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Energy Evaluation of the Use of an Absorption Heat Pump in Water Distillation Process

Rosenberg J. Romero and Sotsil Silva-Sotelo

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Abstract

It is impossible to transform the whole energy into useful work. It is impossible to increase the processes of cultivation of foods without water. It is impossible to separate all ions and minerals from water. Most of the real processes are thermodynamically irreversible. Calculations may indicate the fraction of efficiency of a thermal process. All the above mentioned facts have led to some proposals of cycles that exchange energy in order to produce a useful effect for the society. The key sustainable related parts are: to obtain water free of minerals or ions by distillation process. In this chapter, thermodynamic cycles will be explained for distillation using thermodynamic cycles of thermal machines called absorption heat pumps (AHPs). Distillation process offers to the AHPs an opportunity to diminish the consumptions of fossil fuels. The AHPs are able to work with 2% of mechanical energy to carry out a sustainable distillation process. Most of the energy of an absorption heat pump operation is thermal energy. The operation of the AHPs are defined with the coefficient of performance (COP); the variations of this parameter are shown as function of the different scenarios to obtain sustainable distilled water.

Keywords: distillation, absorption heat pump, thermodynamic cycles

1. Introduction

One of the most useful processes for the sustainability would consider the efficient use of energy, water, and foods. Regrettably to include these three participants involves a process of consumption of those. It is impossible to transform the whole energy into useful work. It is impossible to increase the processes of cultivation of foods without water. It is impossible to separate all ions and minerals from water. The thermodynamics has identified the processes like reversible or irreversible process. Most of the real processes are

irreversible. Calculations may indicate the fraction of efficiency of a thermal process. All the abovementioned facts have led to some proposals of cycles that exchange energy and matter with its surroundings, in order to produce a useful effect for the society. Excepting the production of foods, both key sustainable parts are related: to obtain water free of minerals or ions, it can be carried out with distillation process. In this chapter, thermodynamic cycles will be explained for distillation using thermodynamic cycles of thermal machines called absorption heat pumps (AHPs).

The main advantage of an absorption heat pump is that almost the whole energy that manipulates is thermal. Opposing to the conventional water purification systems, smaller energy is required to carry out the purification. The biggest difference with the heat exchanger is that it carries out the purification of water at different thermal levels. In the case of a heat exchanger, the energy source, where the energy comes, is at a higher thermal level (see **Figure 1**).

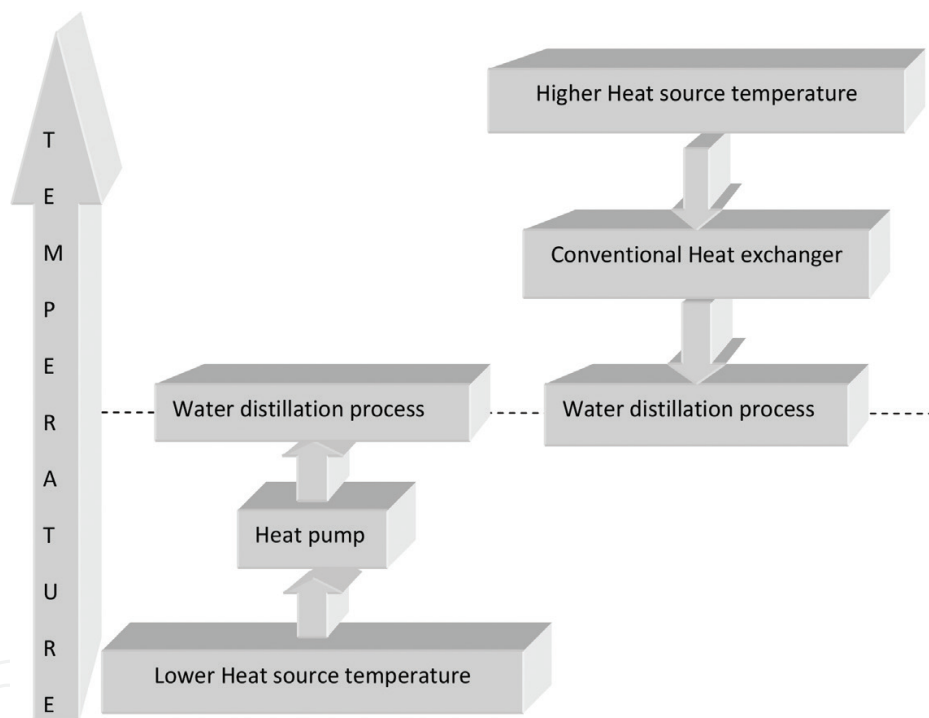


Figure 1. Thermal levels for water distillation.

2. Absorption heat pump

An absorption heat pump is a physic-chemical device made for use of sustainable thermal energy.

One of the obstacles of the technology is the ignorance that one has of them. The heat pumps are a type of thermal machines with subtle popularization. The basic concept is an analogy

with a mechanical pump for water. A mechanical pump for water drains water from a lower level, and by application of mechanical energy, the water goes to a higher level. In similar way, a heat pump takes energy at a lower level and sends it to a higher level, using a part of mechanical energy. This process actually happens, and it is called compression heat pumps (CHPs). If same process happens with thermal energy, then it is called absorption heat pump. The energy may go into a heat pump from several kinds of sources:

- Geothermal [1–7],
- Solar [8–11],
- Natural gas [12–14],
- Air [15–19],
- Groundwater [20–22]
- Even from mechanical energy [23, 24]
- Coal process [25–27]

The next section details the characteristics for compression and absorption heat pumps.

2.1. Compression heat pumps

A mechanical vapor compression heat pump (CHP) is a mechanical device that works with mechanical energy. The process that happens into a CHP is a thermodynamic cycle with two operations: compression and expansion (see **Figure 2**). CHP needs a fluid with the ability to change from liquid to gas. The operating conditions are constants for pressure and temperature all the time. Required energy for these changes is mechanical energy. Energy comes from lower temperature energy to the evaporator at the lowest pressure in the cycle. The delivering energy from CHP to the surroundings (i.e., for water distillation) goes at the highest pressure in the condenser. This process is a cycle, and it requires intermittent or constant energy [28].

2.2. Absorption heat pump

An absorption heat pump (AHP) is a mechanical device that does same function as CHP. It substitutes the compressor by two additional thermal components. The permanent components for a heat pump are a condenser and an evaporator. The additional thermal components which turn a CHP into an AHP are a vapor generator or called desorber and vapor absorber.

The AHP is classified in a simple way [29]: Type I if condenser temperature is higher than evaporator temperature ($T_{CO} > T_{EV}$) and Type II if condenser temperature is lower than evaporator temperature ($T_{CO} < T_{EV}$).

Type I AHP is called “conventional heat pumps,” and Type II AHP is called “inverse heat pumps” or “absorption heat transformers.”

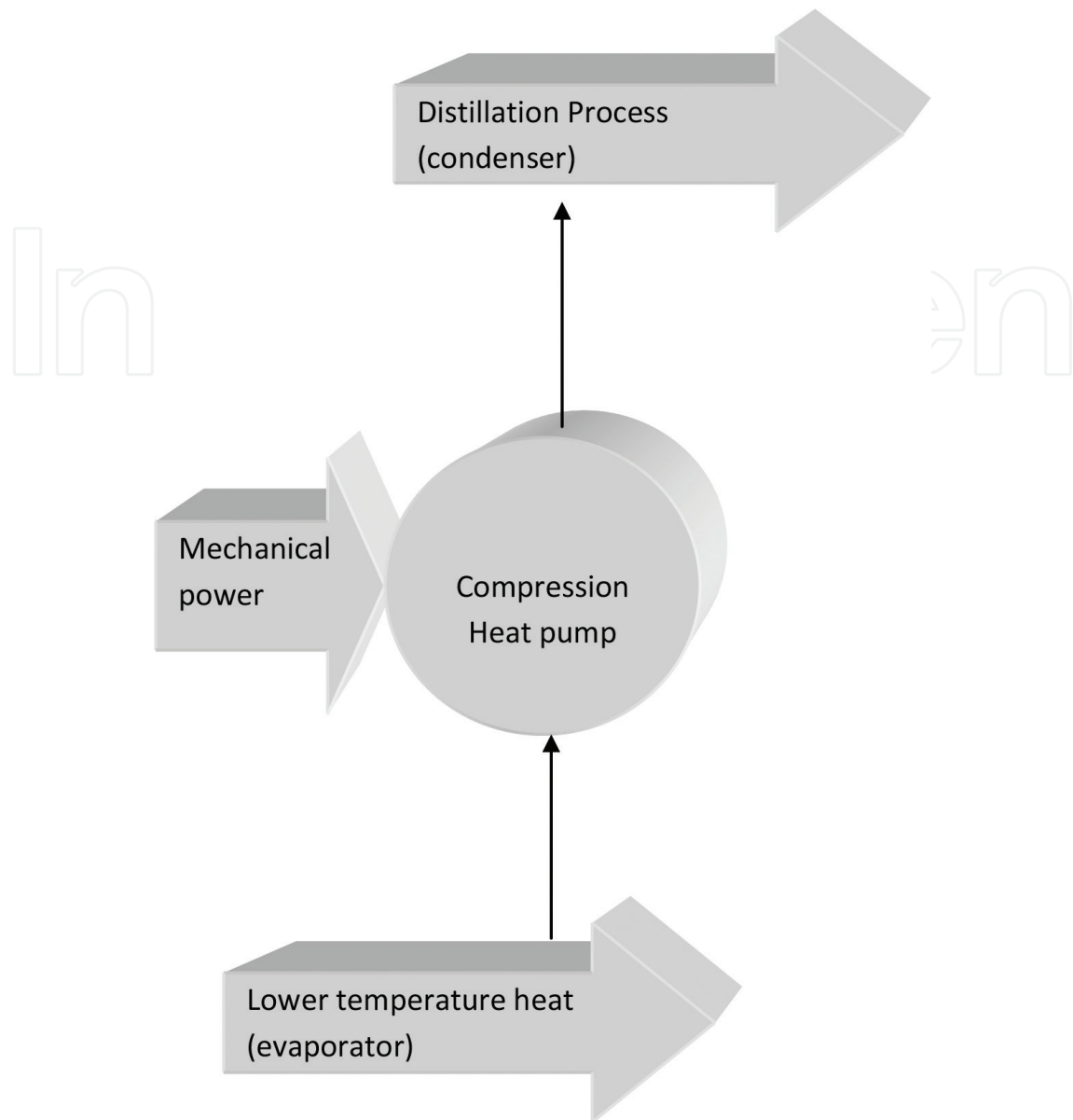


Figure 2. Schematic diagram for compression heat pump.

2.2.1. Type I heat pumps

For heat pumping, an AHP really does a useful energy transference from a lower temperature-level source of energy, free of cost (i.e., air, water, or soil) to a higher temperature level. The cycle is divided into two parts: the first part is a “working fluid” desorption from liquid absorbent at the highest temperature in the system. The second part happens at lower temperature and lower pressure for easy energy transference. When “working fluid” goes in vapor phase with liquid absorbent (separated in the first part), then a heat delivering at intermediate temperature occurs. When vapor is condensed at the highest pressure, it delivers heat at intermediate temperature also. These processes may be possible to obtain almost two thermal

energy units for each thermal energy unit with cost, because the energy with no cost from air, water, or soil is able permanently.

Figure 3 shows schematically these processes. There are three thermal levels in a Type I AHP. **Figure 4** shows the pressure zones and the thermal levels for the particular processes into the thermodynamic cycle.

The high pressure zone is useful for thermodynamic explanation. For a “pair” (“working fluid” and “absorbent”) like water-lithium bromide, the vapor generation happens at

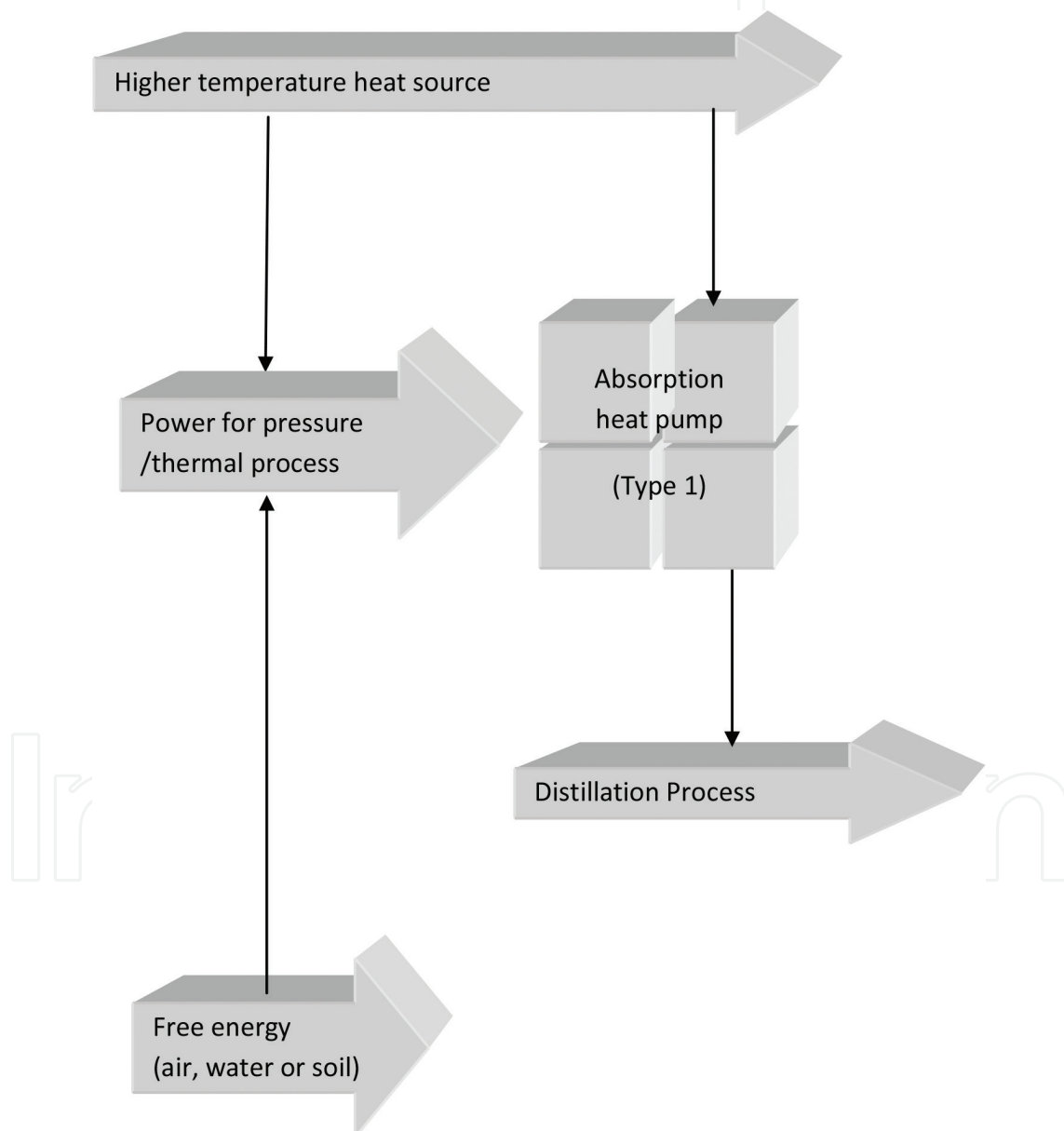


Figure 3. Absorption heat pump (Type 1) schematic concept.

temperatures lower than 100°C because there is vacuum pressure, and then the concept of relative pressure is essential.

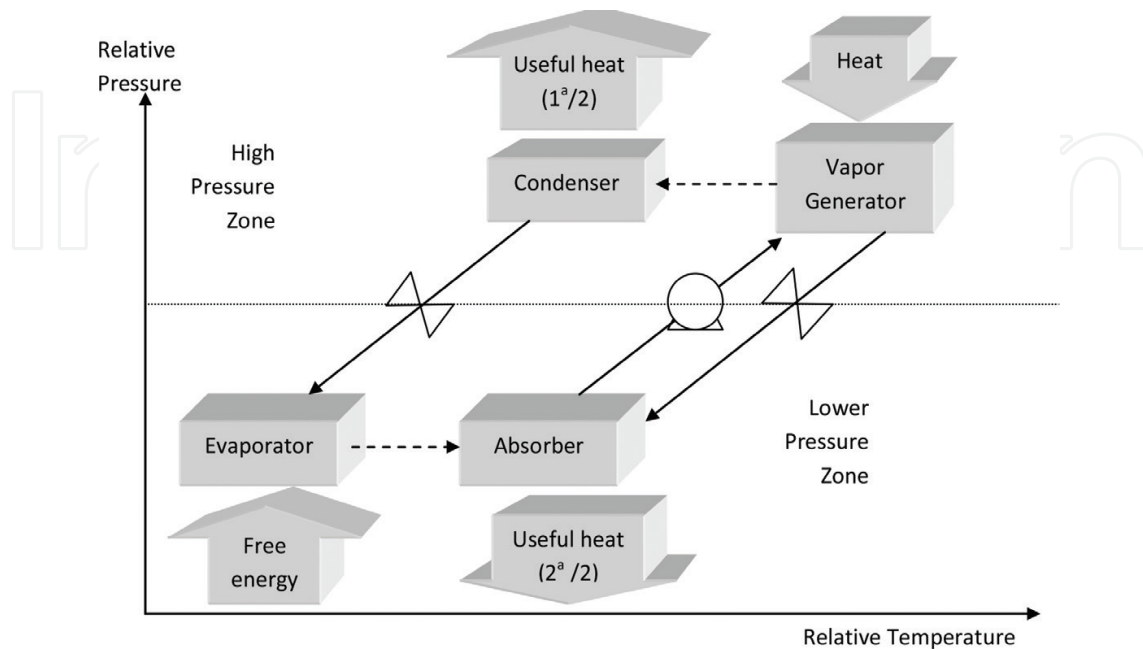


Figure 4. Absorption heat pump schematic cycle.

The thermodynamic cycle starts with energy going to “vapor generator” at higher temperature and higher relative pressure. The “working fluid” is separated from “absorbent,” and it condensates in condenser unit. The condensation process releases useful energy but at lower energy level than “vapor generator.” The liquid from condenser is expanded to the evaporator. In evaporator, “working fluid” is placed in contact with a free cost of energy source (air, water, or soil) at the lowest temperature level of the cycle. This temperature defines the pressure value of the entire lower pressure zone. The evaporator generates vaporized working fluid a low temperature by low-pressure condition while the absorbent with diminished working fluid mass concentration is expanded from the “generator” to the absorber. The liquid that is coming from the generator is placed with the vaporized working fluid into the absorber, and this process delivers useful energy at intermediate temperature. The result for this cycle is that there are two components delivering useful heat for just one energy entry. The solution with absorbent and working fluid is pumping to the generator to restart the cycle. The energy balance is obvious:

$$Q_{GE} + Q_{EV} = Q_{CO} + Q_{AB} \quad (1)$$

where Q_{GE} is the heat at the highest relative temperature entering to the “vapor generator” in the AHP, Q_{EV} is the heat at the lowest temperature level and coming from free cost of energy source, Q_{CO} is the useful energy at intermediate temperature caused by latent heat from vaporized “working fluid” originated in the generator, and Q_{AB} is the useful heat delivering for the junction of absorbent with working fluid at lower relative pressure.

The thermal efficiency for thermal machines is based on “coefficient of performance” (COP). This COP is defined for each system. For this AHP, the COP is defined as the ratio of useful energy by energy with cost. In this AHP process, the pumping work is negligible because that is around 1% of the thermal energy:

$$COP_I = \frac{Q_{CO} + Q_{AB}}{Q_{GE}} \quad (2)$$

This dimensionless value allows comparison with other technologies even with different power capacities, higher or lower. A COP value equal to 1 means all entering energy in the AHP is useful. Values higher than 1 mean that cost-free energy is added to useful energy.

2.2.2. Type II absorption heat pumps

The main difference between Type I and Type II absorption heat pumps (AHP) is basically the switch between the pressure zones. **Figure 5** shows the pressure and temperature levels to note that difference in the operation modes.

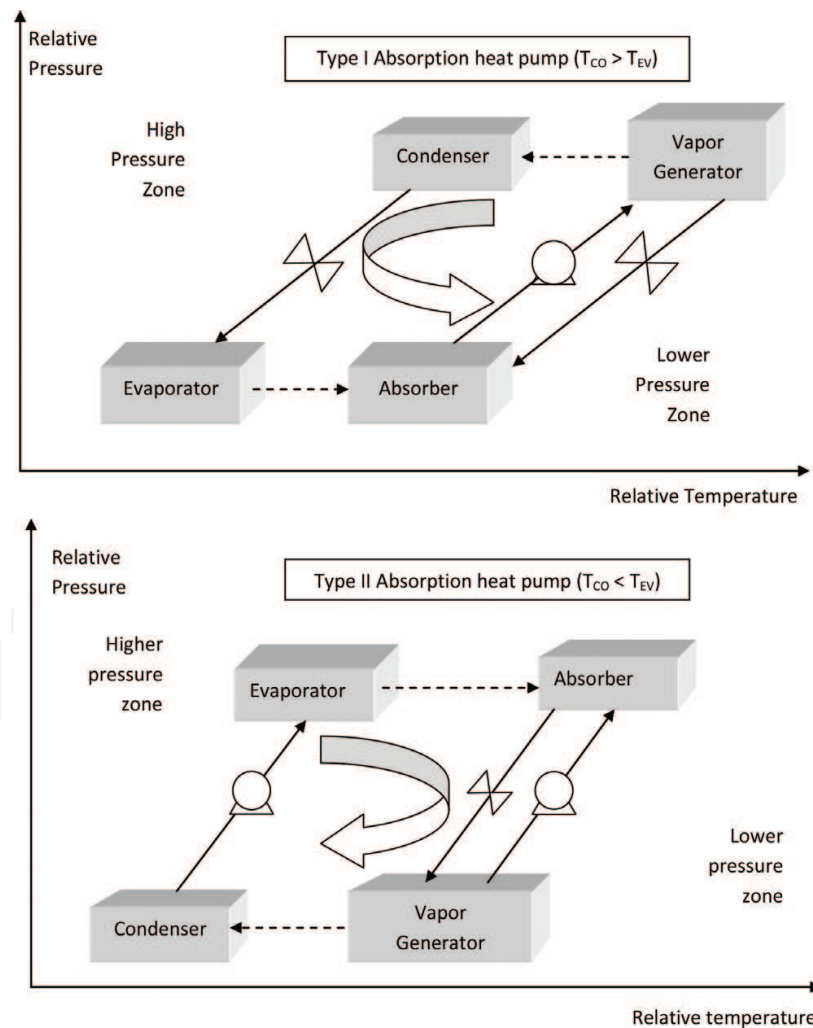


Figure 5. Type I and Type II absorption heat pumps.

Unit operations for both AHP types are the same, but they happen at different pressure and temperature values. So, the mass balance is same for Type I and Type II AHP.

The cycle occurs in similar way (see **Figure 6**). Thermal energy enters to generator and evaporator. Thermal energy is delivered in absorber and condenser. The main advantage is that energy is added at intermediate temperature level, and useful energy is delivered at higher energy level but only in absorber component.

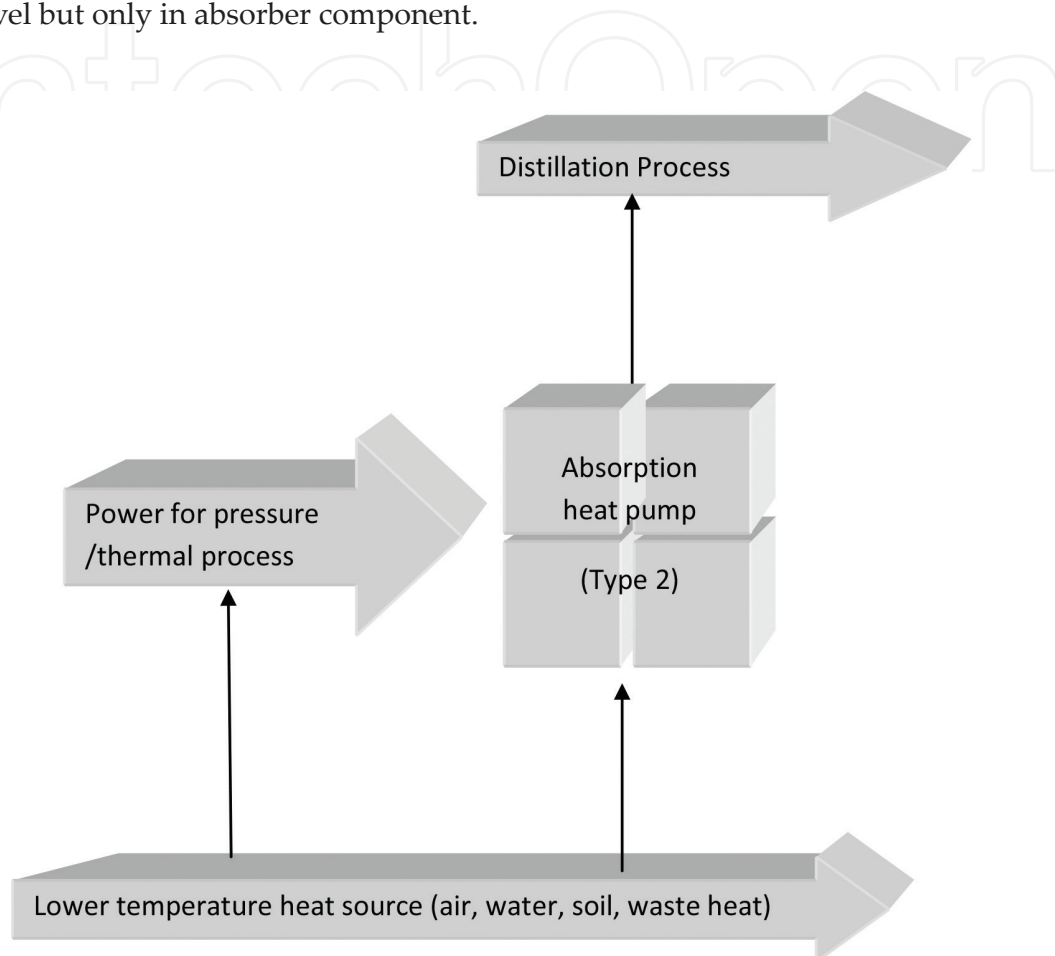


Figure 6. Absorption heat pump (Type 2) schematic concept.

This process has a particular implication: this is the unique technology that transforms thermal energy to mechanical pressure lift to deliver energy at higher temperature than the energy source.

Cycle starts when energy enters to the generator and evaporator. The generator splits working fluid in vapor phase from absorbent. The working fluid is pumping through the evaporator. Evaporator is at higher relative pressure. Evaporator changes to vapor phase from the working fluid. This vapor is contacting with liquid absorbent into the absorber. The liquid absorbent comes from the generator at intermediate temperature. The absorption process delivers energy at the highest pressure in the system. The diluted solution returns to the generator to restart the cycle.

COP for Type II AHP, with negligible 2 % of pumping work, is

$$\text{COP}_{II} = \frac{Q_{AB}}{Q_{GE} + Q_{EV}} \quad (3)$$

This dimensionless value is lower than the unit because the utilized energy is used as part for pressure lift and other energy parts are revalorized. It is notorious to think that if energy comes from renewable energy or waste heat [30], then the results of the CO₂ emission diminish.

3. Distillation process

Distillation process is expensive energetically. This process has two parts: the first part is to rise the liquid's temperature from an actual condition to saturation point, and the second part is to add a lot of energy to phase change process. This process has two processes, and every part has inefficiency depending on heat transfer process into vapor phase or gaseous phase.

Gases exhibit low heat transfer coefficients for the nature of molecular composition. The liquid's molecules have higher thermal conductivity than gases' molecules at same pressure and temperature conditions. Then, it is a better strategy to design energy transfer process with bigger transfer areas for liquid falling films to promote distillation process.

3.1. Water distillation

Water distillation with heat pump is no new [31–33]. However, it has lower reports [34]. The citation to papers indicates that some systems have been implemented for that purpose. The installation has two main problems: low efficiency for comparison with other technologies [35–39] and higher cost compared with conventional systems [40].

Type II AHPs are called “absorption heat transformers” also, and those have been reported for water distillation evaluation [41, 42]. Some configuration has success like “solar ponds” coupled to “absorption heat transformer” [43–45] and solar systems [46] among others renewable energies [33].

The main objective for this technology is to obtain mineral-free water with lower ambient impact [47, 48].

4. Water distillation with absorption heat pumps

Water distillation from seawater or wells may be realized with AHP with a great advantage: lower ambient emission [32, 49, 50] in order to optimize the water distillation with the minimal energy supply [51].

The modeling for this process has been previously reported with author's collaborators (i.e., [52]) that is based on mass and energy balances. It has assumptions and considerations for iterative calculation at steady-state conditions. The assumptions are close to reality to identify

potential operating conditions for water distillation with Type I and Type II AHPs, with a huge amount of waste heat or renewable lower temperature heat.

4.1. Operating conditions

Water distillation requires a constant higher thermal energy. This temperature is a function of sea-level altitude at atmospheric pressure. It is not recommendable to include a vacuum process or artificial pressure increase for water distillation because those increase the energy consumption for mineral separation from distilled water [53]. For this reason, this chapter shows pairs based on water-lithium bromide for water distillation purposes for both AHP modes: Type I and Type II with:

- Lithium bromide-water
- Lithium bromide-ethylene glycol-water (called Carrol [29])

There is a possibility to use advanced AHP (double absorption or double stage [33]), but those configurations have lower COP values, and then they are not shown in the next results. Operating conditions are calculated for water distillation at a sea-level atmospheric pressure.

5. Results

The results are based on dimensionless COP that means how many energy is used for water distillation as function of each thermal energy unit added to the AHP. Of course, this dimensionless COP allows the comparison between the AHP systems.

Figure 7 shows the ratio of energy used for distillation of water with a Type I AHP using water-lithium bromide. It is clear that all energy is not useful. Some part is a waste into the cycle, while evaporator temperature is closed to ambient temperature. The best operating conditions for this distillation are for waste heat at 160°C, with a preheating treatment for water saturation at 80°C and distillation into the absorber component at 105°C.

Figure 8 shows the dimensionless COP for comparison with water-lithium bromide-ethylene glycol as additive to avoid risk in crystallization for lithium bromide. The additive has no variation in the used energy for water distillation. The dimensionless value is almost same for water distillation process at same operating conditions, but there is a variation of 10% away from risk into actual operation for leak of fracture in tubes.

Figure 9 shows the proposal of Type II AHP for water distillation using water-lithium bromide. This is a great opportunity to operate a cycle with revalorization of waste energy. The dimensionless COP value is lower than of Type I, as expected. But the temperature values are lower. Water distillation happens with only 80°C heat source, at 20°C in the ambient temperature. The thermal efficiency goes from 0.38 to 0.48 for waste heat. This is a notorious result. It is not necessary to raise energy at 100°C to water distillation. This technology allows distillation for well water with renewable energy lower than conventional machines.

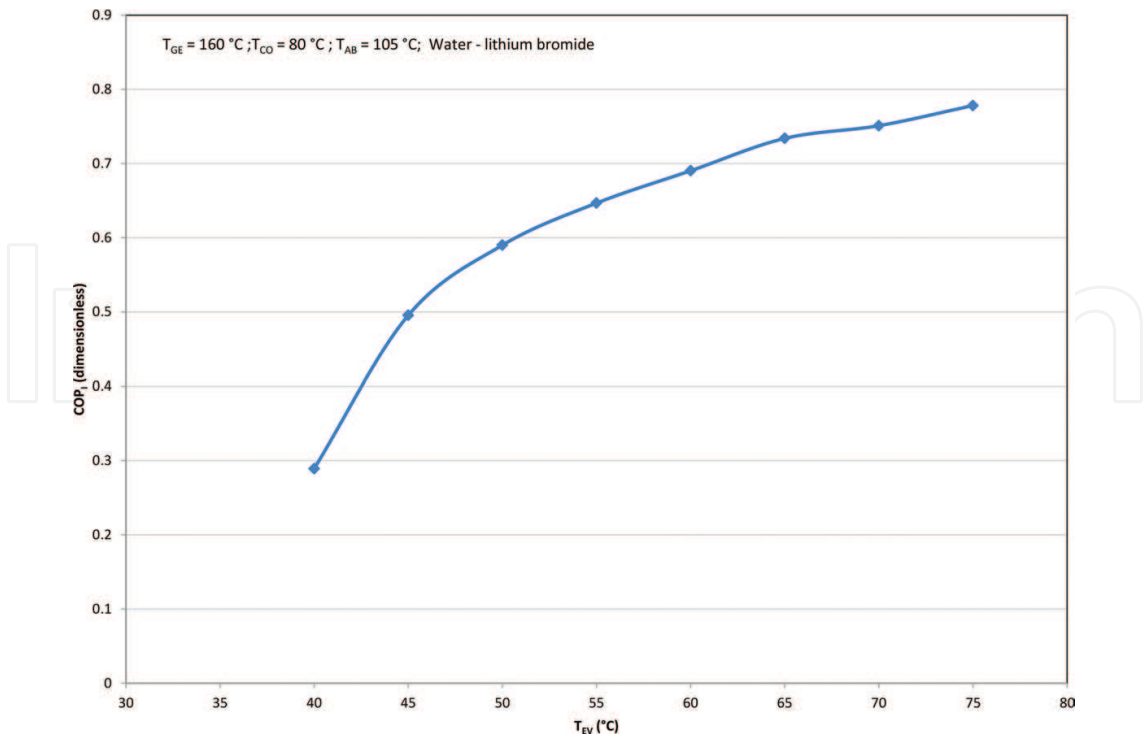


Figure 7. Dimensionless COP Type I AHP for water distillation.

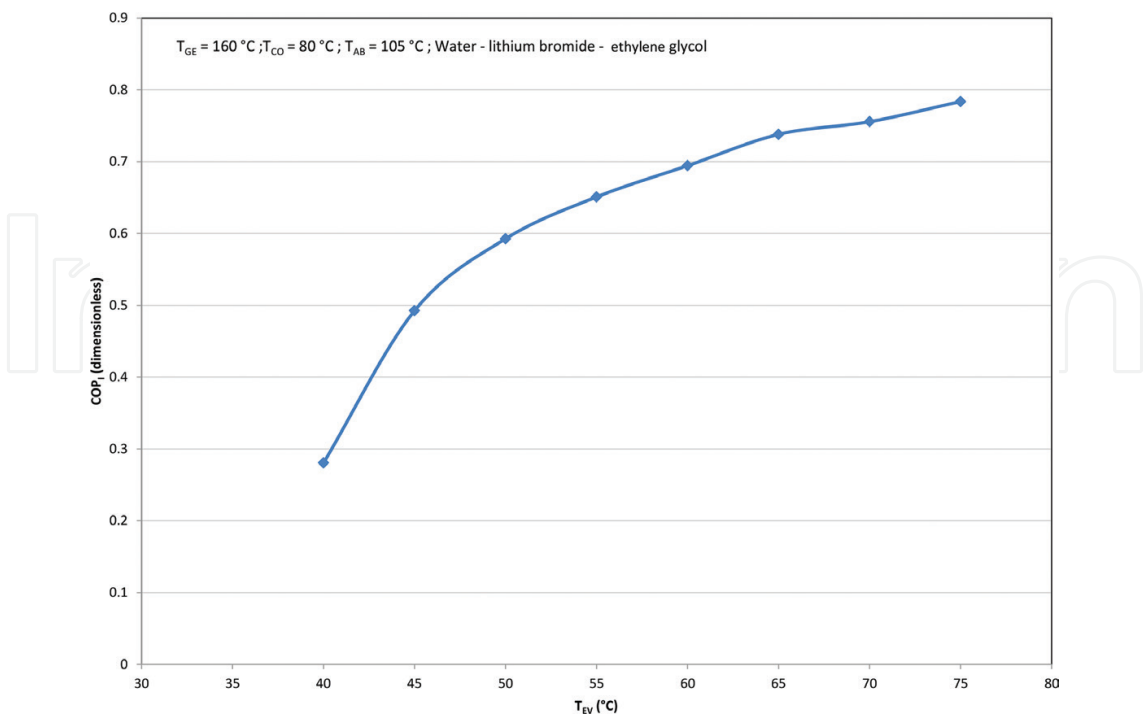


Figure 8. Dimensionless COP Type I AHP for water distillation.

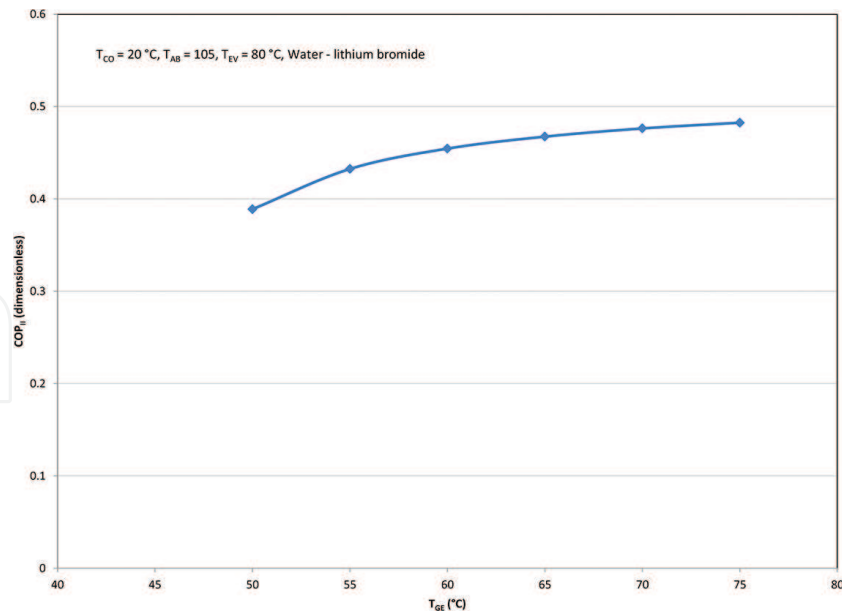


Figure 9. Dimensionless COP Type II AHP for water distillation operating with water-lithium bromide.

Finally, **Figure 10** shows a variation of the last operation conditions. The additive ethylene glycol is used to avoid crystallization. There is no variation in thermodynamic conditions for this distillation purpose, but safety for risk in crystallization is obvious. This actual operation avoids risk around 90% compared to lithium bromide.

The distillation is possible with AHP with thermal efficiencies from 0.38 to 0.78 with no fossil fuels using water-lithium bromide-ethylene glycol as pair.

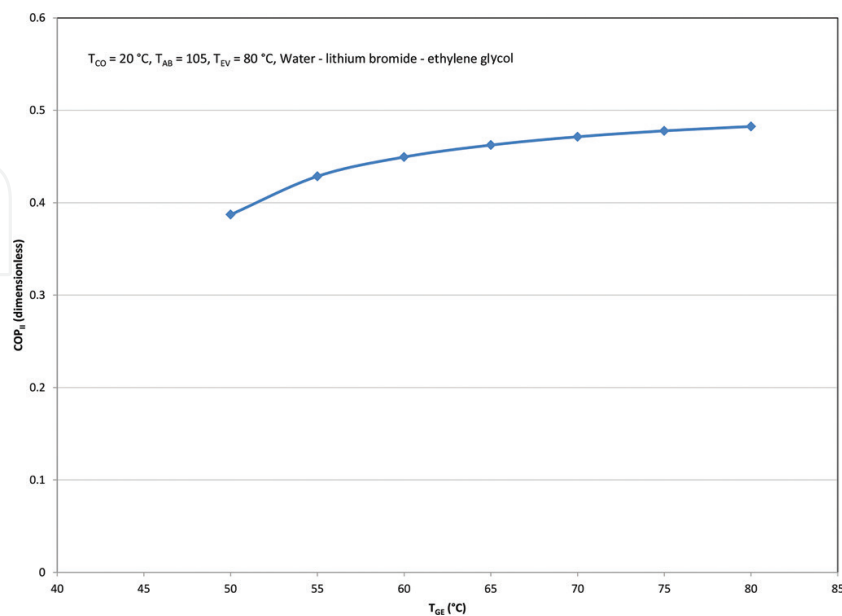


Figure 10. Dimensionless COP Type II AHP for water distillation operating with water – Carrol.

6. Conclusion

The energy-efficient policies with renewable energy integration are not an actual trend; this is a requirement for sustainability. Renewable energies coupled to thermodynamic cycles for water distillation have been reported previously for another authors with energy input of PV + RO around 3–20 kWh/m³ and PV + WIND + RO around 3–16 kWh/m³.

Conventional mechanical vapor compression plants have energy input around 11–14 kWh/m³ for commercial purposes. Some energy for that process comes from fossil fuel with GWP gas emissions.

For absorption heat pumps, the efficient energy use is obvious: the thermal energy for these cycles (Type I and Type II) comes from waste energy or renewable energy; then there are no CO₂ emissions, while these are operated and provide distilled water.

The cycles in this chapter show water distillation at atmospheric pressure with heat exchange at 100°C with two stages: one in condenser unit to preheat the water and a second unit, the absorber, for flash process. This combination allows a distilled energy at 3.75 kWh/m³ for Type I absorption heat pump and 8.5 kWh/m³ for Type II absorption heat pump. These values include the actual COP with a higher distilled water production at the higher evaporator temperature in both types.

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