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Research Paper

EXERGY ANALYSIS OF A LOW TEMPERATURE THERMAL DESALINATION SYSTEM

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This paper presents a novel approach of the work-potential of the available energy in a low temperature phase-change desalination process operating near ambient temperature and low pressure. Exergy analysis is done when the system is operated at evaporator pressures between 1.3 KPa and 2.3 KPa. The thermodynamic efficiency of the major components are evaluated and graphs are presented to show the conditions to minimize exergy destruction. Exergy performance and recommendations to further improve the Exergy efficiency is also proposed.

Keywords: Desalination, Exergy analysis, Exergy destruction, Second law of thermodynamics

INTRODUCTION

The exergy analysis of desalination systems have been studied by many researchers in the areas of Multi-Stage Flash (MSF), Thermal Vapour Compression (TVC), Reverse Osmosis (RO) and also in Multi-Effect Desalination (MED) systems. Some of the components of these systems require energy in the form of heat and some of them require electrical energy to produce fresh water. Thus, every system has its own work potential, i.e., the amount of energy that we can extract as useful work which is known as available energy or exergy. The exergy analysis is basically derived from second law of thermodynamics and gives a clear source of the inefficiencies of a system. The objective of this study is to evaluate sources of inefficiency in the processes of a low temperature system to identify operational parameters and to maximize thermodynamic performance of this process.

Mostafa *et al.* (2010), studied the effect of the system properties as well as the environment dead state on the exergy and flow exergy variation. They also performed exergy analysis for a large MSF and proved that the flow exergy can only have a negative value at pressures lower than the dead state pressure. Alessandra and Enrico (1999) has done an energy and exergy analysis of the RO unit alone and coupled to the MD unit is presented

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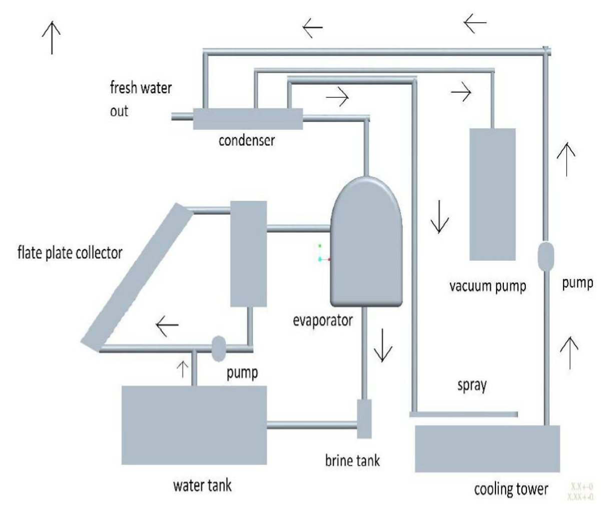
in order to determine the energy requirements related to the integrated system with respect to the RO one. The analysis has been tentatively extended to a complete membrane integrated system where Nano Filtration (NF) has been also considered in the RO feed pre-treatment. From the analysis made, integrated membrane systems seem to be an interesting alternative to the RO process for seawater desalination. Improvement in the performance by the introduction of nanofiltration for water pre-treatment was suggested. Francesca and Enrico (2010) conducted exergy analysis to a seawater membrane-based desalination plant. The exergy of the various saline water streams has been determined and a comprehensive analysis towards the exergy distribution of the major process components has been conducted and concluded that exergy destruction is mainly due to pressure drops in the membrane modules, valves and brine lines. The exergy analysis can also be applied to all thermodynamic systems, chemical processes, solar applications and various psychrometric processes. A new concept of Low Temperature Thermal Desalination (LTTD) (Muthunayagam *et al.*, 2005) was introduced by Muthunayagam (2005) using spray flash vaporization. The saline water is fed to vaporizer from feed tank by reducing the ambient pressure to an extent such that the saturation temperature corresponding to low pressure is below the saline water temperature, the water can evaporate so long as its saturated temperature is kept lower than the water temperature. The superheat comes from the reduced pressure and vapour, so generated at low pressures can be condensed in a low pressure condenser. Low pressure vaporization of sea water is carried out at temperatures 26 °C and 32 °C. The pilot plant shown in Figure 1 is operated at vacuum pressures between 1.3 KPa and 2.3 KPa.

Figure 1: Schematic Diagram of the Pilot Plant



EXERGY METHODOLOGY

When heat transfer occurs between two bodies it is always done at the expense of thermal gradient where the degradation of energy or the quality of energy during the transfer is termed as the exergy loss or availability loss. Exergy also plays a vital role in the economics of the process and the conditions like pressure and temperature. Exergy associated with a given quantity of heat energy Q at a temperature of T can be derived from the Carnot efficiency of a reversible heat engine working between T and the surroundings temperature T_o.

$$E = W_{\max} = \eta_{carnot} Q = [1 - (T_o/T)]Q \qquad ...(1)$$

ANALYTICAL EXERGY ANALYSIS

As, Exergy = sum of Inlet exergy – sum of Outlet exergy, the

Mass balance:

$$0 = \Sigma \dot{m}_i = \Sigma \dot{m}_e$$

Energy balance:

$$0 = Q - \dot{W} + \Sigma(\dot{m} \cdot h)i - \Sigma(\dot{m} \cdot h)e$$

Exergy balance:

$$0 = \Sigma[1 - (T_o / T)]Q - \dot{W}$$

$$+ \Sigma(\dot{m} \cdot h)i - \Sigma(\dot{m} \cdot h)e - \dot{E}_D$$

For a control mass the exergy inflow and outflow associated with the streams entering and leaving the control volume are quantified in terms of the specific exergy e, defined as follows (neglecting kinetic, potential and chemical energy).

$$e = u - u_o + P_o(v - v_o) - T_o(S - S_o) \quad \text{...(2)}$$

For a control volume flow exergy can be calculated by:

$$e_f = (u - u_o) + P_o(v - v_o) - T_o(S - S_o) + v(P - P_o)$$

$$e_f = (h - h_o) - T_o(S - S_o) \quad \text{...(3)}$$

The fraction of the available energy converted into useful work is known as the second law efficiency and can be calculated as:

$$\eta_2 = (W_{net}/availability) = W_{net}/W_{\max} \quad \text{...(4)}$$

also

$$\eta_2 = 1 - [Exergy\ destroyed/Exergy\ supplied] \quad \text{...(5)}$$

Exergy Variation

The exergy change with the temperature, pressure of the initial state with respect to the environment dead state is analyzed. Assuming the environmental dead state is at $P = P_o$, $T = T_o$; and assuming an ideal gas mixture that satisfies the ideal gas relation ($PV = RT$)

Exergy can be written as:

$$e = Cv(T - T_o) + P_o[(RT/P) - (RT_o/P_o)] - T_o[Cp \ln(T/T_o) - R \ln(P/P_o)]$$

For $P = P_o$

$$e = Cv(T - T_o) + R(T - T_o) - T_oCp \ln(T/T_o)$$

Using $C_p = Cv + R$,

$$e = CpT_o[(T/T_o) - \ln(T/T_o) - 1] \quad \text{...(6)}$$

From the graph shown in Figure 2, when the pressure is equal to the environmental state the temperature property is an increasing component and hence it can be concluded that the exergy is positive. And the graph also suggests that when the temperature is higher or lower than the environment state the exergy is positive. Figure 3 shows that when the temperature is equal to the environmental state the exergy is positive. Also from Figure 4 it is noted that the flow exergy of a control volume system may be positive or negative depending on the pressure of the system. Flow stream

Figure 2: Effect of Temperature Ratio on Dimensionless Energy

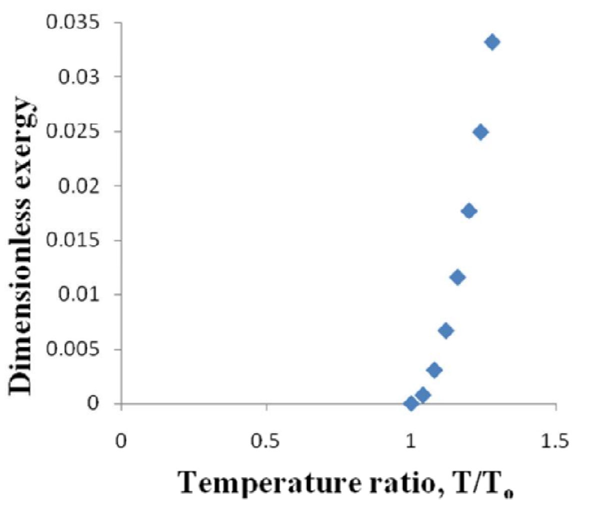


Figure 3: Effect of Pressure Ratio on Dimensionless Energy

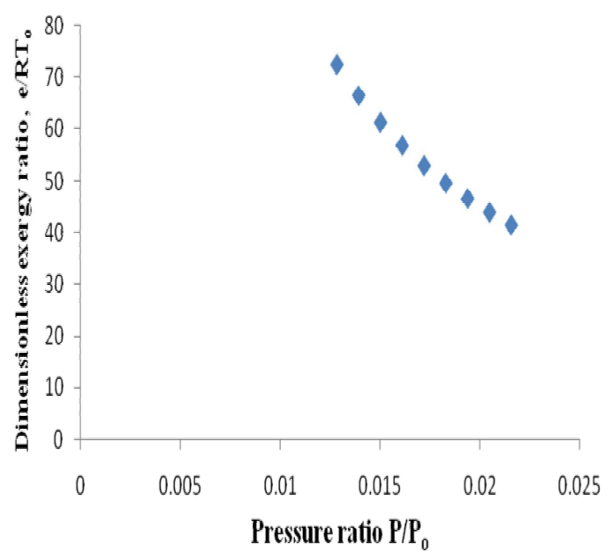
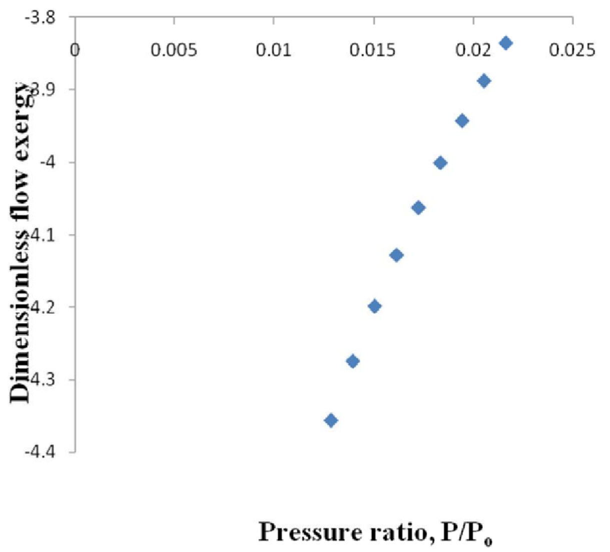


Figure 4: Effect of Pressure Ratio on Dimensionless Flow Exergy



can be expanded reversibly (e.g., using a turbine) to the environment pressure and produce work resulting in a positive flow exergy ($P > P_o$) external work should be applied to compress the flow stream (e.g., using a compressor) to the environment pressure resulting in a negative flow exergy ($P < P_o$).

RESULTS AND CONCLUSION

Exergy balance for Vaporizer:

$$\dot{E}_D = \Sigma[1-(T_o/T)]Q + \dot{m}_s[(h_2 - h_{3fg}) - T_o(S_2 - S_{3fg})] + \dot{m}_w[(h_7 - h_{3fg}) - T_o(S_7 - S_{3fg})] \quad ...(7)$$

$\dot{m}_S$ – Mass flow rate of saline water stream

$\dot{m}_w$ – Mass flow rate of withdrawal stream

Energy balance:

$$0 = -Q_{out} + \dot{m}_v h_4 - \dot{m}_{condensate} h_6$$

Exergy balance:

$$\dot{E}_D = -\Sigma[1-(T_o/T)]Q_{out} + (\dot{m}_S - \dot{m}_w)[(h_{4fg} - h_6) - T_o(S_{4fg} - S_6)] \quad ...(8)$$

The graphs in Figures 5 and 6 shows the variation of exergy and flow exergy for different cases of control mass and control volume taking ideal gas as the working fluid. Exergy analysis is performed for low pressure vaporizer and shell and tube condenser and sources of inefficiency in the process are evaluated to identify operational parameters to maximize thermodynamic performance of this process. The maximum exergy loss in the evaporation chamber is 37.8% (108.804 KW) and the exergy loss in the condenser is 95.58% (199.966 KW). From this analysis, it can be concluded that the highest quantity of exergy loss occurs in the condenser in the form of latent heat dissipation from the water vapour to the environment. Overall exergy efficiency of the process estimated is 2.9% as against the exergy efficiency of a MSF process that

Figure 5: Variation of Enthalpy with Pressure at Various Temperatures

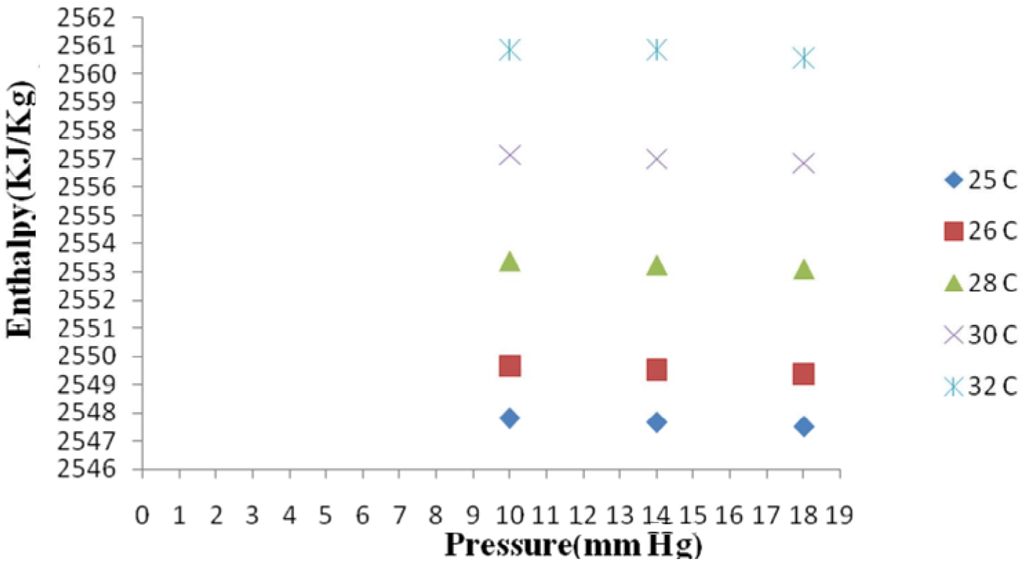
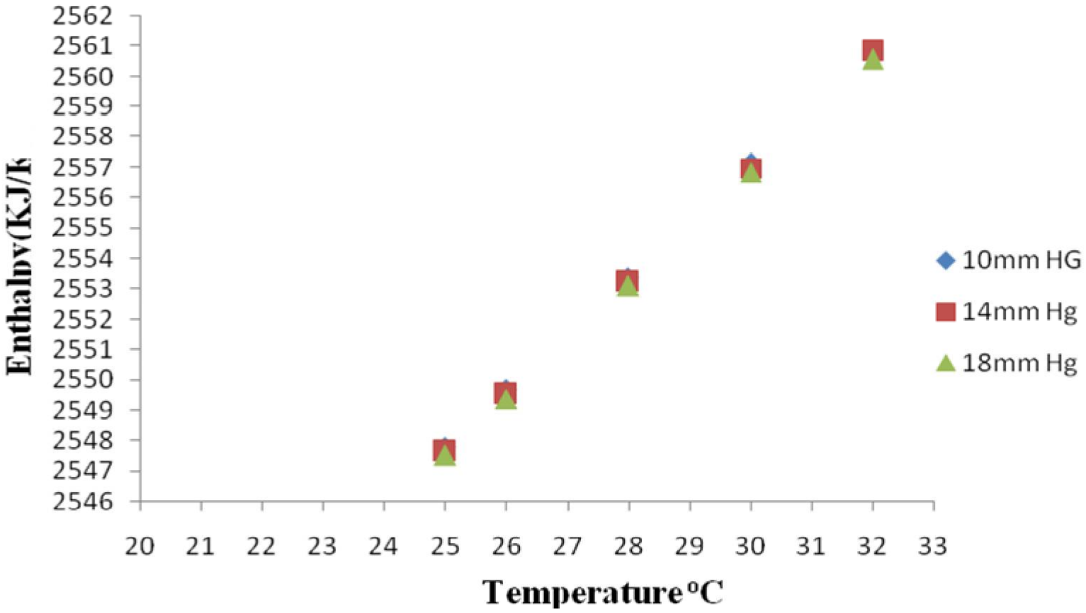


Figure 6: Variation of Enthalpy with Pressure at Various Temperatures



been reported to be 4% and second law efficiencies of membrane distillation and humidification-dehumidification processes 0.5% and 5.7% respectively (Garcia and Gomez-Camacho, 2001; US Department of the Interior, 2003; Sow *et al.*, 2005; Hou *et al.*, 2007; and Banat and Jwaied, 2008).

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APPENDIX

Nomenclature

Cp – Specific heat of ideal gas constant pressure [KJ/Kg – °K]
E – Exergy [KJ]
$\dot{E}$ – Exergy flow rate [KW]
h – Specific enthalpy [KJ/Kg]
$\dot{m}$ – Mass flow rate [Kg/sec]
P – Pressure [KPa]
Q – Heat energy [KJ]
S – Specific entropy [KJ/kg – °K]
T – Absolute temperature [°K]
T_o – Reference temperature [°K]
W – Net work transfer rate [KW]