Notice of Retraction

After careful and considered review of the content of this paper by a duly constituted expert committee, this paper has been found to be in violation of IEEE's Publication Principles.

We hereby retract the content of this paper. Reasonable effort should be made to remove all past references to this paper.

The presenting author of this paper has the option to appeal this decision by contacting TPH@ieee.org.

Thermodynamic Analysis of Direct Heated Solar Desalination System

Tian He, Jiang Juyuan, Cui Mingxian

School of Electrical Engineering
Tianjin University of Technology
Tianjin, China
tianhe@tjut.edu.cn

Abstract—In order to increase thermodynamic performances of direct heated solar desalination system, thermodynamic analysis is done. The results show that the overall exergy efficiency is very low. The system should be upgraded. Flash temperature and distillation temperature should be justly distributed, and highest seawater temperature can be maximized on request of corrosion control. It is an effective medium to promote exergy efficiency that reasonable setting of temperature difference between shell side and tube side. evaporator can be Improved by transverse tubule and falling film. This means can also promote exergy efficiency. Effective use of the high salinity water and cooling water can raise energy using standards.

Keywords- desalination; solar energy; thermodynamic analysis;

I. INTRODUCTION

With economic development in recent years, the use of fresh water is increased sharply, so to explore fresh water resources became an imperative duty[1-2]. In coastal areas, desalination technology is an effective way to solve the short of fresh water. In the past few decades, a lot of desalination methods were invented. All of solar desalination systems fall into two main categories: thermal processes such as multi-stage flash(MSF), multi-effect distillation(MED) and vapor compression(VC) and electromechanical processes as reverse osmosis(RO) and reverse electrodialysis(EDR) [3-4]. For thermal process, the key point of keeping develop desalination is to reduce energy consumption, Out the cycle of energy for water - add to the energy shortage and environmental pollution - water more scarce. it is the key to increasing energy utilization efficiency[5-8].

Thermodynamic analysis is a method that uses the mass and energy conservation principles together with the second law of thermodynamics (entropy equations) for the design and analysis of desalination processes [9]. During the past few decades, thermodynamic analysis has appeared to be an essential tool for system design, analysis and optimization of desalination systems. And thermodynamic analysis of system components should be minimized to increase system efficiency.

II. EXERGY VALUE CALCULATION

When the compressible system is not involved in chemical reaction and diffusion, incomplete equilibrium environmental condition is choosed as a reference condition. In this cas, the exergy is physical exergy E_{ph} . When the system is involved in chemical reaction and diffusion, a complete equilibrium environmental condition is choosed as a reference condition. In this cas, the exergy of system is the sum of physical exergy and chemical exergy[10]:

$$E_x = E_{xph} + E_{xch} \quad (1)$$

There are three material flow in direct heated solar desalination system, sea water, fresh water and water vapour. Because of not highflow velocity and potential difference, kinetic exergy and potential exergy are negligible. So physical exergy can be expressed as:

$$E_{xph} = E_m = H - H_0 - T_0(S - S_0) \quad (2)$$

Where, H is enthalpy of material flow, kJ/kg; H_0 is enthalpy in environmental condition, kJ/kg; S is entropy of material flow, kJ/(kg·K); S_0 is entropy in environmental condition, kJ/(kg·K); T_0 is environmental temperature, K.

Water vapour is saturated vapour, its enthalpy and entropy can be looked over thermodynamic characters. Given: sea water and fresh water are incompressible fluids (pure substance or solution), c_p is constant. It follows that physical exergy E_{xph} is[11-12]:

$$E_{xph} = M \times \{c_p [(T - T_0) - T_0 \ln \frac{T}{T_0}] + v_m (p - p_0)\} \quad (3)$$

Where, T is calculational temperature, K; c_p is specific heat capacity of solution, kJ/(kg·K); v_m is specific volume, m³/kg; p is calculational pressure, Pa.

In order for convenient analysis of a problem, some assumptions are made. It is that seawater is only composed of fresh water d and salt s . lower symbol 0 indicate a standard.

Fresh water chemical exergy per mole is equal to the minimal work of one mole fresh water preparation by separation from infinite supplying seawater under

environmental temperature and environmental pressure. Fresh water chemical exergy is chemical potential difference between the separating and unseparating[13-14]:

$$e_d = -\Phi RT_0 \ln X_{d0} \quad (4)$$

Where, Φ is electrolyte coefficient; R is molar gas constant, $R=8.314\text{J}/(\text{mol}\cdot\text{K})$; X_{d0} is The mol percentage of fresh water. Salt chemical exergy is gotten in similar pattern:

$$e_s = -RT_0 \ln \alpha_{s0} \quad (5)$$

Where, α_{s0} is salt activity.

Seawater in unstandard state is viewed as a mixture of fresh water and salt. But its composition (X_d , X_s) is different from

supplying seawater's composition (X_{d0} , X_{s0}). $\hat{e}_d^o$ and $\hat{e}_s^o$ indicate fresh water partial molar exergy and salt partial molar exergy in unstandard state:

$$e = X_d \hat{e}_d + X_s \hat{e}_s \quad (6)$$

$$\hat{e}_d = e_d + RT_0 \ln \alpha_d \quad (7)$$

$$\hat{e}_s^o = e_s + RT_0 \ln \alpha_s \quad (8)$$

The formula (9) is obtained by substituting the formula(3)(4)(6)(7)into formula(5):

$$\begin{aligned} e^o &= RT_0 [X_d \ln(\frac{\alpha_d}{\alpha_{d0}}) + X_s \ln(\frac{\alpha_s}{\alpha_{s0}})] \\ &= RT_0 [X_d \ln(\frac{X_d}{X_{d0}}) + X_s \ln(\frac{\gamma_s X_s}{\gamma_{s0} X_{s0}})] \\ &= RT_0 \{[(1 - X_s) \ln(\frac{1 - X_s}{X_{d0}})] + X_s \ln(\frac{\gamma_s X_s}{\gamma_{s0} X_{s0}})\} \end{aligned} \quad (9)$$

Where, γ_s is seawater activity coefficient in unstandard state; γ_{s0} is seawater activity coefficient in standard state.

When seawater concentration is known, The relationship between mol percentage and mass percentage is:

$$X_{s0} = (\frac{C_{s0}}{\xi_s}) / (\frac{C_{d0}}{\xi_d} + \frac{C_{s0}}{\xi_s}) \quad (10)$$

$$X_{d0} = (\frac{C_{d0}}{\xi_d}) / (\frac{C_{d0}}{\xi_d} + \frac{C_{s0}}{\xi_s}) \quad (11)$$

$$X_s = (\frac{C_s}{\xi_s}) / (\frac{C_d}{\xi_d} + \frac{C_s}{\xi_s}) \quad (12)$$

Where, ξ_s is molar mass of salt (NaCl), g/mol; ξ_d is molar mass of fresh water, g/mol; C_{d0} is material concentration of fresh water in standard state seawater; C_{s0} is material concentration of salt in standard state seawater; C_d is material concentration of fresh water in unstandard state seawater; C_s is material concentration of salt in unstandard state seawater; X_{s0} is mol percentage of salt in standard state seawater; X_d is

mol percentage of fresh water in standard state seawater; C_s is mol percentage of fresh water in unstandard state seawater.

III. THERMODYNAMIC ANALYSIS IN EACH COMPONENT

Exergy of material flows is calculate. The results is shown in the table I. Standard state parameters are $T_0=298.15\text{K}$, $p_0=0.101\text{MPa}$.

TABLE I. THE RESULTS OF THERMODYNAMIC CALCULATIONS

material flow	mass flow g/d	temperature °C	exergy kJ/d
seawater in highest temperature	917.23	70	12085.5
seawater outlet flash chamber	948.83	56.46	5781.804
charged seawater of evaporator	931.47	36.01	649.586
flash vapor	22.4	55.22	5013.587
vapor produced in evaporator	17.36	35.58	1396.678
fresh water charged out evaporator	22.4	55.22	2211.704
fresh water charged out condenser	17.36	35.58	608.781
inlet cooling water	1885.25	24	12.776
outlet cooling water	1885.25	33.01	802.881

Figure 1. Thermodynamic analysis of components

Thermodynamic analysis of components is showed as figure 1. Seawater in highest temperature heated by solar collector system flow into flash chamber. Because the pressure in flash chamber is less than saturated vapor pressure associated with inlet hot seawater temperature, a part of hot seawater absorbs heat as latent heat of vaporization and evaporate rapidly. temperature of another part seawater decreases, and flows into evaporator. For flash, on the one hand, physical exergy is lost by decreasing seawater temperature, on the other, chemical exergy is increased by an increase in the concentration of seawater. The concentration is increased because of produced flash vapor. The decrease in temperature of saturated water produces the exergy loss ΔE_{xls} .

$$\Delta E_{xls} = T_0 \left[\frac{1}{T_{v1}} - \frac{\ln(\frac{T_{hot}}{T_{bst}})}{T_{hot} - T_{bs}} \right] * Q_s \quad (13)$$

where, T_{hot} is the highest seawater temperature, K; T_{bs} is temperature of seawater outlet flash chamber, K; T_{v1} is flash vapor temperature, K; Q_s is The heat loss, kJ/d.

Exergy loss ΔE_{xls} caused by condensed heat is showed as:

$$\Delta E_{\text{shc}} = E_{\text{schot}} - E_{\text{schbs}} - E_{\text{schv1}} \quad (14)$$

Evaporator is a component utilizing the radiated heat when flash vapor condensed to evaporate the seawater in evaporator shell side. On the one hand, fresh water is produced by cooling the flash vapor using seawater through shell side, on the other, seawater in evaporator is heated and vapors are produced by radiated heat of flash vapor condensed. Exergy loss in evaporator includes heat dissipation exergy loss, heat transfer exergy loss caused by heat transfer temperature difference, resistance exergy loss caused by flow resistance and exergy loss caused by heat of solution. Heat dissipation exergy loss is negligible because heat preservation is made. resistance exergy loss is also negligible because tube in the heat exchanger is short and experimental equipment is small.

The heat is transferred from vapor side to the material side by the temperature differences between on each side of the tube in the heat exchanger. This process is irreversibility, and exergy loss exist in the process. So the exergy loss ΔE_{Izhc} caused by heat transfer temperature difference is showed as:

$$\Delta E_{\text{Izhc}} = T_0 \Delta S_r = T_0 (\Delta S_{v1} + \Delta S_{bz}) = T_0 Q_{zh} \left(\frac{1}{T_{bz}} - \frac{1}{T_{v1}} \right) = T_0 Q_{zh} \left(\frac{1}{T_{out}} - \frac{1}{T_{v1}} \right) \quad (15)$$

Where, T_0 is environmental temperature, K; T_{bz} is seawater temperature of evaporator shell side, K; T_{v1} is flash vapor temperature, K; Q_{zh} is the heat absorbed in fluid shell side, kJ/d; $r(t_{v1})$ is latent heat of vaporization under t_{v1} , kJ/kg; M_{d1} is mass flow of flash vapor, kg/d.

Exergy loss ΔE_{Izhc} caused by condensed heat is showed as:

$$\Delta E_{\text{Izhc}} = E_{\text{schbs}} - E_{\text{schout}} - E_{\text{schv2}} \quad (16)$$

In condenser, vapor produced in evaporator is cooled by cooling water and the condensation of vapor turned into fresh water. Exergy loss in condenser includes two parts, inner exergy loss caused by transmit heat and outer exergy loss caused by cooling water charging.

$$\Delta E_{\text{shc}} = \Delta E_{\text{shc}} + \Delta E_{\text{shc}} = T_0 M_{d1} r(t_{v2}) \left(\frac{\ln \frac{T_{v2}}{T_c}}{T_c - T_c} - \frac{1}{T_{v2}} \right) + E_{\text{schv2}} \quad (17)$$

Where, T_c is cooling water inlet temperature of condenser, K; T_{co} is cooling water outlet temperature of condenser, K; T_{v2} is tempearture of vapor produced in evaporator, K; $r(t_{v2})$ is latent heat of vaporization under t_{v2} , kJ/kg; M_{d2} is mass flow of vapor produced in evaporator, kg/d.

It can be seen by the results showed in table II that inner exergy loss is the majorexergy loss in evaporator and condenser. A lot of exergy loss is caused because of the heat transfer exergy loss caused by heat transfer temperature difference is large. Exergy loss caused by transmit heat can be decreased by some means such as reasonable setting of temperature difference between shell side and tube side, enhanced heat transfer and increasing the heat transfer efficiency. When heat in the high salinity water is used to

preheat supplying seawater, the exergy of the high salinity water is effective used, outer exergy loss is decreased. Exergy losse in condenser could be reduced if supplying seawater is used as cooling water.

TABLE II. RESULT OF THERMODYNAMIC ANALYSIS OF COMPONENTS

		Flash chamber		evaporator		condenser	
	reason of exergy loss	exergy loss (kJ/d)	exergy loss rate(%)	exergy loss (kJ/d)	exergy loss rate(%)	exergy loss (kJ/d)	exergy loss rate(%)
inner exergy loss	caused by transmit heat	1139.03	97.47 %	2996.17	81.66 %	954.24	54.31 %
	caused by condensed	29.55	2.53 %	23.40	0.64 %		
outer exergy loss				649.59	17.70 %	802.88	45.69 %
Total exergy loss		1168.58	100.00	3669.15	100.00	1757.12	100.00

IV. CONCLUSION

Thermodynamic analysis shows that the overall exergy efficiency is very low. The syetem should be upgraded. Flash temperature and distillation temperature should be justly distributed, and highest seawater temperatur can be maximized on request of corrosion control. It is an effective medium to promote exergy efficiency that reasonable setting of temperature difference between shell side and tube side. evaporator can be Improved by transverse tubule and falling film. This means can also promote exergy efficiency. Effective use of the high salinity water and cooling water can raise energy using standards.

REFERENCES

- [1] Said Al-Hallaj, Sandeep Parekh, M.M. Farid, J.R Selman, "Solar desalination with humidification-dehumidification cycle:Review of economics", Desalination, vol. 195, pp. 169-186, 2006.
- [2] SHUN-FU LEE, "Thermoeconomics of lithium bromide/water absorption chillers and heat transformers", A dissertation presented to the graduate school of the university of florida in partial fulfillment of the requirements for the degree of doctor of philosophy, 1999.
- [3] A.Macoun, "Alleviating water shortages-lessons form the Middle East", Desalination Water Reuse, vol. 10, pp.14-20, February 2000.
- [4] A.S.Nafey, H.E.S.Fath, A.A.Mabrouk, " Anew visual package for design and simulation of desalination processes", Desalination, vol. 194, pp. 281-296, 2006.
- [5] Gao Congjie, Chen Guohua, Handbook of seawater utilization technology and engineering. Beijing, China: Chemical Industry Publishers, 2004.
- [6] Zheng Hongfei, He Kaiyan, and Chen Ziqian, Solar desalination technologies. Beijing, China: Beijing Institute of Technology Publishers, 2005.
- [7] E.Mathioulakis, V.Belessiotis, and E.Delyannis, "Desalination by using alternative energy: Review and state-of-the-art", Desalination, vol. 203, pp. 346-365, February ,2007.

- [8] Gemma Raluy, Luis Serra, and Javier Uche, "Life cycle assessment of MSF, MED and RO desalination technologies", *Energy*, vol. 31, pp. 2361–2372, 2006.
- [9] A.S.Nafey, H.E.S.Fath, A.A.Mabrouk, " thermo-economic investigation of multi effect evaporation (MEE) and hybrid multi effect evaporation---multi stage flash (MEE-MSF)systems", *Desalination*, vol. 201, pp. 241-254, 2006.
- [10] ZHU Ziqiang, XU Xun, "chemical engineering thermodynamics", Beijing: Chemical Industry Press, 1995
- [11] İlhan Ceylan, Mustafa Aktaş, Hikmet Doğan, "Energy and exergy analysis of timber dryer assisted heat pump", *Applied Thermal Engineering*, vol. 27, no. 1, pp. 216–222, 2007.
- [12] KONG Naiwen, CHEN Jiabin, YU Zhijia, "chemical engineering thermodynamics", Dalian: Dalian University of Technology press, 2006
- [13] HU San gao, YIN Lian qing, ZHOU Shao xiang et al, "THE EXERGY ANALYSIS MODEL OF MSF SEA WATER DESALINATION SYSTEM AND ITS APPLICATION", *TECHNOLOGY OF WATER TREATMENT*, vol. 25, no. 5, pp. 267-272, 1999
- [14] ZHENG Yan-mei; HAN Yu-lin; LI Xin-gang et al," Exergy Analysis of Three-Effect Falling-Film Evaporation System for Ammonium Chloride Recycle", *Journal of Tianjin University*,vol. 40, no. 3, pp. 377-380, 2007.