**Heat pump application for water distillation**

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**Abstract:** Purification of water is one of the human life importances to get pure water for daily usages. Many methods and instruments are used for that purpose. In the present work, the heat pumps used as the heat source and sink. The hot side of the heat pump supplies the thermal energy that is used for water evaporation. The temperature provided by the heat pump is not enough to evaporate the water under the atmospheric pressure, so that; the pressure in the vessel containing the water to be vaporized must be decreased to induce the water evaporation at the temperature of about 40-60oC. The cold side of the heat pump is used for condensation of water vapor and cooling the water to make it suitable for drinking and other usages. The vacuum pump here is to provide a pressure difference between the evaporation and condensation vessels of water to change the boiling and condensation temperatures of water.

**Keywords:** thermal energy, water distillation, heat pump, energy saving, evaporation, condensation, heat exchanger, sensible heat, latent heat.

1. Introduction

Many types of water purification instruments are used for water distillation. They can be classified into two main types; the first is using chemical treatment for purification as in [1] in which the hardness of water is treated. This type already needs chemical materials to still work and the results from this equipment must be treated to prevent environmental pollution. The advantage of these systems is the little power spending for operation. The second type of water distillatory is physical treatment of water for purification. These systems are subdivided into three types. One of them uses the mechanical softening to remove the solid impurities as in [2] and this type does not affect the hardness of water. The second follows the physical steps of liquid evaporation and condensation in form of distilled water [3] and [4]. The final method which is called "Reverse Osmosis" depends on increasing the pressure applied to water to separate the unwanted components from it [5]. The combination of the chemical and mechanical softeners will give the special type as in [6].

1. Thermal analysis

As known, liquids need heat for evaporation [7]. The boiling temperature depends on the pressure applied on the liquid. Two types of heat are necessary to complete the evaporation process. To raise the temperature of liquid to reach the saturated liquid state (the boiling temperature), sensible heat must be added. The liquid pressure controls its boiling temperature [8]. The relationship between them is direct. As the pressure decreases the boiling temperature also decrease.

Latent heat is necessary to complete the evaporation process at constant temperature and pressure [9]. After the liquid transforms to vapor, its temperature begins to rise again. In this situation, the sensible heat must be added to reach the final temperature. The aim of this project is to evaporate water then condensate it to get establish the aim of this work which is distilled water. All processes that deal with that can be solved thermodynamically. In the figure (1) the representation of all evaporation steps on (T-S) diagram.

**T**

 **S**

1

2

3

4

**Fig. 1.** Evaporation steps on the (T-S) diagram (1-2) sensible heat addition (2-3) latent heat addition, (3-4) sensible heat addition.

The heat adds in the first step may be found through:

$$Q\_{(1-2)}= C\_{p} \left(t\_{2}-t\_{1}\right) (1)$$

Where *Q*(1-2) is the sensible heat (kJ/kg); *Cp*- is the specific heat of water at constant pressure (kJ/kg\* °C); *t*1 and *t*2- are the temperature of water at the beginning and the ending process respectively (°C).

The heat adds through (2-3):

$$Q\_{(2-3)}= \left(h\_{3}-h\_{2}\right) (2)$$

Where *Q*(2-3) is the heat that changes the phase of fluid from the saturated liquid to the saturated vapor (kJ/kg), *h*2 and *h*3: are the enthalpies of fluid at the points 2 and 3 (kJ/kg).

The final step in evaporation is superheating from the point 3 - 4 and the heat absorbed by the vapor will change its temperature, so that; it is sensible. The amount of heat in this part is the following:

$$Q\_{(3-4)}= C\_{p} \left(t\_{4}-t\_{3}\right) (3)$$

Where *Q*(3-4) is the sensible heat through this process (kJ/kg), *Cp*- is the specific heat of vapor at constant pressure (kJ/kg\* °C), t3 and t4- are the temperatures of inlet and outlet vapor to this process respectively (°C).

To get the distilled water, the vapor must be condensate. For that goal, the heat will be removed. The reversing of evaporation process will return the fluid to its original state that means, all thermodynamic processes are assumed to be repeated reversely to get the path as in the figure (2).

**T**

 **S**

4

3

2

1

**Fig. 2.** Condensation steps (1-2) sensible heat removal (2-3) latent heat removal and (3-4) sensible heat removal.

$$Q\_{(1-2)}= C\_{p} \left(t\_{1}-t\_{2}\right) (4)$$

Where *Q*(1-2) is the sensible heat through this process (kJ/kg); *Cp*- is the specific heat of vapor at regular pressure (kJ/kg\* °C), *t*1 and *t*2- are the temperatures of vapor at entry and the end of this process respectively (°C).

$$Q\_{(2-3)}= \left(h\_{2}-h\_{3}\right) (5)$$

Where *Q*(2-3) is the rejected heat that changes the fluid phase from the saturated vapor to the saturated liquid (kJ/kg).

$$Q\_{(3-4)}= C\_{p} \left(t\_{3}-t\_{4}\right) (6)$$

Where *Q*(3-4) is the heat rejected to reach the designed temperature of distilled water (kJ/kg); *Cp*- is the specific heat of water at regular pressure (kJ/kg\* °C); *t*4- is the temperature of water exiting from the system (°C).

The first advantage of heat pump used in this work is to save the power because the heat given by the condenser of these systems is 3 times (at least) more than the electrical power for its operation. This is due to the most normal value of coefficient of performance (C.O.P).The other advantage is to supply drinking water at the required temperature. The classic water cooler depends on the heat pump for water cooling. This modification will give a domestic model or artificial model that uses any type of water to give the drinking water.

The heat pump is the system that extracts the heat from its source which may be at a low temperature and handles to the other media [10], [11] and [12]. The simplest heat pump consists of five components which are: the compressor, the condenser, the expansion device, the evaporator and the working material [13].

The aim of the compressor is to raise the pressure of working material to force it to the condenser. In the condenser, the refrigerant will be cooled to liquefy it before the next part. In this situation, the liquefied refrigerant at high pressure enters the expansion device. As the working material is released to low pressure in the evaporator, it will begin to vaporize. The heat needed for evaporation has been taken from the surrounding (air and later condensate water) of the evaporator [14]. Finally, the working gas returns to the compressor to complete the cycle then repeats all processes above.

Many types of working materials are used in heat pumps. In this work the refrigerant (R-134a) was selected. This gas has several advantages to make its selection. Some of these advantages are: nonflammable, has no effect on the atmosphere, economic, available everywhere, non- toxic and others.

The representation of this station on (P-H) and (T-S) diagrams will show the work of this system thermodynamically. Figure (3-a) indicates the cycle on (P-H) diagram and (3-b) on (T-S) chart.

**T**

**S**

4

3

2

1

**P**

 **H**

4

1

3

2

(a) (b)

**Fig. 3.**

The compressor supplies energy to carry out the refrigerant from 1 to 2. The mechanical power of compressor can be determined by:

$$P\_{c}=\dot{m}(h\_{2}- h\_{1}) (7)$$

Where: *P*c is the power of the compressor (kJ/kg), *ṁ* is the mass flow rate of the refrigerant (kg/s); *h*1- is the enthalpy of refrigerant before compression (kJ/kg); *h*2- is the refrigerant enthalpy at the entrance of the condenser (kJ/kg).

 The compression process leads to increasing the temperature of the working material because the relationship between pressure and temperature is direct [15], so that; the condenser is cooling the refrigerant at constant pressure to change it to a liquid state. The heat rejected by the condenser may be found by the following function:

$$Q\_{c}=\dot{m}(h\_{2}- h\_{3}) (8)$$

Where *Q*c is the heat rejected by the condenser (kW); *h*3- is the liquid refrigerant enthalpy before entering the expansion device (kJ/kg).

In the third component of this system, there is an isothermal process in which it is assumed that there is no heat transfer to or from the working material, therefore; the enthalpy will not change, (i.e. *h*3 = *h*4). The final part of the heat pump is the evaporator. The purpose of it is to vaporize the refrigerant to cool the objects inside and to supply the refrigerant in form of superheated gas before entering the compressor because the compressors is designed to deal with gases only. The vaporizing process needs the heat taken from the evaporator environment [16].

$$Q\_{e}=\dot{m}(h\_{1}- h\_{4}) (9)$$

Where Qe is the heat absorbed in the evaporator (kJ/kg); h4- is the enthalpy of the refrigerant at the evaporator entrance (kW).

In heat pumps there are two thermal sides. One of them absorbs heat (cold side) and the other rejects the heat (hot side). Each one of them is used for different purposes [17]. When using the cooling cycle, the performance is a function of the cooling effect [18]. The relationship between the cooling effect and the work done by the compressor represent the cooling coefficient of performance (C.C.O.P.) as in the following formula:

$$C.C.O.P. = \frac{cooling effect}{work of the compressor} ⇒ C.C.O.P.= \frac{h\_{1}-h\_{4}}{h\_{2}-h\_{1}} (10)$$

 The coefficient of performance is a dimensionless number [18]. Its magnitude ranges from (3 - 8). The value of (C.C.O.P.) depends on several variables which are: pressure differences between the hot and cold sides, type of materials used in manufacturing the heat exchangers, the refrigerant inside the system, system efficiency and others [19].

The heating coefficient of performance (H.C.O.P.) relates between the heat coming out from the condenser and the work done by the compressor. The (H.C.O.P.) is useful when the system is used for heating [20]. The relation (11) gives the value of the (H.C.O.P.).

$$H.C.O.P. = \frac{heating effect}{work of the compressor} ⇒ H.C.O.P.= \frac{h\_{2}-h\_{3}}{h\_{2}-h\_{1}} (11)$$

In the previous figure (3), it showed that the heat rejected in the condenser is equal to the summation of the heat absorbed in the evaporator and the work done by the compressor (in the ideal case), so that;

$$h\_{2}- h\_{3}=\left(h\_{1}- h\_{4}\right)+\left(h\_{2}- h\_{1}\right)$$

Therefore;

$$H.C.O.P. = \frac{\left(h\_{1}- h\_{4}\right)+\left(h\_{2}- h\_{1}\right)}{h\_{2}-h\_{1}}$$

Then:

$$H.C.O.P. = \frac{\left(h\_{1}- h\_{4}\right)}{h\_{2}-h\_{1}}+1 ⇒ H.C.O.P.= C.C.O.P. +1 (12)$$

In this work, the additional power is needed to operate the vacuum pump to evacuate the space containing the condenser to decrease the boiling temperature of the water to ensure the sufficient cooling for condenser as well as to induce the water for evaporation. This additional work will change the form of (10, 11, and 12) equations because those formulas are used for usual vapor compression cycle while here a modification on this system happened during the use of vacuum pump. The pump power (*Ppv*) can be estimated by:

$$P\_{pv}=\dot{V}\*Δp\_{v} (13)$$

Where $\dot{V}$ is water vapor volumetric flow rate m3/s and *Δpv*pressure difference between condenser and evaporator containers N/m² (see figure 4).

The thermal coefficient of performance of the modified system can be find through the combination of the equations (10, 11, and 13), so that;

$$C.O.P.= \frac{\dot{m}\_{ref.}\left[\left(h\_{1}-h\_{4}\right)+\left(h\_{2}-h\_{3}\right)\right]}{\dot{m}\_{ref.}\left(h\_{2}-h\_{1}\right)+\dot{V}\*Δp\_{v}} (14)$$

Where: *ṁref.* the refrigerant mass flow rate of the vapor compression cycle, kg/s.

1. Thermal design

In the present work, there is a compaction between two different systems. Each one of them must be designed separately depending on the data given by the other. The first is the heat pump which represents the heat source and heat sink for the distillation process. The second is water distillation vessels. The condenser in the heat pump is a heat source for water. The permissible design temperature of the condenser doesn't reach the boiling temperature of water under usual atmospheric conditions which is (100°C) [21], therefore; the pressure in the vessel that contains the condenser must be reduced till it reaches the critical pressure in which the water is vaporized at the condenser designed temperature or less than that. Figure (4) shows the details of the compact model.



**Fig. 4.**Schematic diagram of distillation system. 1- The compressor. 2- The evaporator inside controlled volume. 3- The condenser inside a closed vessel. 4- The expansion valve. 5- The heat exchanger. 6- The vacuum pump. 7- Distilled water exiting valve. 8- Make- up water valve. 9- The concentrated salty water exit.

The container of the condenser has two valves. One of them (8) is to supply the make-up water lost by evaporation. This valve is controlled by the float to keep the water at a constant level. The second valve (9) is to release the concentrated water to avoid salt collection inside the container.

 As a usual cycle, the refrigerant moves from the condenser to the expansion device to enter the evaporator. The expansion device is the borderline between the hot and the cold side because the liquid refrigerant will begin the evaporation directly after it [22], therefore; the pipeline between the expansion device and the evaporator is cool. The water vapor leaving the vaporizing zone (3) is almost in condensing temperature. As known, the density is a function of the temperature. The aim of the heat exchanger (5) is for water vapor cooling to increase the mass flow rate of the vacuum pump therefore reduces the pumping power. As the vapor enters the pressurized cold space, the condensation process starts to produce the distilled water which exits from the instrument through the valve (7).

1. The design assumptions and results

The refrigerant used in this system is (R- 134a). Condenser design temperature is 60°C. Evaporator temperature is 5°C to avoid the water freezing. The pressure in condenser vessel is 15 kpa absolute pressures, (- 86.3 kpa gauge pressure). The water boiling temperature at that pressure is 53°C.

From the (P-H) diagram of the refrigerant, the heat rejected by the condenser can be found through the difference in enthalpy which is (*h2 – h3*). The difference in enthalpy through the compressor is (*h2 – h1*).

To vaporize the water, two types of heat must be added. Sensible heat will increase the temperature of the water until it reaches the boiling temperature under the applied pressure as in the equation (1). The latent heat is converting the water from liquid to gas phase at constant temperature (note eq. (2)). The following steps are to find the amount of water which can be distilled during an hour.

$$Q\_{sensible}=m C\_{p} ∆t\_{w} (15)$$

Where *m*- the mass of water (kg), *∆tw*- is the difference in temperature between the supply water and boiling temperature at design pressure. The supply water considered at room temperature (24°C).

$$Q\_{sensible}=m \left(4.18\right)\*\left(53-24\right)= 121.22m$$

The latent heat:

$$Q\_{latent}=m h\_{fg} (16)$$

Where: *hfg* $h\_{fg}$- the amount of heat needed to change the water from liquid to vapor that is equal to (2378 kJ/kg) at 53°C, so that;

$$Q\_{latent}=2378m$$

The total heat for evaporation is the summation of the sensible and the latent heat.

$$Q\_{total}= Q\_{sensible}+Q\_{latent}$$

In this project, the total heat is that given by the condenser of the heat pump, so that;

*Qcond*. = 2499.22*m* →→ *m* = *Qcond*./2499.22 (kg/s)

In the other side of the station (cold side), the pressure is at atmospheric pressure or more than that. The water vapor will condensate because the temperature at that side is lower than the saturation temperature of water under the atmospheric pressure which is 100°C. This container will make the water at the suitable temperature for drinking; so that; it can say the instrument is a water cooler as well as water distillatory.

1. Discussion and Conclusions
2. By typical calculation, it can be said that the system which use a small size compressor (250w) is able to provide approximately (1.5 liter/hr.) or more than that in depending on the pressure difference occurred by the vacuum pump.
3. The condenser of the heat pump is the heat source for water evaporation in this system.
4. The designed temperature of the condenser is higher than the boiling temperature of pure water under the vacuum pressure inside the container which is used as a water evaporator.
5. The designed temperature of the evaporator of the heat pump is suitable to provide the permissible temperature of the drinking water.
6. The additional power used in these systems is just that for vacuum pump operation because the ordinary systems of water coolers also use the heat pumps, so that; these systems decrease the cost of water purification.
7. The project can be manufactured in different size according to usage, so that; it can be made in domestic or artificial size.
8. References
9. Sharon O. Skipton and Bruce I. Dvorak. Water softening (Ion exchange). Drinking water treatment, NebGuide, 2014.
10. Bruce I. Dvorak and Sharon O. Skipton. Sediment filtration. Drinking water treatment, NebGuide, 2013.
11. Himsar Ambarita, Study on the performance of natural vacuum desalination system using low grade heat source, Case Studies in Thermal Engineering, 2016, pp. 346-358.
12. Ihsan Hamawand, Larry Lewis, Noreddine Ghaffour, Jochen Bundschuh, Desalination of salty water using vacuum spray dryer driven by solar energy, Desalination 404, (2017) 182–191.
13. Bruce I. Dvorak, Sharon O. Skipton, Reverse Osmosis, Drinking Water Treatment, NebGuide, 2014.
14. Adam Shull, The Design and Creation of a Portable Water Purification System, graduate program in Engineering & Computer Science at Andrews University, 2012.
15. W. Li, X. Feng, L.J. Yu, J. Xu. Effects of evaporating temperature and internal heat exchanger on organic Rankine cycle. Applied Thermal Engineering 31 (2011) 4014e4023.
16. Joseph M. Powers. Lecture notes on thermodynamics. 2017, pp:45.
17. Dayong Gao and Michael C. McGoodwin. Engineering Thermodynamics, 2016, pp: 26.
18. Ir. P. Pattijn, Alex Baumans, Fifth-generation thermal grids and heat pumps, 12th IEA heat pump conference. 2017.
19. [K.J.Chua](https://www.sciencedirect.com/science/article/pii/S030626191000228X?via%3Dihub#!), [S.K.Chou](https://www.sciencedirect.com/science/article/pii/S030626191000228X?via%3Dihub" \l "!)[W.M.Yang](https://www.sciencedirect.com/science/article/pii/S030626191000228X?via%3Dihub" \l "!). Advances in heat pump systems: A review. [Applied Energy](https://www.sciencedirect.com/science/journal/03062619). [Volume 87,](https://www.sciencedirect.com/science/journal/03062619/87/12) 2010, Pages 3611-3624.
20. Zuo Cheng, Wenxing Shi, Baolong Wang, Vapor injected heat pump using non-azeotropic mixture R32/R1234ze(E) for low temperature ambient, 12th IEA heat pump conference. 2017.
21. Compact Heat Pumps, 12th International Heat Pump Conference 2017, Rotterdam, The Netherlands.
22. Bijan Kumar Mandal, Madhu Sruthi Emani, Ranendra Roy, Energy-Efficient Refrigeration Systems, cooling India, vol. 13, No. 6, January 2018.
23. Shao, Long, Ma, Xinling, Wei, Xinli, Hou, Zhonglan, Meng, Xiangrui. Design and experimental study of a small-sized organic Rankine cycle system under various cooling conditions, Energy, 2017.
24. [VincenzoTufano](https://www.sciencedirect.com/science/article/pii/S135943119600018X?via%3Dihub#!). Heat recovery in distillation by means of absorption heat pumps and heat transformers. [Applied Thermal Engineering](https://www.sciencedirect.com/science/journal/13594311). [Volume 17](https://www.sciencedirect.com/science/journal/13594311/17/2), 1997, Pages 171-178.
25. Null, H.R. Heat pump in distillation. Chemical Engineering Progress. Volume 72, 1976, Pages 58-64.

1. [W.Rivera](https://www.sciencedirect.com/science/article/pii/S0360544210005992?via%3Dihub" \l "!), [A.Huicochea](https://www.sciencedirect.com/science/article/pii/S0360544210005992?via%3Dihub" \l "!), [H.Martínez](https://www.sciencedirect.com/science/article/pii/S0360544210005992?via%3Dihub" \l "!), [J.Siqueiros](https://www.sciencedirect.com/science/article/pii/S0360544210005992?via%3Dihub" \l "!), [D.Juárez](https://www.sciencedirect.com/science/article/pii/S0360544210005992?via%3Dihub" \l "!), [E.Cadenas](https://www.sciencedirect.com/science/article/pii/S0360544210005992?via%3Dihub" \l "!). Exergy analysis of an experimental heat transformer for water purification. [Energy](https://www.sciencedirect.com/science/journal/03605442). [Volume 36,](https://www.sciencedirect.com/science/journal/03605442/36/1) 2011, Pages 320-327.
2. [W.Rivera](https://www.sciencedirect.com/science/article/pii/S1359431110002139?via%3Dihub#!), [J.Siqueiros](https://www.sciencedirect.com/science/article/pii/S1359431110002139?via%3Dihub#!), [H.Martínez](https://www.sciencedirect.com/science/article/pii/S1359431110002139?via%3Dihub#!), [A.Huicochea](https://www.sciencedirect.com/science/article/pii/S1359431110002139?via%3Dihub#!). Exergy analysis of a heat transformer for water purification increasing heat source temperature. [Applied Thermal Engineering](https://www.sciencedirect.com/science/journal/13594311). [Volume 30,](https://www.sciencedirect.com/science/journal/13594311/30/14)  2010, Pages 2088-2095.

1. [EduardoDíez](https://www.sciencedirect.com/science/article/pii/S1359431108002767?via%3Dihub" \l "!), [PaulLangston](https://www.sciencedirect.com/science/article/pii/S1359431108002767?via%3Dihub#!), [GabrielOvejero](https://www.sciencedirect.com/science/article/pii/S1359431108002767?via%3Dihub#!), [M. DoloresRomero](https://www.sciencedirect.com/science/article/pii/S1359431108002767?via%3Dihub#!). Economic feasibility of heat pumps in distillation to reduce energy use. [Applied Thermal Engineering](https://www.sciencedirect.com/science/journal/13594311). [Volume 29,](https://www.sciencedirect.com/science/journal/13594311/29/5)  2009, Pages 1216-1223.
2. J.P. Chyng, C.P. Lee, B.J. Huang. P erformance analysis of a solar-assisted heat pump water heater. Solar Energy 74 (2003) 33–44.
3. Schibuola L. Heat pump seasonal performance evaluation: a proposal for a European Standard. Applied Thermal Energy 20, 2000, pp: 387–398.