The Versatility of a Vortex Bubble Distillation Reactor (VBDR)

by
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REHOS Product Designs

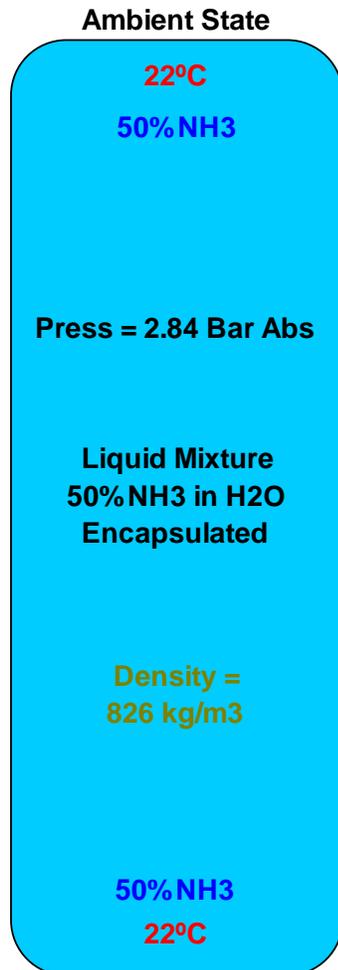## Heidelberg
South Africa

Abstract:

This paper discuss the physics of the absorption heat transformer (AHT) from basic principles for the better understanding of the AHT fabricated for utilization as water chiller, developed jointly as a product for use as de-humidification plant better known as atmospheric water generator (AWG) for a client of ours.

The principles involved were tested on a pilot plant, originally designed for a 20 kW evaporator heatload, but actual heat absorption ~ 50 kW built and tested in various states of completion at the client's premises in Cape Town, South Africa over the time period September 2019 - May 2020.

From testing results, further research and practical considerations layouts of the prototype for any new REHOS device, whether it is an AHT chiller like figure 8, a small cheap RAW-Pump like figure 9, or several MWe utility-scale heat recovery power generator with modular, pre-fabricated containerized REHOS Autarkic Power (RAP-Generators) are presented.

1.) Characteristics of a Zeotropic Binary Liquid Mixture enclosed (encapsulated) in a Vertical Column

Figure 1

Ambient State

22ºC

50%NH3

Press = 2.84 Bar Abs

**Liquid Mixture
50%NH3 in H2O
Encapsulated**

**Density =
826 kg/m3**

50%NH3

22ºC

A binary mixture is said to be zeotropic if the two chemicals in the mixture boil at different temperatures. The two chemicals can therefore easily be separated with the addition of heat. This paper look at the mixture of ammonia (NH3) and water (H2O) as binary zeotropic solution only.

Encapsulating the NH3-H2O binary mixture, implies that no other chemicals are present inside the capsule, and the mixture is in saturation condition at all positions inside the capsule, therefore the pressure inside the capsule would be the saturation pressure at the average temperature of the mixture.
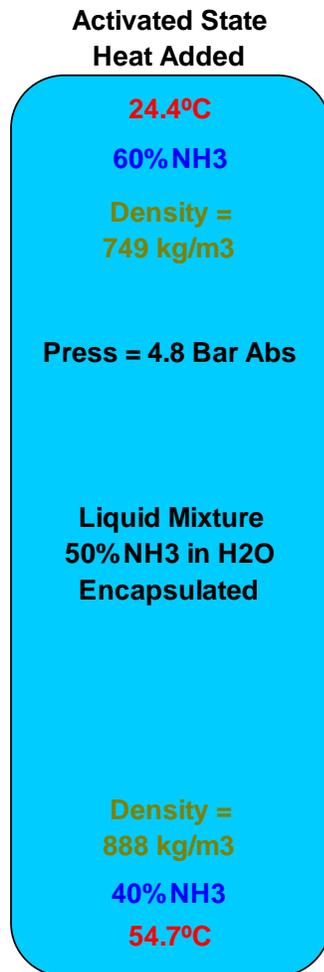
The zeotropic nature of the NH3-H2O mixture allow isobaric temperature gliding, so heat added at a specific point on the capsule, would boil off some NH3, as the local liquid temperature increase, but the pressure in the capsule is not really affected. The NH3 concentration at the point of heating decrease as NH3 boils off, leaving a higher density, higher temperature, but lower NH3 concentration at the point of heating, although it is still in saturation and have the same saturation pressure. The NH3 boiled off from the point of heating, move to a cooler place where it is absorbed again, increasing the NH3 concentration at the point of absorption. The mixture with the higher concentration NH3 now has a lower density, but it also stay in saturation at the same internal capsule pressure.

Also, when NH3 and H2O dissolve in each other, heat is released and we call this energy the heat of solution (HOS). The dissolving process is said to be exothermic. The opposite is also true, namely the process of separating the NH3 and H2O (increasing the NH3 concentration in the distillation process) is endothermic, absorbing heat from the liquid, and thereby cooling it down. The higher NH3 concentration mentioned in the previous paragraph would therefore not only have a lower density, but also a lower temperature. The combination of zeotropic nature and the HOS effect, may create large isobaric temperature glides when the density differences act in a gravitational (or centrifugal) field.

This temperature gliding can have a profound effect when the capsule (which is an enclosed long pipe) is placed in a gravitational field. In a vertical column, the density differences generated by heat cause temperature differences, but also start a migration process where higher temperature, higher density liquid with a lower NH3 concentration

migrate to the vertical bottom of the column, while the higher NH3 concentration, lower density and temperature liquid would migrate to the column top. The saturation

Figure 2

**Activated State
Heat Added**

24.4⁰C

60% NH3

**Density =
749 kg/m3**

Press = 4.8 Bar Abs

**Liquid Mixture
50% NH3 in H2O
Encapsulated**

**Density =
888 kg/m3**

40% NH3

54.7⁰C

pressure, being the same throughout the mixture, would slowly increase, as more and more heat is added to the column. It is understandable that in the long term, the saturation pressure would follow the average internal energy in the liquid mixture.

2.) The nature of the two stable states, namely the Ambient State & Activated State:

The ambient state, or de-activated state is shown in figure 1, above, and it represent the state when the contents of the capsule have been thoroughly mixed and all internal points are at the same ambient temperature. The internal energy would be the ambient, zero-point benchmark with the lowest entropy.

Should heat be added to the capsule, as explained before, NH3 would boil off, initiating the temperature glide process described above. The upwards migration of the NH3 rich mixture and the downwards migration of NH3 lean mixture would set up the NH3 concentration gradient with the highest concentration at the column top, as well as a temperature gradient with the highest temperature (still lower than the heat source we used to provide heat to the capsule) at the bottom of the column, as shown in figure 2. Note that with initial heating added, the internal energy increase inside the capsule while we are adding heat, forcing the pressure to gradually increase, and not necessarily the top temperature to decrease below 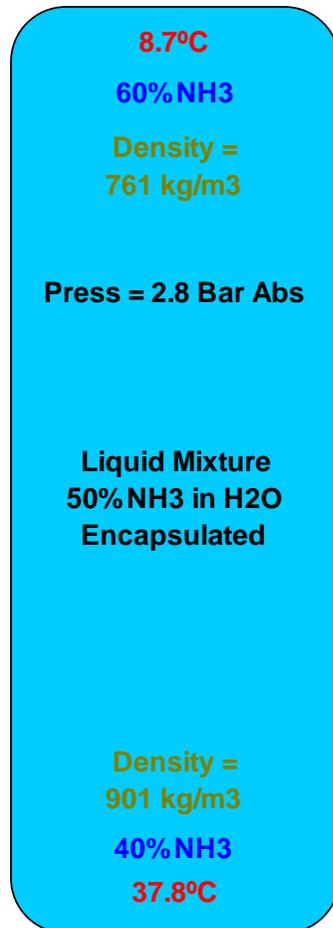ambient. The result would look like the capsule sketched in figure 2, with the column bottom temperature much higher than ambient, but the top temperature about ambient or just a degree or two above it. The heat we added was utilized to set up the gradients and put the column into the Active state, kept in place by the density differences in the gravitational field. Unlike a pure water column, internal convection is effectively inhibited, as heat causing temperature rise increase the liquid density instead of decreasing it like pure water, and if we ignore radiation, the only gradient-depletion process would be thermal conduction heat flowing back from the hot bottom to the much colder top. As the column length is very much more that it's diameter, and the resistance to thermal conduction of the liquid mixture is fairly high, gradient depletion is extremely slow, making it a fairly stable state for the capsule.

The higher the temperature of the heat source we used to activate the capsule, the larger the gradients would be.

Should we remove heat from the hot bottom of the column, we would deplete the gradients, but if we remove heat from a middle position of the column, we are more likely to decrease the average internal energy without affecting the gradients. This has the effect of decreasing the pressure, keeping the gradient sizing, but shifting it into a lower energy state. It is easily understandable if we remember the complete column is saturated at all positions within the column. Pressure drop resulting from heat removal, would flash liquid to vapor at all positions in the column, allowing the vapor flashed off to rise a little before being re-absorbed. NH3 concentration therefore increase at the top, but the pressure is lower, forcing the saturation temperature lower at the top. With the temperature of the hot bottom decreased and closer to the ambient, while the

Figure 3

**Activated State
Heat Removed**

8.7ºC

60%NH3

**Density =
761 kg/m3**

Press = 2.8 Bar Abs

**Liquid Mixture
50%NH3 in H2O
Encapsulated**

**Density =
901 kg/m3**

40%NH3

37.8ºC

temperature at the column top decrease to be lower that ambient, **still keeping close to the same gradients size** (difference between column top to bottom), as shown in the sketch of figure 3.

Another way of achieving this activated state, would therefore be to add heat to the bottom for creating the correct sizing of gradients, and then removing heat (at ambient temperature of available cooling water) in the column middle, to drop the pressure in the saturated mixture of the column, and thereby force the top temperature down below ambient (even below 0°C).

In a system that is not completely encapsulated, this active state may also be achieved by removing vapor from the column top, compressing it and pushing it into the column bottom. With the very low compression ratio required (just to overcome the hydraulic column pressure), this compression function would practically be economically done by a vapor powered ejector, extracting vapor from the column top (causing some flash cooling) while recovering the latent heat and HOS of the ejector output by adding it to be absorbed in the already hot column bottom.
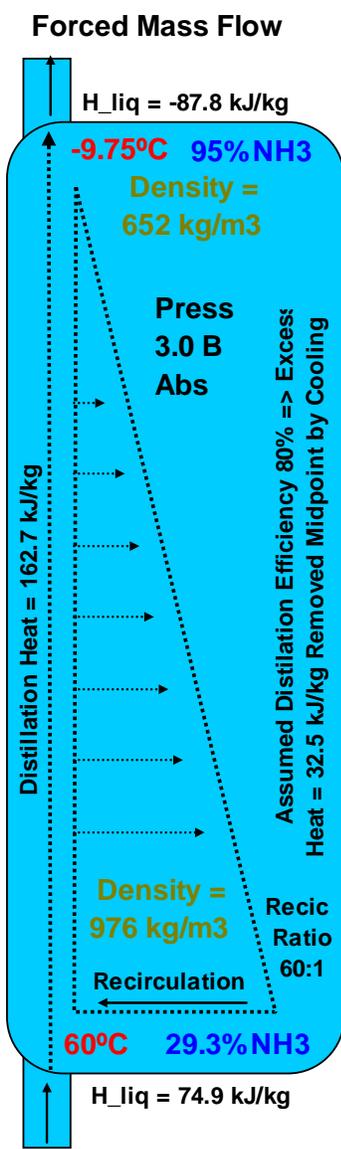
This is why the start-up device to put the column into the active state, is generally chosen as the simple vapor powered ejector. Once the system is started and the column (or reactor) is put into the active state, heat removal from the column midpoint is adequate to maintain the gradients, as heat leakages may be kept very low.

3.) Opening the capsule top and bottom for liquid flow:

When adding inlet and outlet conduits to the capsule for mass inflow and outflow, we call the column a "Reactor", and working with the reactor we always assume that it is in

the active state, realizing how stable the active state really is. We should, however, take care not to force inputs and outputs that would cause gradient degradation or loss, without a mechanism to re-activate the reactor. When we pump liquid mixture from the reactor top, we are removing mass from the top at the same enthalpy as the mixture present there. Similarly, mass we want to pump into the reactor hot bottom, should be at the same enthalpy (or higher) than the enthalpy of the liquid present in the bottom. If the energy level of the mass we force into the reactor bottom is too low, it will decrease the bottom temperature, partially killing the gradients, thereby partially de-activating the reactor! Obviously if it is too high, the excess energy will have to be removed, either as flashed vapor from the reactor top, or midpoint cooling to avoid reactor top heating, again, killing the gradients. The reactor sketched in figure 4, below, represent the

Figure 4

Forced Mass Flow

H_liq = -87.8 kJ/kg

-9.75ºC   95%NH3
Density = 652 kg/m3

Press 3.0 B Abs

Distillation Heat = 162.7 kJ/kg

Assumed Distillation Efficiency 80% => Excess Heat = 32.5 kJ/kg Removed Midpoint by Cooling

Density = 976 kg/m3

Recic Ratio 60:1

Recirculation

60ºC   29.3%NH3

H_liq = 74.9 kJ/kg

actual tested process variables of the tests done of the pilot model built. Liquid pumped from the reactor top was at a temperature of (-9.75°C) with an NH3 concentration of 95%NH3 with enthalpy of (-87.8 kJ/kg). With the reactor bottom temperature at 60°C, the bottom liquid enthalpy was (74.9 kJ/kg), making the real distillation heat (162.7 kJ/kg) and assuming the distillation efficiency of 80% means that 20% of this distillation heat, (32.5 kJ/kg) would be the excess heat, to be removed from the reactor, either by cooling the reactor midpoint, or by removing flashed vapor from the reactor top. This excess heat drive the internal circulation (isobaric temperature gliding) by vapor-lift action. It is easy to recognize that when the forced mass flow decrease to zero, the distillation efficiency would rise to 100% and the excess heat to be removed would decrease to zero. Note that in this example calculation the mass inlet into the hot reactor bottom should have the enthalpy of 107.4 kJ/kg (20% higher than the bottom liquid enthalpy) and if this energy level is any higher, it would just add to the excess heat to be removed. Should this excess not be removed, or the midpoint cooling designed for it is somehow interrupted, the reactor top would heat up, also increasing the pressure, and with large vapor flow as bubbles in the column, mixing the contents thoroughly, killing all remnants of temperature and concentration gradients!

The energy level of the mass entering the reactor bottom being 20% more than the saturation enthalpy of the liquid inside the reactor bottom, implies some vapor is present. This vapor form bubbles, rising in the liquid column as result of buoyancy, and create the internal circulation, driven by the vapor lift principles, required for distillation, driving the higher concentration NH3 to the reactor top. If this 20% additional

energy in the form of vapor was not present, the distillation process would not take place at all due to the lack of circulation.

Due to vapor bubbles present inside the reactor, (at the bottom the vapor hold-up or void calculates to 16.4%) the liquid level inside the reactor would vary at the top position where we need to extract liquid for pumping from. It is therefore extremely important to realize that the reactor would need a mechanism eg. a ballast reservoir to add binary liquid from when the level decrease, and to use as a storage space for accumulating excess liquid when the liquid level rise. This level control, operated in conjunction with a 3 point float switch and two solenoids, is required and very important to stabilize the liquid level, so you are able to design the pump suction inlet line so that no negative head occurs. Saturated zeotropic binary liquid cannot sustain negative head, as vapor from the more volatile component (NH3 in this case) is immediately flashed off on any attempt to draw suction, to the detriment of the pump, of course, going into cavitation. Another way to solve this problem involve a moving pump inlet line, made from a flexible hose tied to a float, so the pump inlet would move vertically up or down inside the reactor, depending on the void present in the reactor.

Mass flow through the reactor and the physical dimensions of the reactor determine the internal recirculation ratio, and the distillation efficiency determines the excess energy that would be arriving at the reactor top, if cooling does not remove it. In our example as sketched in figure 4, the distillation efficiency being 80%, meaning the 20% excess energy is carried in vapor bubbles rising in the reactor, driving the internal circulation with this vapor lift pump action. The maximum enthalpy of the mass entering the hot reactor bottom therefore calculate to $H\_liq\_max = 107.4$ kJ/kg. With the actual mass flow set at 3.599 e-2, the true distillation energy calculate to 5.87 kW, while the excess heat for removal calculate to 1.17 kW.
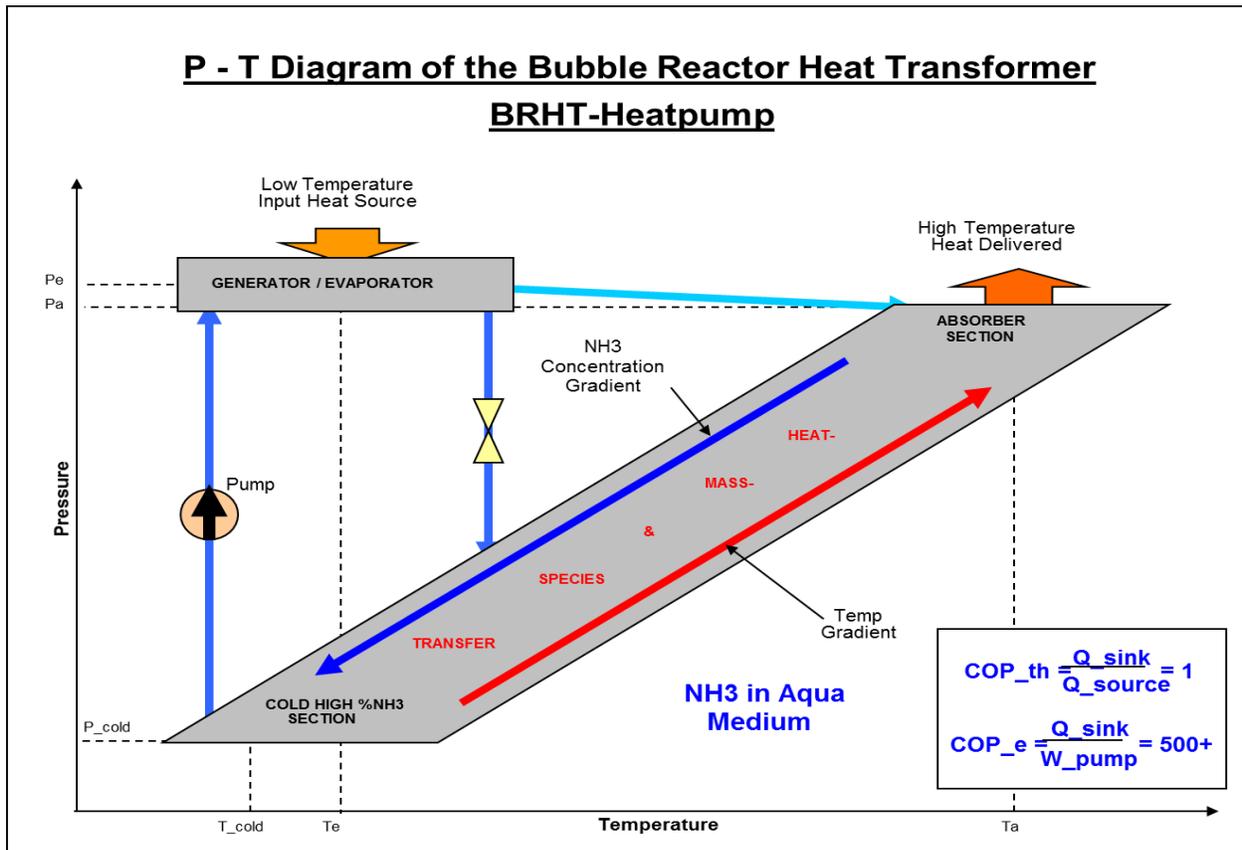
The operation of bubble reactors like this was already investigated by many researchers and the recent (2019) review paper by Shu et al [7], on multiscale, multiphase phenomena in bubble column reactors grouped together many researchers' results. Heat and mass transfer from vapor to liquid in the interface, as well as bubble and liquid countercurrent velocities and other parameters, proved to not only depend on physical properties of a vapor bubble in the micro-scale, but also the effect of clusters of bubbles and macro-effects of walls encapsulating the binary mixture flow, needed to be considered to clearly understand heat and mass transfer in these reactors. In this regard the work of Al-Hemiri & Ahmedzeki [8] and [10], for the calculation of heat transfer coefficients in this type of bubble reactors are very useful. It is clear that the actual bubble diameter of vapor bubbles formed have a major effect on bubble rising velocity, drag and turbulence, not to mention void fraction created and heat transfer. With detailed tables of process variables of NH3-H2O mixtures available, derived from the work of [1], Ganesh & Srinivas, 2017, enabled us to calculate the heat and mass transfer processes, and correlated with other literature like Govindaraju [4] of 2005 to confirm ballpark figures.

Assuming a worst-case scenario, with the average bubble diameters ~ 5 mm diameter and the reactor pressure of 3 Bar Abs at the process parameters as shown in figure 4, the calculated heat exchange of vapor to liquid across the interface, boiled down to a rate of 0.88 MW / m3 and with the height to diameter ratio of similar distilling bubble reactors in the literature, recommended as 9:1, it becomes straightforward to calculate the reactor dimensions for proper distillation operation, keeping the active state in the reactor, while utilizing the 5.87 kW for the distillation process when the reactor midpoint is cooled removing the excess of 1.17 kW before it reaches the cold reactor top.

4.) Absorption Heat Transformer (AHT) Principles:

An activated bubble reactor as described above, has a source of saturated, high concentration NH3 (95%), cold (-9.75°C) binary mixture available at the reactor top. We also have a source of hot (60°C) low concentration (29.3%NH3) but also saturated
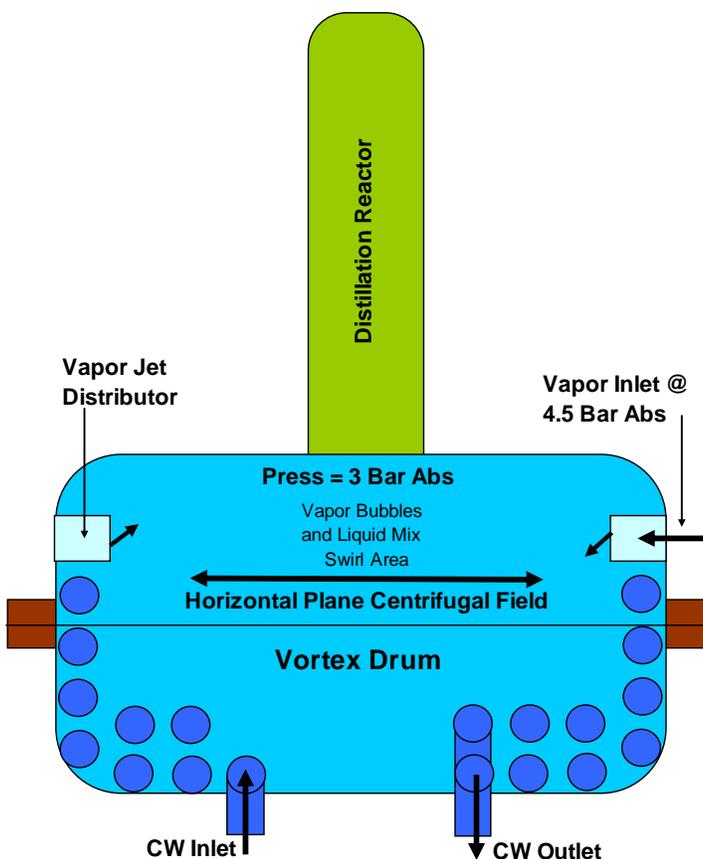
Figure 5

P - T Diagram of the Bubble Reactor Heat Transformer
BRHT-Heatpump

$$COP\_th = \frac{Q\_sink}{Q\_source} = 1$$

$$COP\_e = \frac{Q\_sink}{W\_pump} = 500+$$

binary liquid mixture available in the bottom of the activated bubble reactor. As an AHT is a device utilizing driving heat (instead of electricity) to pump waste heat from a low temperature heat source, to a higher temperature for use by heat machines, the activated bubble reactor may easily form the backbone of an AHT.

Should we add a liquid pump and an evaporator to the activated bubble reactor of figure 4, it is not difficult to see the cold, high %NH3 saturated liquid pumped from the saturated 3 Bar Abs pressure, to a slightly higher pressure of 4.5 Bar Abs, (now subcooled by ~ 10°C due to the pumping pressure increase) form the feedstock mass able to evaporate at 0°C, (the saturation temperature at this pressure) in an evaporator. Any waste heat entering the evaporator will become the driving energy, with the first sensible heating operation of the subcooled binary liquid from -9.75°C to liquid at 0°C, and then, saturated, using more external driving heat (latent heat of evaporation) to evaporate the liquid, absorbing large amounts of latent heat from the evaporator. This large heatload of vapor at a pressure higher than the activated bubble reactor pressure, could be routed to the hot reactor bottom where an absorption process would generate heat, both the latent heat of condensing the vapor, as well as the heat of solution (HOS) of the mixing NH3-H2O, would contribute to usable absorption heat for generating higher temperature heat reservoirs. This may be driving ORC or other heat operated machines. Figure 5 above, show a pressure-temperature diagram of this typical, very simple AHT process.

Figure 6

The complete activated column actually has a dual function, namely the distillation process taking place along the full length of the bubble reactor as described already, as well as an absorption process taking place in a specific area of the reactor bottom, generating a lot of heat, to be removed and routed via heat exchanger (H/E) to external heat users.

Because the distillation process is extremely sensitive to heat input variations (for a fixed mass flow it needs a very specific amount of heat input), it makes sense to dedicate the reactor bottom part to the absorption process, separating it from the distillation process, and providing a very specific pre-conditioned absorber output mass with the correct energy level, to meet the requirements of the distillation process very accurately at the interface between absorber an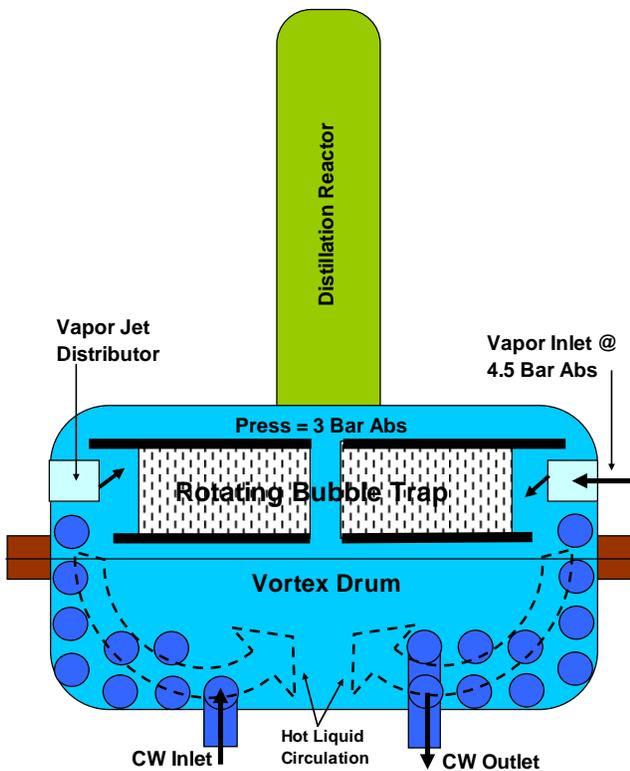d still, or distillator. It still operate at the same pressure as the vertical column bubble distillation reactor, though.

5.) The dedicated Absorber fitted to the Distillation column:

The purpose of the absorber is to receive the drive vapor from the evaporator and utilize the chemical heat (HOS) as well as the latent heat in the vapor in an absorption process, transferring the energy to heat the low NH3 concentration liquid mixture received from the distillation reactor. This absorber also has the purpose of transferring a large part the absorption heat that was added to the liquid, to an external machine via a liquid-liquid heat exchanger (H/E). Lastly, after performing the two tasks set out above, deliver the resulting binary mass with the correct remaining energy level (maximum some16.4% vapor in the liquid at 60°C to be the correct enthalpy) to the distillation reactor.

The effect of bubble size and interfacial area with void in a co-current downflow column reactor with micro-bubble dispersion was investigated by Hernandez-Alvaro et al [2] in 2017, confirming results of other literature showing the heat transfer enhancement that could take place in the presence of turbulence working with micro scale bubble diameters. Chemical engineering reactors used vapor jets to generate centrifugal force, seriously enhancing heat transfer. In this regard Kuzmin et al [3], already in 2005
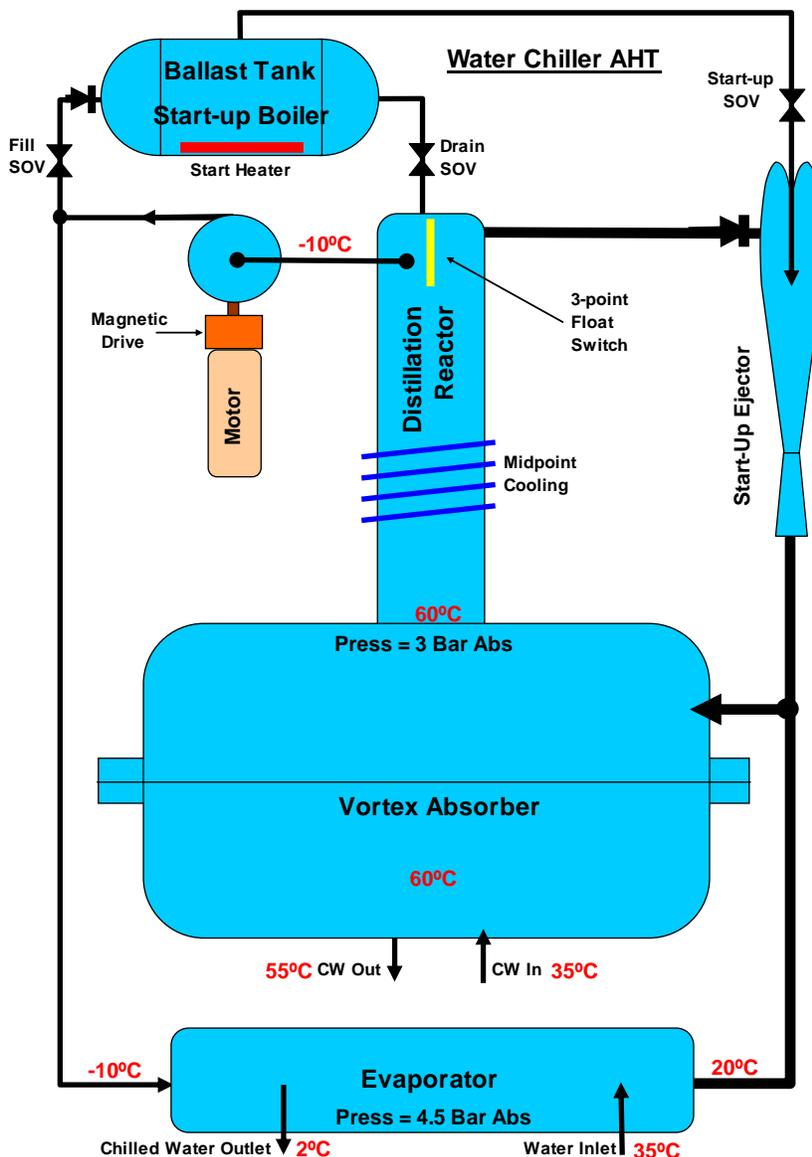
Figure 7

introduced a vortex centrifugal bubbling reactor using air-water mixtures with very high mixing and heat transfer characteristics. Taking this as guide, we designed the absorber as drawn in figure 6, above. The casing of the absorber formed by bolting together two flanged end-caps of large pipes, was fitted with an internal circular ring vapor jet distributor, where the inlet vapor (at 4.5 Bar Abs coming from the evaporator) is jetted at a tangential angle into the rotating liquid where the pressure in the vapor is converted to kinetic energy, forcing liquid rotation with calculated speeds to generate some 5 G to 10 G of centrifugal force to enhance turbulence. This vapor-liquid forced swirl enhance vapor absorption, heating the liquid. Also mounted inside this vortex drum, are the CW H/E coils fixed to the drum lower part inside as shown in figure 6. The higher temperature binary liquid has the highest density, and therefore the swirl would push the hot liquid towards the radial outer periphery and to the absorber bottom.

Upon discovery that the configuration as drawn in figure 6 still have a heat transfer rate that proved too low to absorb enough vapor, we designed a bubble trap. For further enhancement of heat transfer, we placed a rotating bubble trap consisting of two radial

plates, the top one slightly larger in diameter, with a winding of stainless steel sieve plate with 1 mm square holes perforating the sieve. This can be seen in the sketch of figure 7. Rotating with the liquid, vapor flow radially inwards towards the rotation centre against the centrifugal force direction, breaking up into bubbles of ~ 1mm diameter and also being forced through the set of several sieves. Liquid counter flow force the liquid to flow radially outwards, while it is heated by the vapor absorption process. Heat is also distributed more in the binary mixture as a result of the conducting metal the sieves are made off. With vapor inflow sufficient to maintain a void of ~ 30% and the vapor bubbles on average 1 mm diameter inside the rotating bubble trap, subjected to about ~ 5G centrifugal force, would likely provide H/E in excess of ~ 20 MW / m3, providing a means to calculate the required dimensions of the rotating bubble trap accurately. This high transfer rate only occur inside the pack of multiple sieves in the rotating bubble trap.

Figure 8

Also, standard liquid/liquid H/E principles allow us to calculate the H/E coils required inside the vortex drum, bringing us to ~ 5.21 MW / m3 if you consider the complete vortex absorber drum as a whole. This make the dimensions of the vortex drum also easy to calculate for any heat load. The H/E rate is a function of the differential pressure between the evaporator (4.5 Bar Abs) and the distillation reactor (3 Bar Abs), as this determine the swirl velocity and therefore the actual centrifugal force, and as the liquid pump control this evaporator pressure, it also control the rate of heat transfer in the absorber!

The dimensioning of a typical Vortex Bubble Reactor for utilization as a thermally powered heat pump or AHT, would look very close to figure 7, above, due to the various

heatloads involved. Remember that the energy required for the distillation reactor needed only ~ 16% of the liquid pumped from the cold top to be in vapor form. The balance of ~ 84% of the pumped liquid may be vaporized in the evaporator absorbing large amounts of very low temperature (between 0°C and 15°C) waste heat while generating a huge chilling heatload, that must be discarded again at a temperature of 55°C - 60°C in the vortex absorber H/E. For our example calculations, the evaporator heatload would be 50 kW while the heatload to be discarded to the cooling water circulating in the vortex absorber was ~ 42 kW.

Figure 8, above, sketch a typical zeotropic binary liquid bubble column, or **"Vortex Bubble Distillation Reactor" (VBDR)**, utilized as the core element of an AHT delivering chilled water. This AHT has a calculated electrical coefficient of performance (COP_e) of greater than 1000, as a result of the low electrical power requirement of the liquid pump, even though the pump isentropic efficiency was assumed as only 35%, as it is a positive displacement pump. The calculated thermal coefficient of performance (COP_th) is 0.83 but this number is totally irrelevant for evaluation of the electricity used for the chilling operation. The AHT use ambient heat to power the chiller, pumping heat with a temperature below ambient (between 0°C - 15°C) to the high temperature of 60°C, disposed of in the cooling water (CW) circuit.

The ballast tank have multiple functions in the design of the AHT above. Firstly, it holds some 50% of the internal volume of the tank as buffer liquid for level control, to be able to provide liquid to the distillation column should the liquid level be too low, detected by the 3-point (low-correct-high) level switch inside the distillation reactor top. The solenoid valve "Drain SOV" is opened to do this. Should the level inside the distillation reactor be too high, the "Fill SOV" solenoid valve would be opened and liquid pumped from the reactor back into the ballast tank. With the level switch on "correct" position, both SOV's would stay closed. The volume the ballast tank should hold in reserve is calculated as double the displacement of the void factor during operation of both the distillation reactor and the vortex absorber.

Secondly, the ballast tank is also a start-up boiler with an electrical heating element fitted inside the tank. On start-up, this heater is switched on, heating the ballast tank contents, building pressure to the 7 Bar Abs required to operate the start-up ejector efficiently. After the start-up valve is opened, the heating element control the pressure while vapor is generated to feed the ejector. The ejector suction line remove vapor from the distillation reactor top, flashing some NH3 off as vapor and reducing the temperature and pressure to design conditions. At the same time the ejector outlet is fed into the absorber, heating it to design values. Once the correct gradients of temperature and NH3 concentration have been reached, start-up is completed, and the vortex bubble distillation reactor (VBDR) is in the "Active" state, ready to commence operation as AHT. Pressure control of the distillation reactor now reverts to cooling flow adjustments of the midpoint cooling system. The heat delivered to the absorber by the ejector should be ~ 20% of the design point heatload of the evaporator, to keep start-up time reasonably low.

Thirdly, the ballast tank is also a pressure vessel, able to withstand the higher pressures to 10 - 15 Bar Abs. During start-up the heating element heat the contents to its evaporation temperature, starting at the ambient temperature (as on start-up average concentration NH3 at the reactor top temperature is pumped into the ballast tank during operation), but as more NH3 is boiled off, the NH3 concentration decrease, gradually increasing the saturation temperature to > 80°C. The rest of the complete vortex bubble distillation reactor, (VBDR) operates on the low pressure of 3 Bar Abs, because this saturation pressure dictate the specific temperatures (-9°C at the top and 60°C at the bottom) we designed the AHT for. Also, the evaporator have an operating point of 4.5 Bar Abs (providing saturation temperature of nearly 1°C to avoid the chilled water freezing), but this value may vary between 3.5 and 5.5 Bar Abs as it is also a control variable. The ballast tank should therefore be manufactured from stainless steel and also thermally insulated to avoid overpressure as the mixture heat up, but all other vessels may be made from fiberglass or a hard plastic like C-PVC (allowable to 98°C while normal standard PVC is only good to ~ 60°C) or polypropylene (82°C) and the piping & tubing from a suitable plastic like PTFE, nylon, neoprene or PPS (Ryton). H/E element coils both in the evaporator as well as inside the vortex absorber should be made from stainless steel (316 or 304) though, as the higher metal conductivity make more efficient H/E coils.
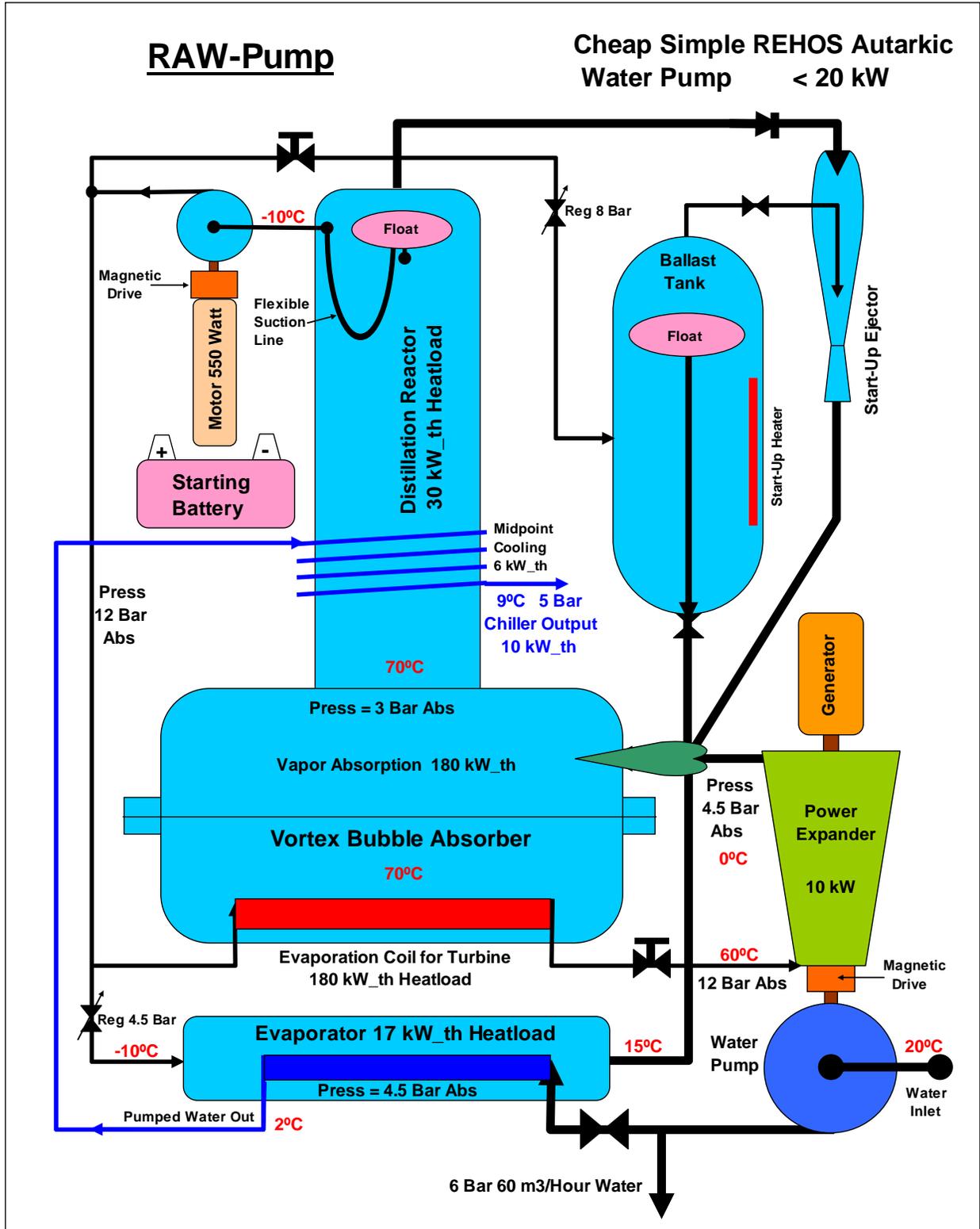
Pressure control of the Vortex Bubble Distillation Reactor (VBDR), during operation may be done by coarsely controlling the main CW flow through the vortex absorber, with a control valve, with fine tuning of the pressure by controlling the coolant flow through the midpoint cooling coil shown in figure 8.

The evaporator pressure is kept constant at 4.5 Bar Abs by the pump regulator. This value guarantee the saturation temperature of the binary mixture entering the evaporator is above 0°C so as to avoid freezing of the chilled water outlet. The evaporator outlet is fitted with a control valve to control the evaporator vapor outlet temperature at a specific fixed point, eg. 20°C, chosen lower than the available water inlet (in figure 8 sketched as 35°C). During operation, binary mixture liquid with a NH3 concentration of eg. 95%NH3 in aqua, enter the evaporator at a temperature lower than 0°C, but is heated (sensibly) quickly to the saturation temperature of about 1°C, from where the temperature would glide at constant pressure to the controlled outlet value of 20°C.

During start-up, the pump is stopped, allowing the start-up ejector, powered by the start-up boiler vapor pressure generated by the heating element inside the ballast tank, to put the VBDR into the "Active State" with temperature and ammonia concentration gradients set up. After the start-up phase, normal operation with the control as described take over with the starting of the pump.

The described complete VBDR, is fitted with suitable additional components to utilize it as a **water chiller, as shown in figure 8, form the basis and is the subject of a current patent held by our client, describing a novel de-humidifier for the atmospheric water generation (AWG) industry.**

Figure 9

RAW-Pump

Cheap Simple REHOS Autarkic Water Pump   < 20 kW

Magnetic Drive

Motor 550 Watt

Starting Battery

-10ºC

Float

Flexible Suction Line

Distillation Reactor 30 kW_th Heatload

Reg 8 Bar

Ballast Tank

Float

Start-Up Heater

Start-Up Ejector

Midpoint Cooling 6 kW_th

9ºC 5 Bar Chiller Output 10 kW_th

Press 12 Bar Abs

70ºC

Press = 3 Bar Abs

Vapor Absorption 180 kW_th

Vortex Bubble Absorber

70ºC

Generator

Press 4.5 Bar Abs

0ºC

Power Expander

10 kW

Evaporation Coil for Turbine 180 kW_th Heatload

60ºC

12 Bar Abs

Magnetic Drive

Reg 4.5 Bar

-10ºC

Evaporator 17 kW_th Heatload

15ºC

Water Pump

20ºC

Water Inlet

Press = 4.5 Bar Abs

Pumped Water Out   2ºC

6 Bar 60 m3/Hour Water

Several other products may also be defined **utilizing the patented REHOS process (thermodynamic cycle) held by REHOS Product Designs**. The same core Vortex Bubble Distillation Reactor (VBDR) may easily also be used to generate heat (eg. 50°C to 80°C) in a radiator for use in very low cost space heating and air conditioning.

In more efficient utilization of the VBDR, it may not only provide the heat source for an ORC power generator, but may also function as the perfect ORC heat rejection sink, fully regeneratively re-using all the waste heat in the form of low pressure saturated vapor rejected by the ORC expander. The ORC operating between these low temperature levels may have a thermodynamic efficiency < 5%, due to the large heat rejection, but in this configuration where all the rejection heat is recovered, the efficiency soar to > 70%. For small machines (< 20 kWe) the temperature gradient of 0°C to ~ 60°C would suffice, but for larger machines eg. 50kWe - 100kWe, a larger temperature gradient (eg. 0°C to 80°C or 90°C) is used. This combination of Vortex Bubble Distillation Reactor, regeneratively combined with a standard ORC, form the revolutionary patented **Regenerative Heat of Solution (REHOS) thermodynamic cycle,** with a heat to power conversion efficiency of 70% - 80%. Details in a full description of the REHOS technology was compiled by the author of this document and published as [11], already in November 2018, while economic aspects are laid out in the paper [12], published in February 2019.
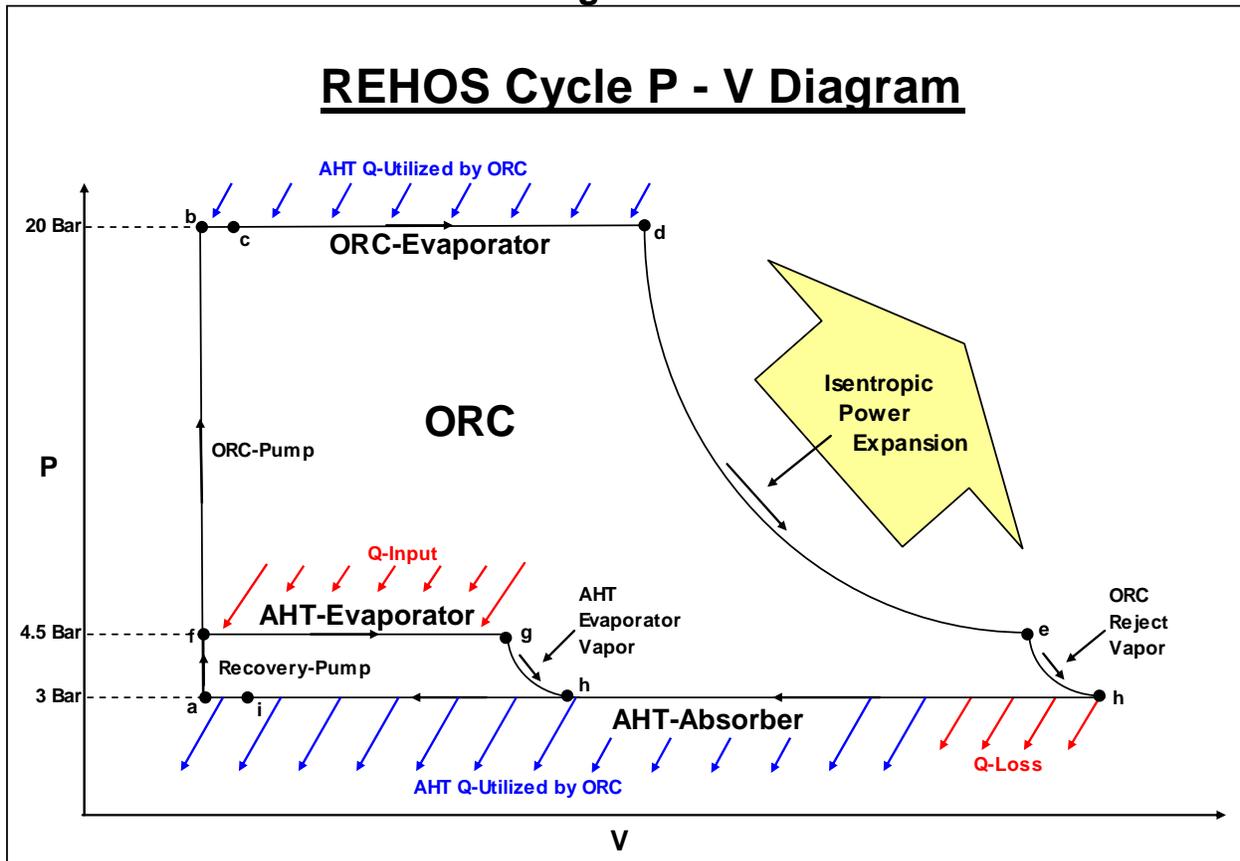
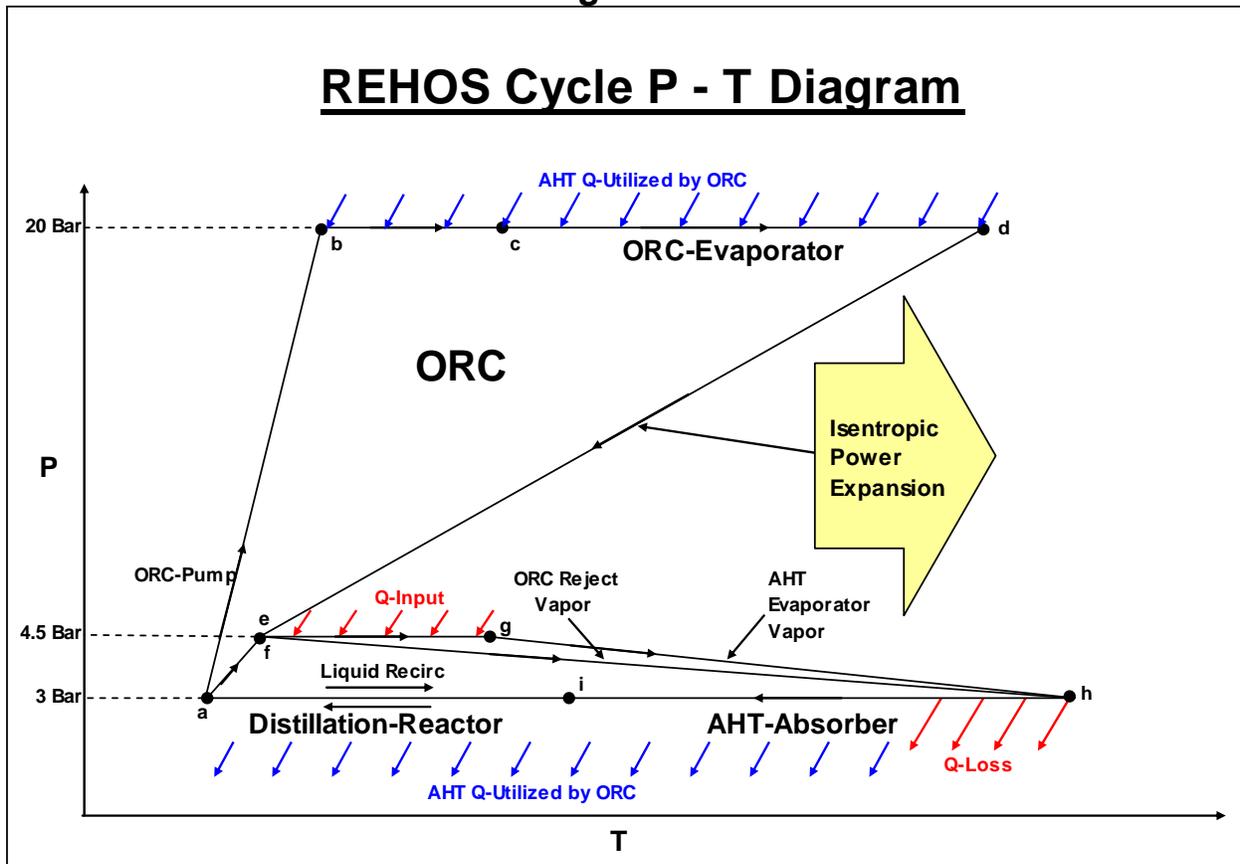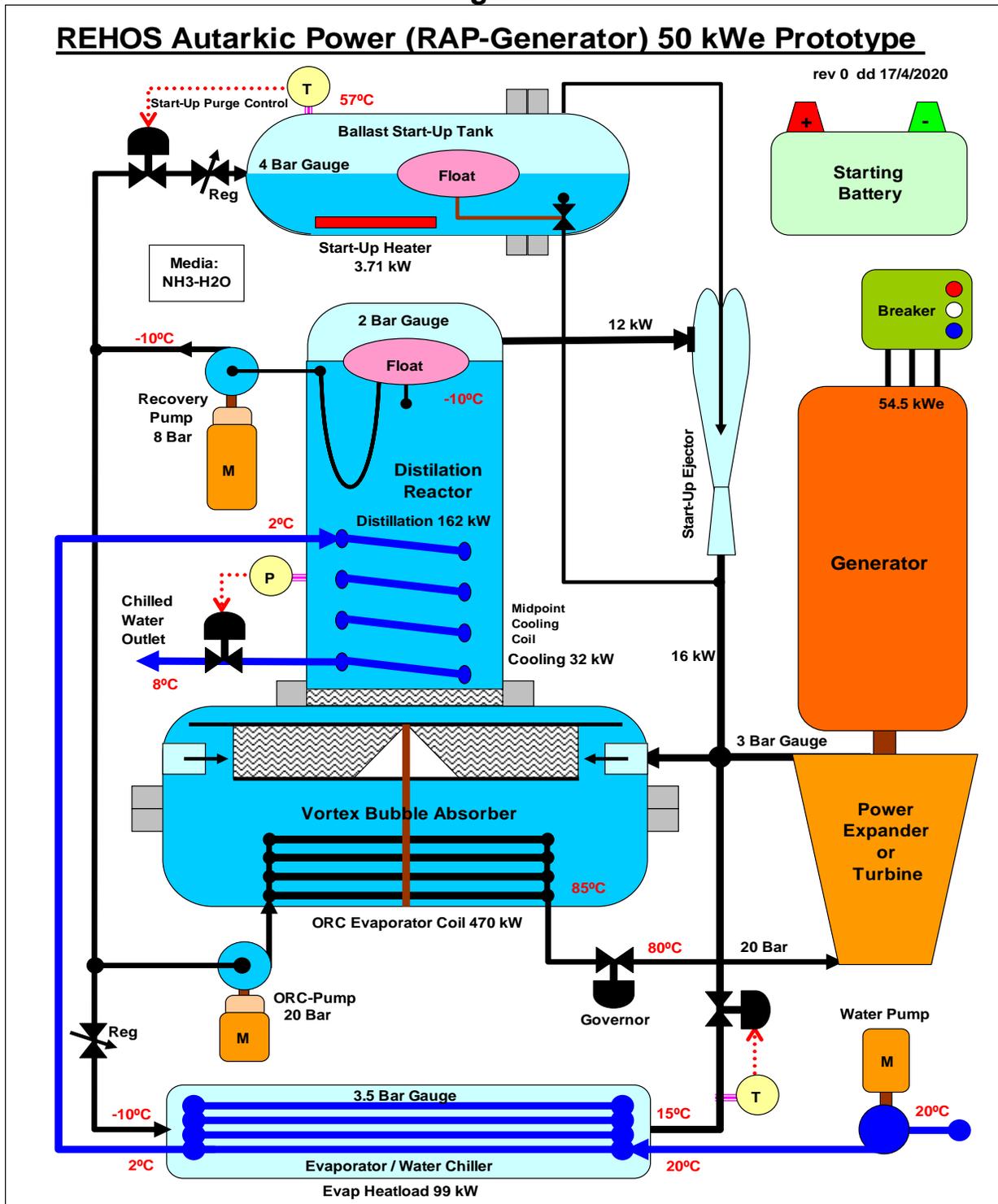## Figure 10

Figure 11

REHOS Cycle P - T Diagram

Figure 10, 11 and 12 represent the REHOS thermodynamic cycle P-V Diagram, P-T Diagram and T-S Diagram respectively as utilized in the RAW-Pump sketched in figure 9, as well as the larger (50 kWe) RAP-Generator sketched in figure 13. From these diagrams sketched in figure 10, 11 and 12, the AHT and the ORC is clearly distinguishable and the alphabetical position identifiers make referring to the real process and also comparison between the different P-V, P-T and T-S diagrams easier.

The ORC operate between 4.5 Bar (Abs) and 20 Bar (Abs), while the heat external input as well as heat recovery (of ORC rejecton heat) of the AHT operate at pressures of 3 Bar (Abs) and 4.5 Bar (Abs). The core element of the AHT, namely the VBDR is operating at constant pressure of 3 Bar between the high temperature @ (i) and the low temperature (-10°C) @ (a), with the high NH3 concentration while the hotter end at about 85°C @ (i) will have an NH3 concentration of about 17%NH3 in aqua.

The HP ORC-Pump increase the pressure of the high concentration NH3 from 3 Bar @ (a) to 20 Bar @ (b), where the liquid is heated to point (c), being in H/E with the AHT Reactor (a - i) and AHT Absorber (i - h). From (c) to (d) the liquid is vaporised at constant pressure, experiencing the isobaric temperature glide, and the HP vapor is expanded isentropically as it flows from (d) to the low pressure (4.5 Bar) @ (e). During this expansion power is produced in the turbine and converted to electrical energy in the

coupled generator. Expander exhaust vapor @ (e) is routed through an injector into the AHT Absorber @ (h) operating at 3 Bar.

Figure 12

REHOS Cycle T - S Diagram

A second liquid pump, called the Recovery Pump, increase the liquid @ (a) pressure from 3 Bar to the AHT Evaporator pressure of 4.5 Bar @ (f), from where the liquid is heated sensibly from -10°C to 0°C and then evaporated at constant pressure (with temperature glide from 0°C to about 15°C) @ (g), in H/E with a sensible heat source in the form of ambient water entering at about 20°C. The ambient heat source water is chilled in the process. The AHT generated vapor @ (g) is mixed with and added to the ORC rejection vapor, also injected into the AHT absorber @ (h). For overall heat balance of the REHOS thermodynamic cycle, the mass flow of high concentration NH3 in aqua pumped by the recovery pump is only ~ 17% of the ORC liquid flow.

The low temperature vapor (mixture of turbine exhaust, and AHT Evaporator vapor) entering the hot (85°C) AHT Absorber @ (h) where it is absorbed to generate a lot of heat (latent heat of condensation as well as heat of solution) in the absorption process while flowing to (i). Some of this high temperature heat is lost (radiated out) while the bulk of this heat is transferred in H/E with the ORC Evaporator (c - d) as well as the liquid heater (b - c). A small percentage of this heat is retained in the liquid @ (i), used for the NH3 concentration process (distillation) flowing from (i) back to (a), to repeat the cycle.

Figure 13

REHOS Autarkic Power (RAP-Generator) 50 kWe Prototype

Due to the low temperatures used, the thermal losses can be readily minimized with thermal insulation to render very high cycle thermodynamic conversion efficiencies around 70% - 80%.

6.) The "Vortex Bubble Distillation Reactor" (VBDR) as regeneration device used for recovering rejection heat from a power expander:
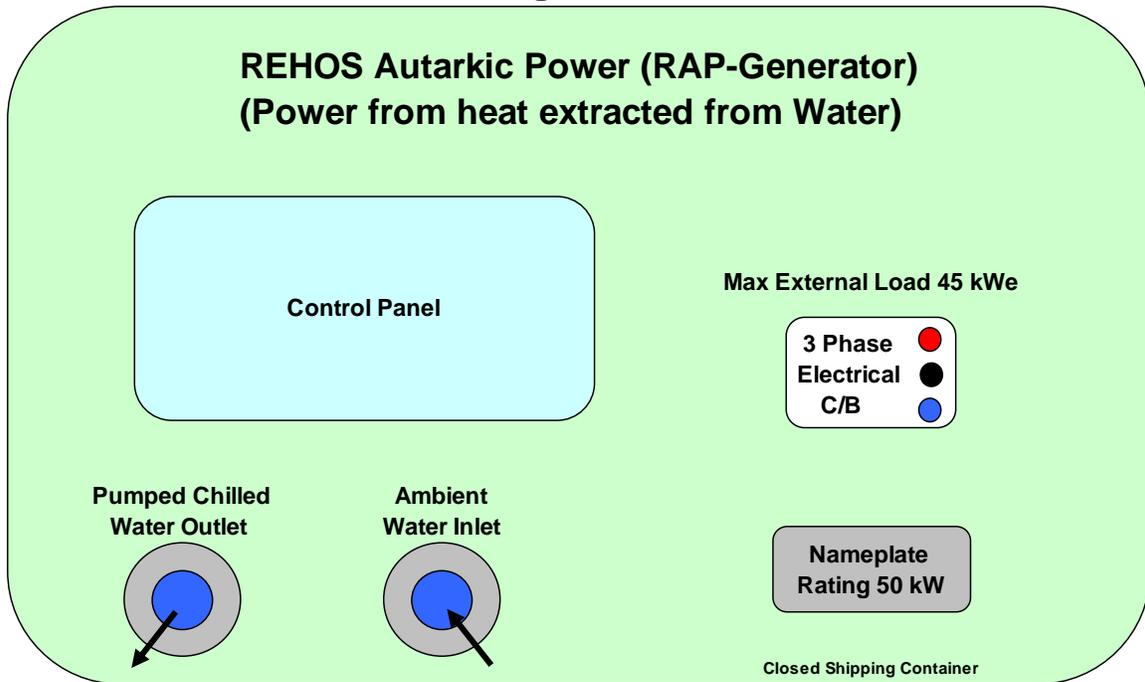
The AHT we described above, incorporating the VBDR, may also easily form the base for a power generator designed to utilize the thermal energy in ambient water for powering a water pump. We call this a REHOS Autarkic Water Pump (RAW-Pump) and is designed to be powered from the sensible heat in ambient water to deliver hydraulic power of pumped water, combined with a small amount of electricity for powering its own pressure pump, as well as some surplus power to charge a start-up battery. As shown in the sketch of figure 9, above, the RAW-Pump may also be adapted to deliver chilled water, with the chilling effect enlarged with a low mass flow, but high pressure water pump utilized in the machine. From figure 9 above, it should be clear the AHT base is modified only very slightly to form a RAW-Pump from the chiller machine described earlier.

The cooling water system we used for cooling the vortex absorber, has now been replaced with an NH3 high pressure evaporator tubing coil to generate vapor at 12 Bar Abs, for driving the power expander. Note the expander heat rejection low pressure (4.5 Bar Abs) and low temperature (~ 1°C) vapor form the major portion of the vapor feed to heat the vortex absorber during the absorption process. Due to the temperatures used, the organic rankine cycle (ORC) used here will have a thermodynamic efficiency of only slightly better than 8%, (assuming the expander can deliver power with a 65% isentropic efficiency) so 92% of the absorber heat provided by the H/E as 12 Bar HP vapor, will be rejected by the expander as low temperature (1°C) and pressure (4.5 Bar) **saturated vapor and recovered in the absorber section** of the VBDR, to **re-use the heat.**

Obviously the balance of 8% and some losses (assume another 10%) additional required heat would come from the sensible heat in the water being pumped, extracted as vapor in the evaporator and added to the power expander exhaust. The regeneration process used, make the heat to power conversion efficiency very high, **delivering some 70% - 80% of the sensible heat extracted from the ambient temperature water as power**, shared between electrical and hydraulic loads, depending on the nature of the client's requirement, eg. water distribution, agricultural irrigation, or power generation combined with refrigeration / air-conditioning (HVAC) etc.

Larger RAW-Pump machines (> 20 kW) normally would have to be adapted to the most expensive component, namely the turbo-generator combination, and for that reason the REHOS cycle is built using a VBDR able to use higher pressures and temperatures to suit the larger ORC turbine. A RAW-Pump designed for producing electricity rather than water hydraulic power would have a much larger generator, and very small pump, used only for water circulation through the evaporator and heat exchangers. Such a machine would be called a **REHOS Autarkic Power Generator (RAP-Generator),** and would typically have the process layout configuration as sketched in figure 13, above. The complete machine would be built into an enclosed shipping container, with a faceplate similar to the sketch in figure 14, below.

Figure 14

Utilizing this RAP-Generator for a very efficient (70% to 80% thermal to electrical efficiency) utilities cooling water (CW) heat recovery power generator built in eg. 10 MWe containerized units (a small 50 kW unit is being built as pilot plant, of which the process layout configuration is sketched as figure 10, above) would revolutionize decarbonization efforts of electricity utilities across the globe! The fact that it is modular, and containerized, make it easy to mass-produce the fully commissioned units of different sizes, in a factory. Remember this REHOS Generator use recovered CW waste heat, and therefore no fuel, take 10 MWe coal fired power generation requirement away (unit may deload but still, with the recovery unit's 10 MWe, deliver full load) and decrease the power station's combustion coal requirement with the coal that would have generated 10 MWe power, as well as decrease the CO2 emitted correspondingly. Obviously this utilization also remove the requirement of 10MW from the cooling requirement of the station. It's water use would also decrease by the water that would have been needed to generate this 10 MWe, and with an estimated cost of ~ 3500 USD/kWe (see the paper presented by the same author [12] in February 2019) it is easy to see the commercial value........**Decarbonization of utilities across the globe may now become profitable, done in a phased way**, instead of producing dead capital white elephants as stranded assets, abandoned and discarded fossil power generation dinosaurs.

Wind and PV Solar plants currently being utilized to decarbonize some utilities, have been bought with serious financial consequences, costing billions in decarbonization finance...in sharp contrast to the RAP-Generator, capable of financing itself, recovering the required capex in 3 - 4 years from savings produced!

Large marine ships would utilize the RAW-Pump as sketched in figure 10 differently, as a very high percentage of the delivered power would be required for propulsion, and much less for electricity. It would therefore utilize a smaller generator, but a huge water pump suitable for the propulsion, extracting the energy required direct from the sensible heat in the seawater..........**Possibilities are endless....**

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A Selection of Previous Publications by J. Enslin:

11. The document "Key Principles of the REHOS Cycle" was written by Johan Enslin in November 2018 and published in the Open Access Bioenergetics Journal at https://www.omicsonline.org/open-access/key-principles-of-the-rehos-cycle-2167-7662-19-154.pdf in January 2019, as well as on my own website http://www.heatrecovery.co.za/.cm4all/iproc.php/Key Principles of the REHOS Cycle.pdf

12. The document titled "Economic Aspects of Utilizing Heat Transformer Technology.pdf" was written by Johan Enslin in February 2019 and published on my website http://www.heatrecovery.co.za/.cm4all/iproc.php/Economic Aspects of Utilizing Heat Transformer Technology.pdf

13. Website for REHOS Product Designs, formerly traded as Heat Recovery Micro Systems, where the above publications are listed from: www.heatrecovery.co.za