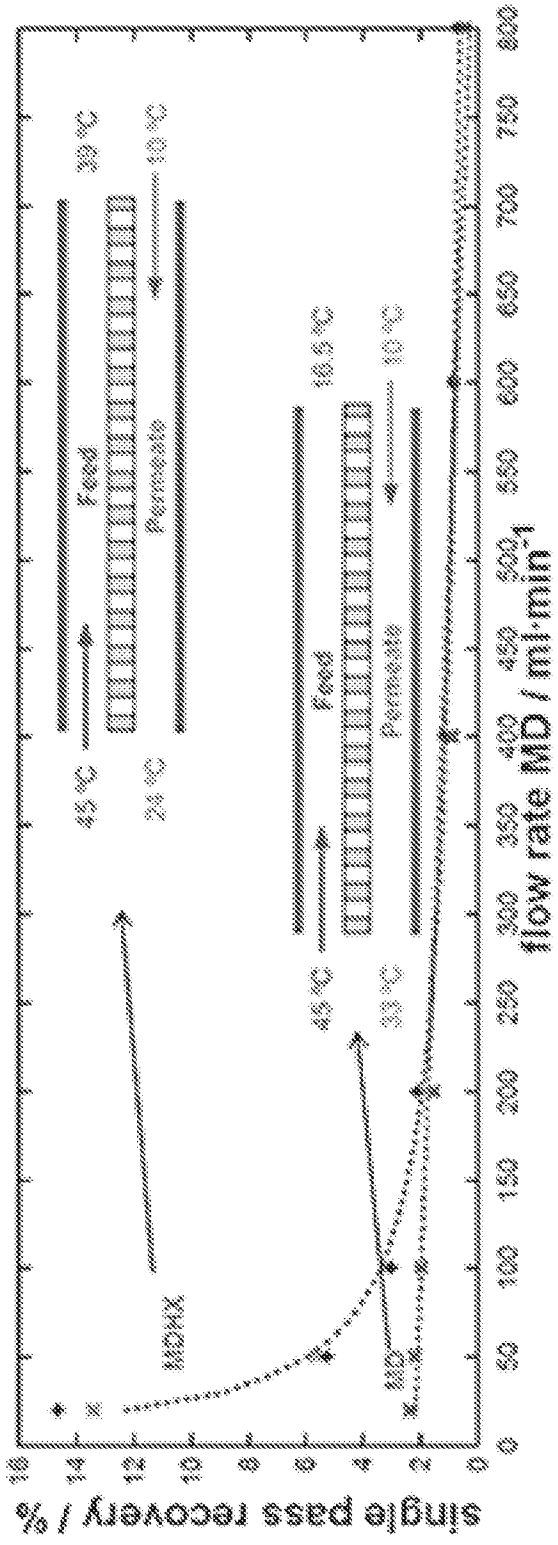


FIG 3

FIG 2


Treated Water
Discharge pump
16
Heat sink
26
16A
26
Reject
18
22
Membrane module
30
20
Cold cycle pump
Heat source
14
12
24
14A
Heat recovery (optional)
36
32
Hot cycle pump
Feed pump
10A
12
Feed


Hot out
Feed in
Hot in
Feed out


single pass recovery / %
flow rate MD / ml·min⁻¹
MD/MX
MD
Feed
Permeate
45 °C
24 °C
20 °C
10 °C
46 °C
38 °C
16.5 °C
10 °C

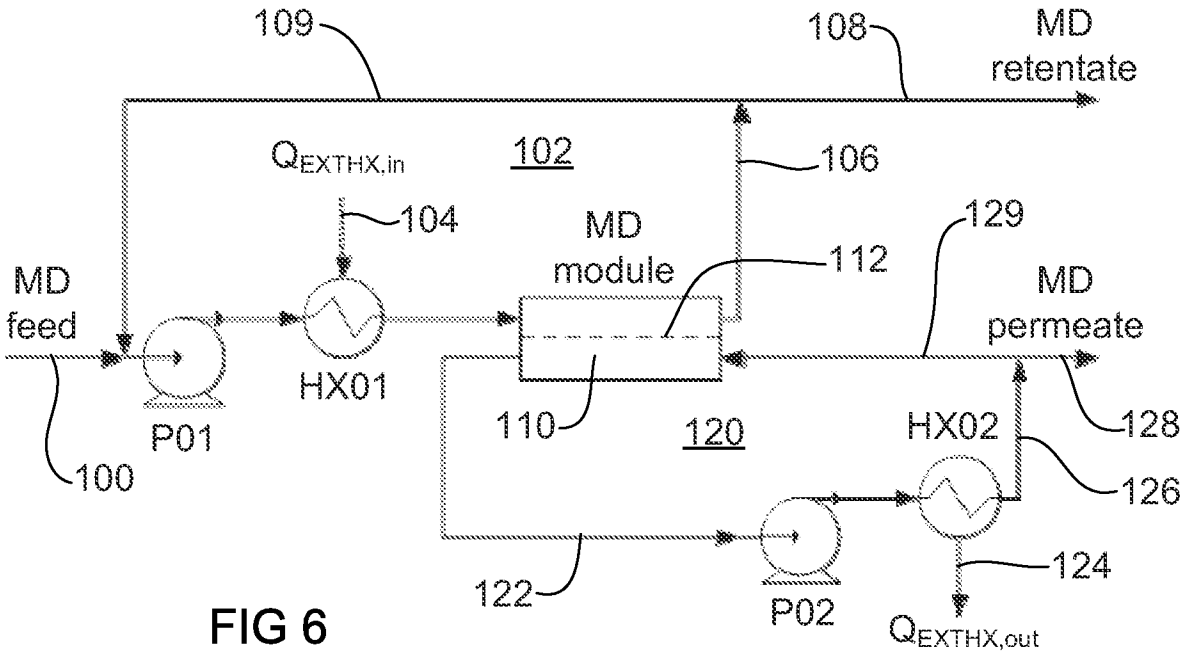

109
108
MD retentate
$Q_{EXTHX,in}$
102
106
104
MD module
112
129
MD feed
MD permeate
HX01
110
120
HX02
128
100
P01
126
122
124
P02
$Q_{EXTHX,out}$

FIG 6

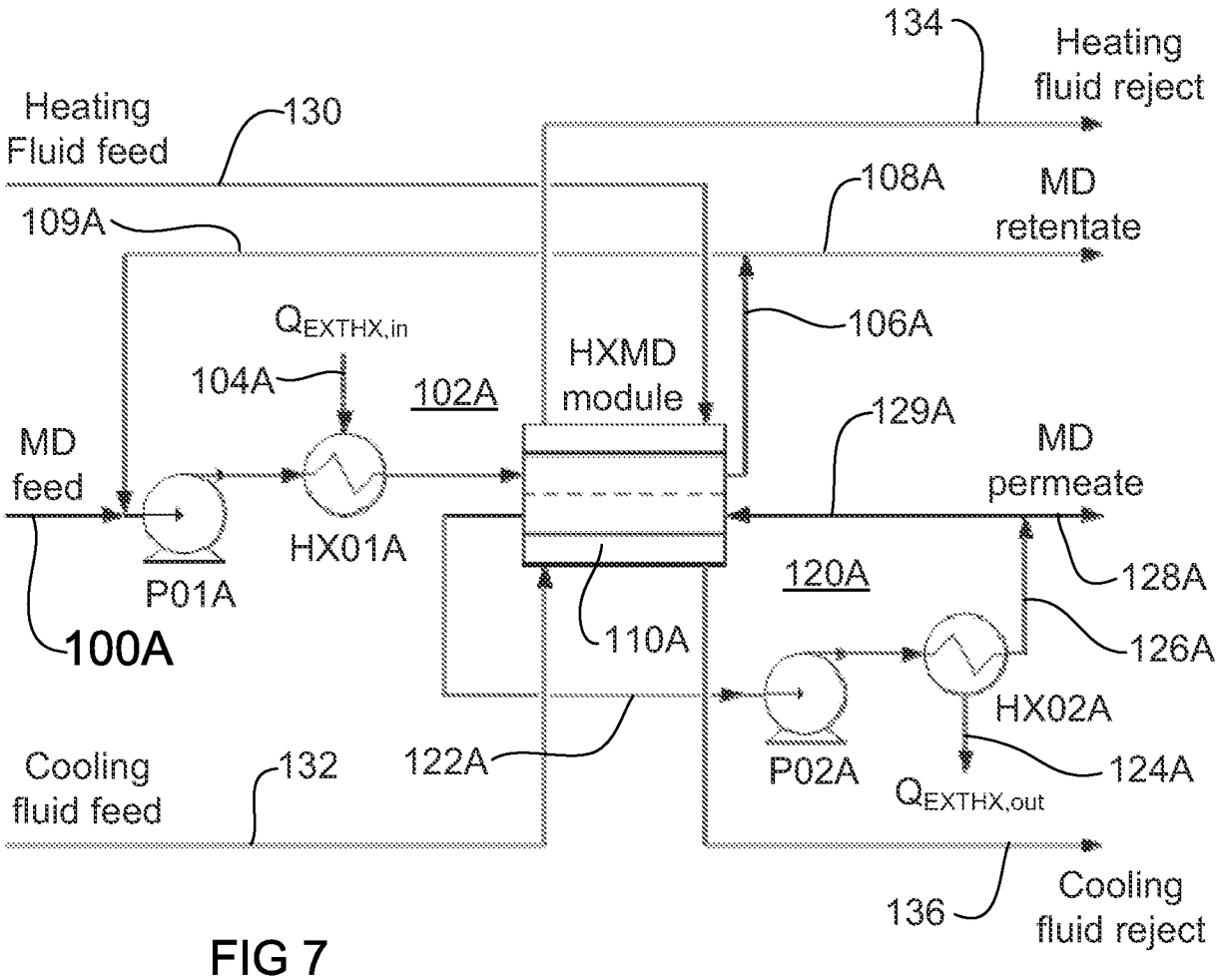

134
Heating fluid reject
Heating Fluid feed
130
108A
MD retentate
109A
$Q_{EXTHX,in}$
106A
HXMD module
104A
102A
129A
MD feed
MD permeate
HX01A
P01A
120A
128A
100A
110A
126A
HX02A
122A
P02A
124A
Cooling fluid feed
132
$Q_{EXTHX,out}$
136
Cooling fluid reject

FIG 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2012/000215

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

B01D 61/36 (2006.01) ***B01D 63/00*** (2006.01) ***F28B 1/00*** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPODOC, WPI with class marks; B01D61/LOW, B01D63/LOW, B01D65/LOW, C02F1/44/LOW, F28B1, F28B3/LOW, F28B5/LOW, F25J/LOW and Keywords: membrane, distill+, pervaporat+, separate+ ,dephlegmat+, condens+, cool+, liquif+, +vapo(u)r+, gas+, volati+, steam+, heat w (exchang+ or transfer+), intergrat+ , combine+ , conservat+ , sav+ , network+, preheat+ and recover+.
USPTO, ESPACENET, GOOGLE Advanced Patent Search, FREEPATENTSONLINE and PATENTLENS with keywords; membrane distillation or pervaporation, vapour, condense, milk or whey or dairy, heat exchange, heat recovery and similar words

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	WO 2010/019751 A1 (SIEMENS WATER TECHNOLOGIES CORP. [US]) 18 February 2010	
X	Fig. 2, page 1: lines 3 -21, from line 3 of page 2 to line 15 of page 3 and page 4: last paragraph	1- 9, 12-15, 18 - 26, 29-32, 35
Y	As above	16 - 17, 33 -34
	WO2010/021545 A1 (NEDERLANDSE ORGANISATIE VOOR TOEGEPAST-NATUURWETENSCHAPPELIJK ONDERZOEK TNO [NL]) 25 February 2010	
X	Figures 1a, 1b & 3, from line 3 of page 4 to line 17 of page 5, and page 6: lines 20-23	1 - 11, 18 -28, 35
Y	As above	16 -17, 33 – 34
	US 2010/0300946 A1 (NGUYEN et al.) 02 December 2010	
Y	Abstract and paragraph [0048]	16 - 17, 33 - 34

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

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

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
0 April 2012	26 April 2012

Name and mailing address of the ISA/AU	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2012/000215

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2004/0211726 A1 (BAIG et al.) 28 October 2004 Abstract, Figs. 9 & 10 and Paragraph [0072]	1 – 35
A	US 2010/0072135 A1 (HANEMAAIJER) 25 March 2010 Abstract, Figs. 1 – 5 and paragraphs [0049] – [0052]	1 – 35
A	JP 62-057611 A (SASAKURA ENG CO LTD) 13 March 1987, English Abstract retrieved from Espacenet. Abstract	1 – 35

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU2012/000215

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
WO	2010019751	AU	2009281935	EP	2313172	US	2011132826
WO	2010021545	CA	2733039	EP	2156880	EP	2331241
		JP	2012500114	US	2011266219		
US	2010300946	AU	2008336259	CA	2708529	CN	101939085
		EP	2234702	WO	2009073921		
US	2004211726	AU	2002312683	CA	2351272	US	7459084
		WO	03000389				
US	2010072135	AU	2007314728	CA	2667758	CN	101600492
		EA	200970430	EP	1925355	EP	2094376
		JP	2010508137	KR	20090094080	MX	2009004559
		NZ	576854	WO	2008054207	ZA	200903124
JP	62057611	NONE					

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX