Clarification of COP calculations for Absorption Heat Transformer (AHT) Type Heat Pumps

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Abstract:

Absorption Heat Transformers (AHT) of the hybrid type (vapor compression assisted) have two distinct different ways of calculating the efficiency as heat pump, or coefficient of performance (COP). Intermediate heat is used and (partially) upgraded to higher temperature called the temperature lift, using some of the intermediate temperature heat as power source for this process. With (Qa) being the delivered, upgraded high temperature heat delivered by the AHT absorber, and (Qd) the input intermediate heat absorbed by the AHT desorber, the thermal efficiency may be written as:

$$COP\_th = \frac{Qa}{Qd}$$

and values range from ~ 0.1 - 1.2 (but generally < 1), depending on system temperatures and pressures mainly. The amount of electrical power required to drive the vapor compressor may be written as Wc, and the electrical COP is written as:

$$COP\_e = \frac{Qa}{Wc}$$

which is mainly dependent on the compression ratio of the vapor compressor. The smaller the compression ratio, the higher the COP_e value, as the compression energy requirements decrease with decreasing compression ratio. Small compression ratio's to overcome the hydraulic pressure of a column of binary liquid of a few meters high acting on gravity may therefore result in very high COP_e values, as high as 50 - 100. Lower values resulting from liquid column low operating pressures of ~ 1 Bar Abs, and the higher values obtained with operating pressures of 4 - 5 Bar Abs.

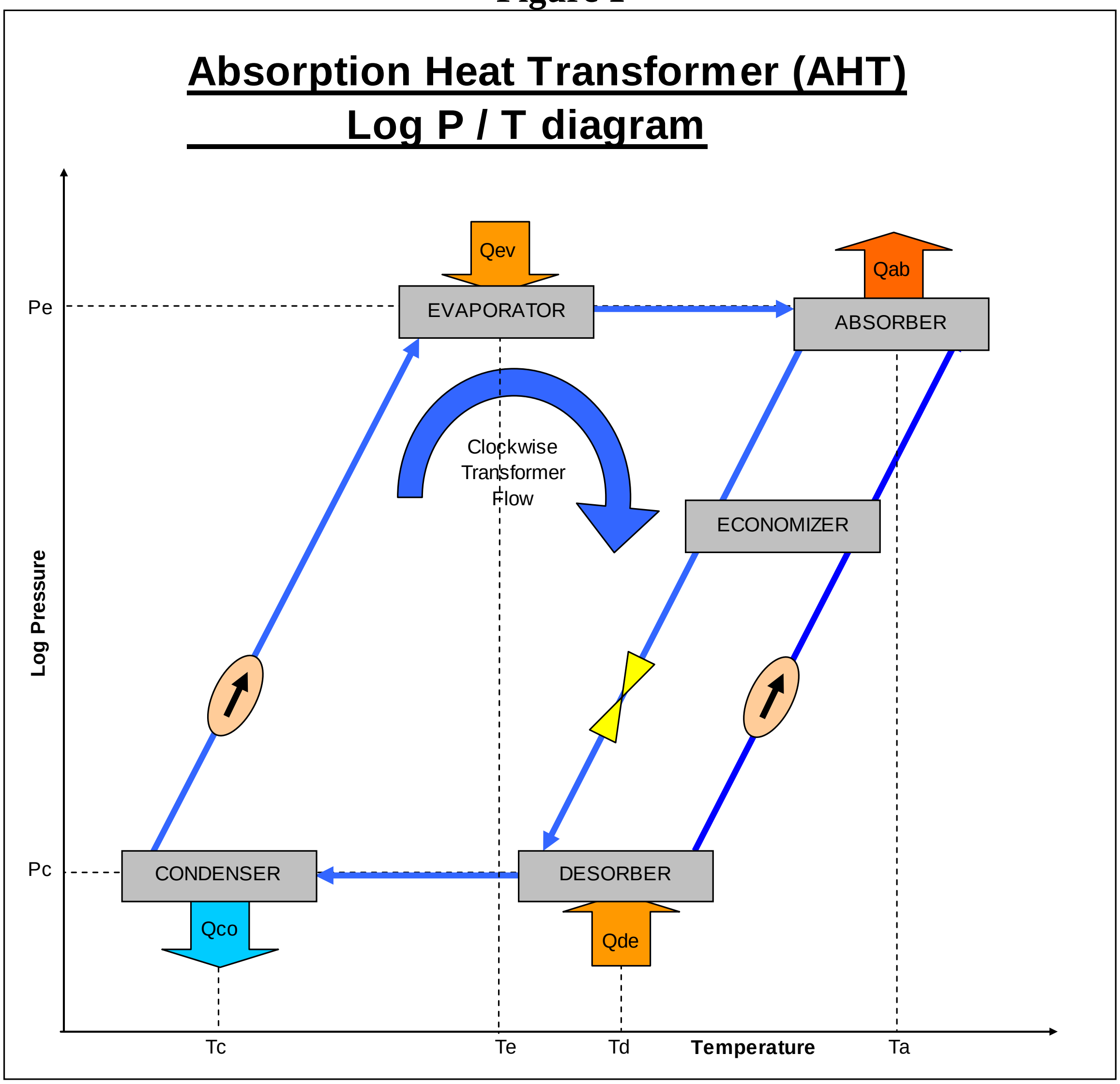
Introduction:

Around discussions on heat pump performance, the efficiency, or coefficient of performance (COP) created some confusion, as the expected COP for the HOS Bubble Heat Pump was given as 50 - 100, while expectations of some people were values < 1 for the discussed temperatures. Can this huge difference be related to different interpretations of the COP calculation definition? We get some answers in the IEA Handbook referenced [2] to spell out different COP values, as well as the other referenced papers.

The Conventional Absorption Heat Transformer (AHT):

Figure 1 below, sketch a pressure vs. temperature diagram of a typical conventional AHT in use commercially for the past 20 - 30 years. It defines the intermediate temperature

Figure 1



heat input into the desorber as (Qde) at temperature Td, and intermediate temperature heat for the evaporation process as (Qev) at temperature Te. The high temperature output heat is shown as (Qab) from the hot absorber at temperature Ta.

Vapor generated in the desorber flows to the condenser on the same pressure level (Pc) where it is condensed by cooling water removing the latent heat (Qco) from the vapor stream. Condensate is then pumped to the elevated pressure level (Pe), in the evaporator, where additional intermediate heat evaporate the condensate, to be sent to the absorber, where the vapor is absorbed into a lean mixture stream that was pumped from the desorber to the higher absorber pressure. The combined latend heat in this vapor, as well as the heat of solution (HOS) set free by the absorption process in the absorber, is able to elevate the temperature of the absorbend liquid mixture and deliver high temperature (Ta) heat (Qab) for use by external processes.

The efficiency of the AHT can be calculated as coefficient of performance (COP):

$$COP = \frac{Qab}{(Qde + Qev + W_{pumps})}$$

but the work done by the pressure pumps are at least 2 orders of magnitude smaller than the heat components, and are therefore mostly ignored in calculations. The COP is therefore:

$$COP = \frac{Qab}{(Qde + Qev)}$$

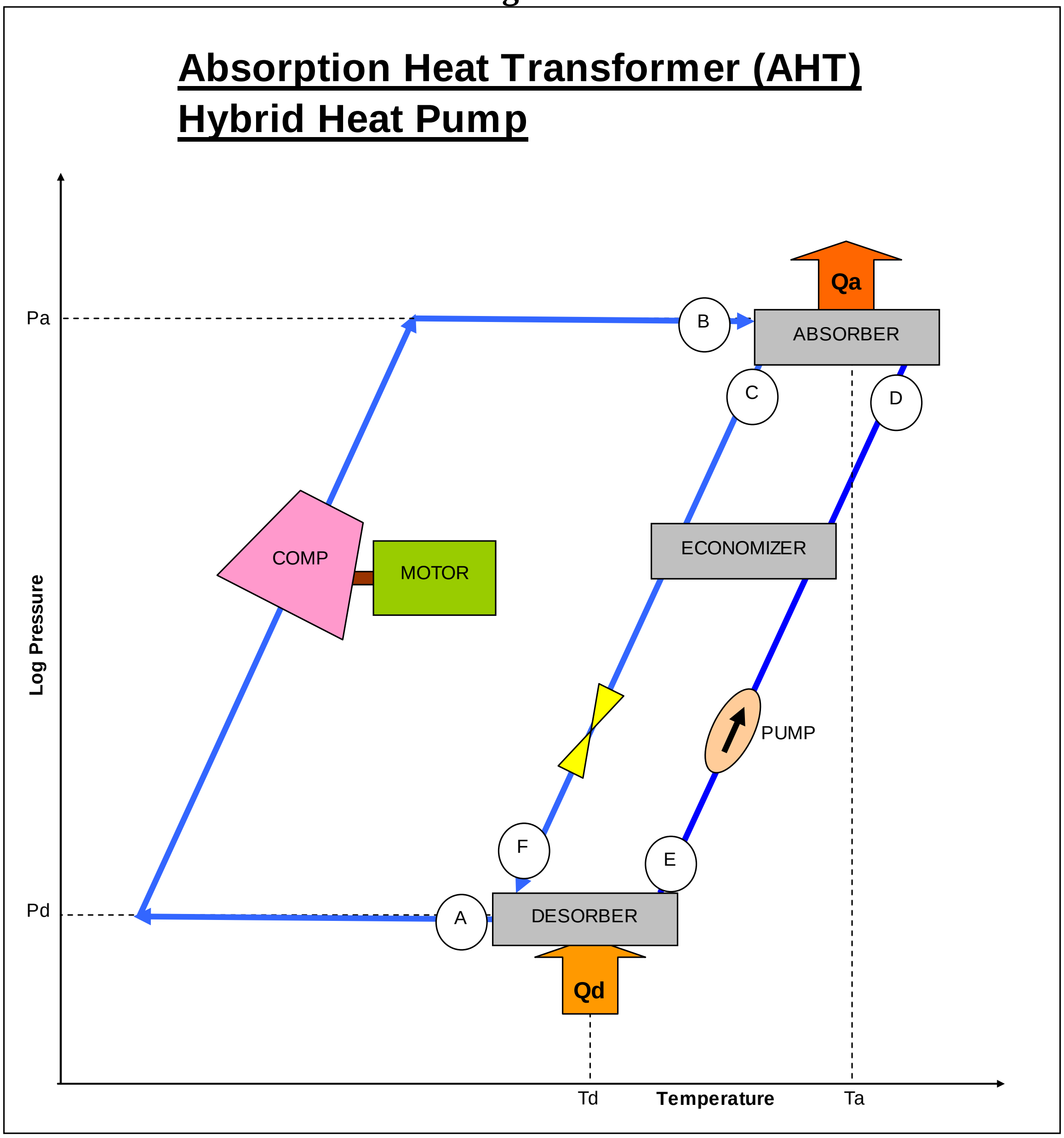
and typically range (0.1 - 0.5) in single stage, with the meaning that some 10% up to 50% of the intermediate heat may be upgraded to higher temperature, depending on temperature levels and heat exchanger efficiencies. This information on the standard state-of-the-art AHT is taken from W. Rivera [3] compiled already in 2000.

<u>The AHT Hybrid Heat Pump:</u>

From the sketch below, figure 2, the clockwise direction of vapor (flow A -> B -> C -> F) characterize the hybrid heat pump machine as a heat transformer (AHT) with clockwise flow, rather than a heat pump, where the flow is anti-clockwise. The major difference being, in absorption heat pumps, heat is added at high temperature (70 to 120°C), pumping heat from the low evaporation temperature (-20 to 0°C) to an intermediate temperature (30 to 50°C), where it is rejected. In the absorption heat transformer (AHT) as sketched in figure 1, above, heat is added at an intermediate temperature (30 to 50°C) and pumped or upgraded to higher temperature (70 to 120°C), at the expense of losing some heat to rejection at the cold temperature. The temperature difference between the intermediate input temperature and the high output temperature is referred to as the temperature lift. In the traditional single stage AHT the temperature lift would typically be 20 to 50°C. The energy required to create this temperature lift, is derived from the heat flow from intermediate temperature level to a lower, heat rejection temperature.

In the NH3 in aqua AHT Hybrid Heat Pump as sketched in figure 2, intermediate input heat (Qd) is used to boil off some NH3 vapor (A) from the strong NH3-rich solution

Figure 2



entering the desorber at line (F). The resulting weak liquid solution leave the desorber at line (E), to be pumped to higher pressure, (Pa) of the hot absorber. The pumped NH3-lean solution line E -> D is also in heat exchange (economizer) contact with the NH3-rich solution line C -> F flowing from the hot absorber back to the low pressure (Pd) cold desorber.

In the hybrid heat pump sketched in figure 2 above, a vapor compressor is used to replace the condensing, liquid pumping and re-evaporation processes in the conventional AHT sketched as figure 1, above. Intermediate temperature heat (Qd) is still used and upgraded to higher temperature, but this is augmented (hybridized) with electrical power to drive the compressor. In the traditional AHT the electrical power used for the two liquid pumps is at least two orders of magnitude smaller than the heat flow, and is therefore normally ignored. The vapor compressor use more power, however, very dependent on the compression ratio (Pa / Pd). Using this vapor compression, have the added advantage of being able to lower the intermediate waste heat input desorber temperature, even to values below ambient, to allow waste heat at lower (ambient) temperature levels to be absorbed as intermediate temperature heat sources. Two different expressions of efficiency is therefore used in this hybrid AHT, firstly the thermal heat produced (Qa) at elevated temperature with respect to the intermediate temperature heat (Qd) absorbed, called the thermal COP:

$$COP\_th = \frac{Qa}{Qd} \quad (0.1)$$

where Qa is the high temperature output heat available from the absorber, and Qd is the heat absorbed at intermediate temperature at the desorber used for boiling off some vapor NH_3. The COP_th value would in general be < 1, but may rise above 1 as result of the additional frictional heat generated by compressor inefficiencies (raising the vapor temperature above the adiabatic compression value instead of just adiabatically compressing it) added to the output heat (Qa). Typically COP_th ranges would therefore be (0.1 - 1.2) , depending on temperatures applicable. The second expression of efficiency relate the thermal heat produced at elevated temperature with respect to the electrical energy used by the compressor, called the electrical COP, with values totally dependent on the compression ratio of the vapor compressor:

$$COP\_e = \frac{Qa}{Wc} \quad (0.2)$$

where (Qa) again represent the high temperature output heat available in the absorber and (Wc) is the power used by the compressor to compress the low pressure (Pd) vapor from the desorber to the high pressure (Pa) of the absorber. This way of calculating COP is actually thermodynamically incorrect, as COP should be the delivered heat (Qa) divided by the combination of heat (Qd) and compression power (Wc), calculating to a much lower value. Should the energy in the intermediate heat input (Qd), be totally free and the electricity used come at some real cost, it is usefull to know the electricity cost of the heat pumped, even though it ignores the heat input to the delivered output heat. The high value of COP_e therefore serve a distinct purpose, in that it represent a simple way of calculating the **correct electricity cost** of commercial AHT Hybrid heat pumps.

The referenced paper by Nordtvedt et al [1] compiled into the IEA Handbook [2] detail a Hybrid Heat Pump delivering 650 kW_th heat for the Norwegian Food Industry built in 2007. Waste heat from a water stream at 45 - 50°C is extracted to power the desorber, cooling the waste heat stream by 10°C to 35 - 40°C in the process. This average temperature around 43°C represent the intermediate temperature heat input to the AHT. Hot water is available from the absorber via a heat exchanger at 83°C, and the absorber itself is heated from 45 - 50°C to the output temperature of 87°C. For this 40°C temperature lift, the efficiency calculations are **COP_th = 1.08** while **COP_e = 12.9** with the compression ratio of the vapor compressor **Pa/Pd = 2.87** and assuming a compressor isentropic efficiency of 70%.

In the above calculation of the actual example installation, the temperature lift is only 40°C, with intermediate temperature at 43°C and the output temperature at 83°C. Should a higher temperature lift (of 70°C) be required to be able to use ambient heat as intermediate temperature input (ambient heat would spontaneously flow into the desorber, being kept at 0°C), the theoretical simulation calculation would give results as follows: The compression ratio would increase to **Pa/Pd = 8.88** with a corresponding reduction in COP value (as expected) **COP_e = 6.1**, as the compressor have to work very much harder in the compression process, while the **COP_th = 1.2** slightly increased from the previous example temperatures.

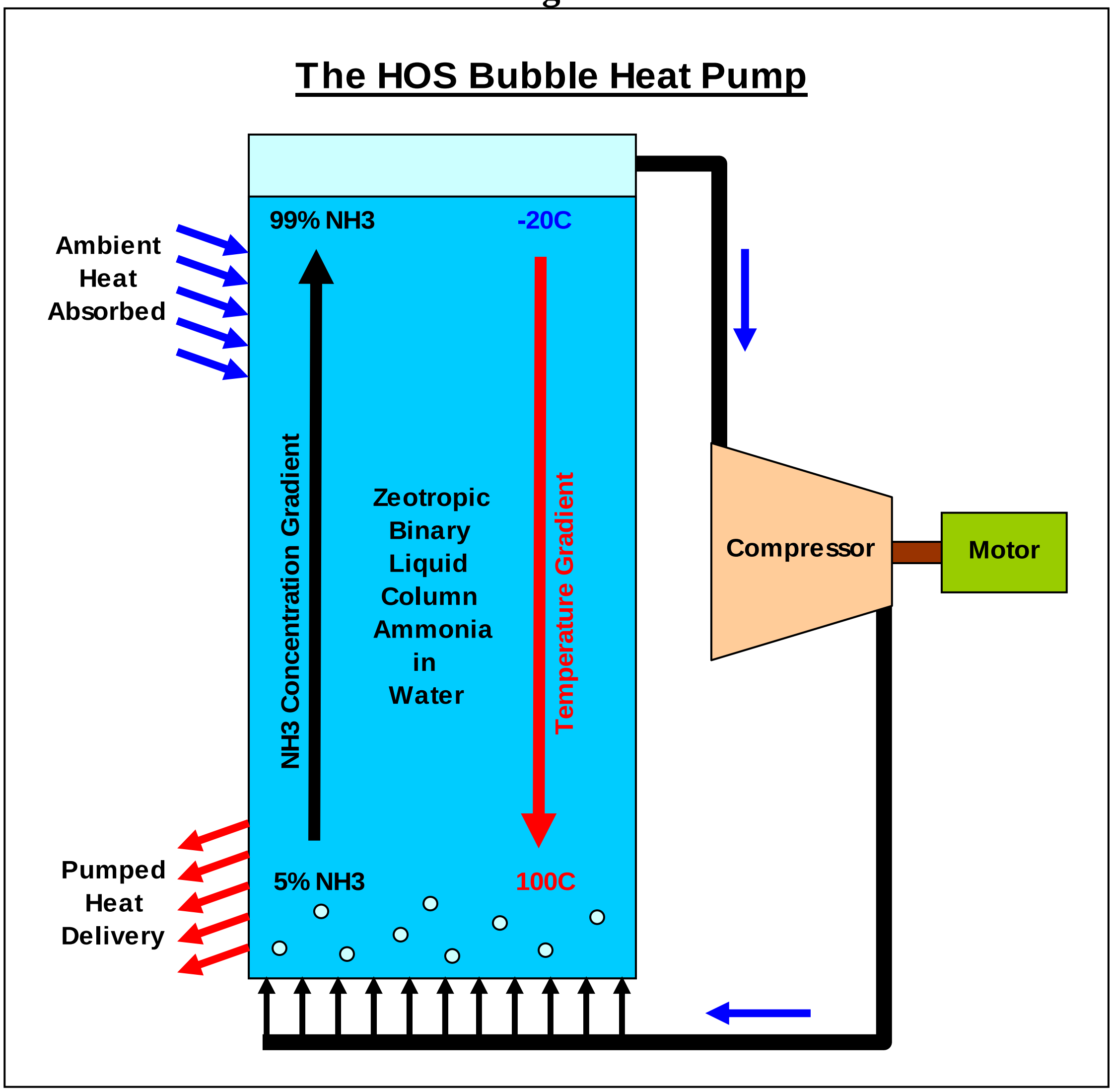
In this type of hybrid heat pump, heat is exchanged in the economizer (see figure 2) between the weak ammonia solution flowing from the cold desorber to the hot absorber (line E -> D in figure 2), and the strong ammonia solution returning from the absorber to the desorber (line C -> F in figure 2), but no mass- and species exchange is possible in the discrete lines, therefore the ammonia concentration cannot change to influence the compression ratio. The compression ratio (Pa/Pd) is therefore totally dependent on the temperatures of the desorber and absorber, using the fixed NH3 concentration.

The HOS Bubble Heat Pump:

The heat of solution (HOS) Bubble Heat Pump as configured in figure 3 below, closely resembles the hybrid AHT as described above, but the strong and weak ammonia solution flows (line E -> D and line C -> F) are both contained in the single vertical column bubble reactor, and are counter flows of the binary liquid mixture pumped by vapor lift pump action and seperated by gravity as a result of density differentiation. The recirculating counter flows are subjected not only to direct contact heat transfer, but also to mass-, and species transfer changing the NH3 concentration of the cold desorber (top end of the bubble reactor) with respect to the hot absorber (bottom end of the bubble reactor), in so doing, decreasing the applicable compression ratio (Pa/Pd) for the same temperatures as described in the hybrid heat pump. As the bubble reactor is a single liquid column, the pressure differential (Pa - Pd) is the hydraulic pressure of the liquid column acting on gravity, while the absolute pressure values of Pa and Pd represent the saturation pressure of the NH3 in aqua solution at the saturation temperatures, Ta and Td respectively.

For the temperature lift of 70°C (desorber (reactor top area) at Td = 0°C, and absorber (reactor bottom area) at Ta = 70°C) the NH3 concentration gradient (desorber at 61.14% NH3 in aqua, while the absorber has a concentration of 32.89% NH3 in aqua) bring down the compression ratio **(Pa/Pd) = 3.46** (vs. the hybrid machine compression ratio of 8.88 for the same temperature delta), resulting in **COP_th = 1.15** while **COP_e = 7.5** (vs. the hybrid machine COP_e value of 6.1). The absolute pressure Pd, may be altered by changing the total mass of NH3 present in the reactor relative to the total mass water present. A smaller mass of NH3 in the reactor would decrease the pressure, and after heat added to the reactor created the temperature and NH3 concentration gradients, the %NH3 concentration at the top and bottom of the reactor may balance out as follows: With this greater %NH3 difference between the absorber (bottom) and desorber (top), keeping the desorber pressure constant at Pd = 1.69 Bar Abs (by keeping the NH3 concentration in the reactor top area 61.14% NH3 in aqua at the 0°C saturation temperature), while the absorber pressure (saturation pressure of the NH3 in aqua mixture at 70°C) was reduced

Figure 3



from 5.85 Bar Abs to Pa = 1.99 Bar Abs, (with the reduction of NH3 concentration in the absorber to 15.19% NH3 in aqua from the previous 32.89%), resulting in the real

compression ratio of 1.18 (down from the previous 3.46), with the resulting efficiency calculations:

COP_th = 1.02 while the **COP_e = 53.6**

This high heat pump performance can be further enhanced by increasing the reactor over-all operating pressure. By increasing the average NH3 concentration in the reactor, adding in more NH3 liquid, both the desorber and absorber saturation pressure is increased at the temperatures of 0°C and 70°C respectively. Using this same temperatures, and keeping the pressure differential at 30 kPa (representing the hydraulic backpressure of a 3 meter column of liquid mixture), the high desorber NH3 concentration of 70% - 90% NH3 in aqua at 0°C would create a saturation vapor pressure of 3.18 Bar Abs at the reactor top in the desorber area, while the NH3 concentration of 23% - 30% NH3 in aqua in the absorber area at the reactor bottom, have a saturation vapor pressure of 3.48 Bar Abs. This spell out the compression ratio **Pa/Pd = 1.09** (reduced from the previous 1.18), giving rise to the efficiency calculations:

COP_th = 1.01 while the **COP_e = 71.6**

It is therefore quite clear that the electrical energy required to power a heat pump built on these AHT principles, in combination with a low compression ratio vapor compressor is extremely small, the balance of the energy requirement being absorbed from the low intermediate temperature waste heat source, with COP_e values ranging from 50 - 100 in well-designed heat pumps operating with extremely low compression ratio's. As waste heat at ambient conditions are not calculated as an expense, only the electrical COP_e values are important in expense calculations for high temperature heat delivery.

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