DESALINATION BY FLUE GAS HUMIDIFICATION-DEHUMIDIFICATION USING TWO DIFFERENT FLUE GAS COMPOSITIONS

M.Sc. Elnahas M. H. [1], PhD. Ghallab A. O. [1]
Department of Chemical Engineering, Faculty of Engineering – Cairo University, Egypt [1]

mostafa.nahas@eng.cu.edu.eg

Abstract: *The objective of the work is to utilize waste heat from power stations' flue gases in desalination of seawater by humidification-dehumidification. Two power station fuels namely fuel oil and natural gas are considered. The two fuels differ in composition, calorific value, and usage of percent excess air requirements. In order to achieve the same electric power production, the composition (moisture content and specific heat) and amount of flue gases ensuing from combustion of the above two fuels will be different. One humidification-dehumidification desalination scheme is generated and results are compared with respect to the anticipated cost of produced water versus the source of flue gases. Cost is calculated on the basis of energy balance and design equations. The scheme includes: preheating of seawater using hot flue gas, humidification of an air stream by direct contact with seawater, and dehumidification of the same stream by indirect cooling in a condenser. In case of fuel oil combustion, desulphurization of the flue gas by seawater is also included. The cost of produced fresh water includes the fixed cost of heat exchangers, condensers, humidifiers, packing, pumps and fans based on the cost index of 2018, and the operating cost is based on the current electricity cost. The results show that the total cost of the produced water is much less in the case of using flue gases ensuing from natural gas fueled power stations. This happens because the flue gases in this case have a very high humidity ratio which will result in the condensation of a significant amount of water on cooling. As a result, the total amount of fresh water produced is greater than in the case of fuel oil flue gases.*

Keywords: DESALINATION; SEAWATER; HUMIDIFICATION; DEHUMIDIFICATION; FLUE GAS; DESIGN

1. Introduction

Water desalination has always been an important source of fresh water in many regions and communities, especially in coastal areas that are far away from any reliable source of fresh water. Through the years, people have been developing many techniques to get fresh water from seawater. Since desalination in general is a high energy consuming process, more and more optimization and integration techniques have been applied to the process in order to produce fresh water with the least possible cost.

These techniques need accurate mathematical models to be as efficient as possible. One of the most important variables in these models is the water physical properties which vary with temperature and concentration, which change widely in any desalination process[1].

Also the available source of energy is one of the most decisive factors to choose the suitable technique in each case. Some techniques can operate perfectly on waste energy or solar energy, while other techniques operate by electricity. Some techniques also can be integrated with other industrial processes, saving both energy and logistic resources[2,3].

This work aims to investigate the performance of a humidification-dehumidification seawater desalination system that operates on waste energy in the form of hot flue gases from electric power stations that operate on either Heavy Fuel Oil or Natural Gas. An additional processing step may be added to this integrated system in order to remove SO_2 from the flue gas, if present.

2. Fuel and Flue Gas

The quantity and composition of the emitted flue gases depend on the rated power plant electrical power generation capacity and the type of fuel burned. Heavy fuel oil (mazot) and natural gas will be considered as fuel sources. The composition of the flue gas is calculated on the basis of typical fuel compositions and the corresponding air to fuel ratio as commonly used with natural gas and heavy fuel oil. The amount of flue gas generated per kWh is based on the calorific value of each fuel and the reported industrial values of the power plant efficiencies.

Based on the typical compositions of heavy fuel oil and Natural Gas, taking the average amount of excess air needed for combustion of fuel as 15% in case of Fuel Oil and 5% in case of Natural Gas, the composition of the flue gases was calculated using simple material balance equations. The humidity ratio in both cases could thus be calculated on the basis of the previous calculations.

The calorific value (CV) [4] of the fuel and the electric generation efficiency η [5] are used to estimate the fuel rate need in generating electricity (per kWh) and hence the amount of flue gas produced. The calculated data are presented in Table 1.

Table 1: *Flue Gases Compositions and Fuel Ratings*

Fuel		Fuel Oil	Natural Gas
% excess air		15	5
C.V.	MJ/kg	41	47.3
	kWh/kg	11.39	13.139
FG composition by mass	CO_2	0.179	0.141
	H_2O	0.057	0.11
	SO_2	0.003	0
	O_2	0.028	0.01
	N_2	0.733	0.738
η %		30	30
Humidity Ratio, (kg water/kg drygas)		0.060185	0.12413
fuel rate	kg/kWh	0.2927	0.2537

3. The proposed Desalination Scheme

Flue gas is used to indirectly heat a stream of seawater which will be contacted with a circulating stream of air in a counter current humidification tower. Seawater is preheated to 40°C in the humid air condenser, then part of this stream is heated to 100°C in a heat exchanger against flue gas which is cooled down to 50°C. The dehumidification condenser allows a minimum temperature approach of 10°C, which means that the saturated air will leave the condenser at 40°C. This stream will meet the hot seawater in the humidifier which will act as a cooling tower with a temperature approach of 5°C at the bottom. The leaving air stream is assumed to reach 95% of the saturation humidity. Finally the cold flue gas will be desulphurized in a counter current absorber using seawater as a solvent. Fig. 1 shows this flow scheme.

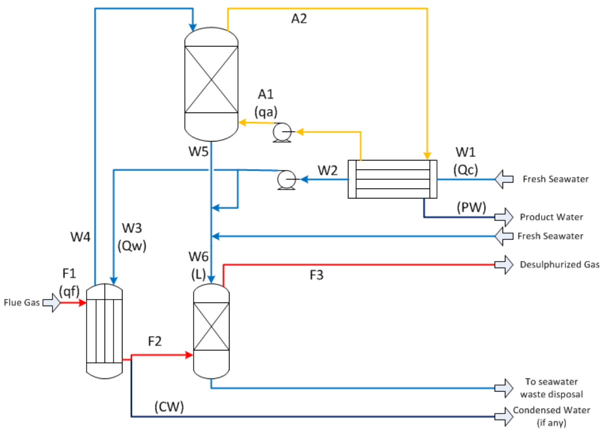

Fig. 1 *Humidification-Dehumidification Desalination Scheme*

4. Model

In the Flue Gas Heat Exchanger, the inlet and outlet flue gas enthalpies are given by:

$$H_{F1}=q(CgT_{F1}+(CwT_{F1}+\lambda)W_{F1}) \quad (1)$$

$$H_{F2}=q(CgT_{F2}+(CwT_{F2}+\lambda)W_{F2}) \quad (2)$$

While the inlet and outlet seawater enthalpies are given by:

$$H_w=Q_wCpT_w \quad (3)$$

Therefore the quantity of seawater can be calculated from:

$$Q_w=(H_{F1}-H_{F2})Cp_4T_{w2}-Cp_3T_{w1} \quad (4)$$

Where Q_w: Mass flow rate of seawater (kg/h),

Cg: Specific heat capacity of air (kcal/kg.°C),

Cw: Specific heat capacity of water vapor (kcal/kg.°C),

λ: Latent heat of vaporization of water (kcal/kg),

T_{F1}: Inlet temperature of flue gas = 150°C,

T_{F2}: Outlet temperature of flue gas = 50°C,

W_{F1}: Inlet humidity of flue gas (kgwater/kgdrygas),

W_{F2}: Outlet humidity of flue gas (kgwater/kgdrygas),

Cp: Specific heat capacity of seawater (kcal/kg.°C),

T_w: Temperature of Seawater (°C),

q_f: Dry flue gas rate (kg/h)

The area of the heat exchanger can thus be obtained from

$$Area = (H_{F1}-H_{F2})/Ue\Delta Tm \quad (5)$$

Where

$$\Delta Tm = ((T_{F2}-T_{w3})-(T_{F1}-T_{w4}))/\ln((T_{F2}-T_{w3})(T_{F1}-T_{w4})) \text{ (°C)} \quad (6)$$

Ue: Overall heat transfer coefficient (kcal/m2.°C.h)

In the air humidifier, the exit temperature of the humid air is obtained by heat balance assuming that it will be 95% saturated with water vapor at this temperature. The enthalpies of the streams entering and leaving the humidifier are given by:

$$H_{A1}=q(CgT_{A1}+(CwT_{A1}+\lambda)W_{A1}) \quad (7)$$

$$H_{W4}=Q_wCpw_4T_{W4} \quad (8)$$

$$H_{W5}=(Qw-qa(W_{A2}-W_{A1}))Cp_{W5}T_{W5} \quad (9)$$

$$H_{A2}=q(CgT_{A2}+(CwT_{A2}+\lambda)W_{A2}) \quad (10)$$

Where qa: Dry air recirculation rate (kg/h)

T_{A1}: Inlet temperature of air (°C)

T_{A2}: Outlet temperature of air (°C)

W_{A1}: Inlet humidity of air(kgwater/kgdrygas)

W_{A2}: Outlet humidity of air(kgwater/kgdrygas)

Given the percent saturation of air and by mass balance, the relation between T_2 and W_2 may be expressed as

$$W_{A2}=0.95(T,C)Pt-P(T,C)MwMa \quad (11)$$

Where P (T, C): Vapor pressure of seawater at temperature (T) and concentration (C) (mmHg),

Pt: Total Pressure (mmHg), Mw: Molecular weight of water (g/mol), Ma: Molecular weight of air (g/mol)

The concentration of seawater leaving the humidifier is calculated from:

$$C_{W5}=C_{W4}Q(Qw-qa(W_{A2}-W_{A1})) \quad (12)$$

The volume of the humidifier can thus be calculated as

$$Vp=H_{W4}-H_{W5}kp\Delta Tm \quad (13)$$

Where Vp: Volume of the packed section (m3)

$$\Delta Tm=((T_{W4}-T_{A2})-(T_{W5}-T_{A1}))/\ln((T_{W4}-T_{A2})(T_{W5}-T_{A1})) \text{ (°C)} \quad (14)$$

kp: Volumetric heat transfer coefficient in the packed section

(kcal/h.m3.°C)

Assuming an exit gas velocity of 1.5 m/sec and given the density of the exit gas and the number of in parallel needed columns, the cross section area of each column can be calculated from

$$Area=qa/\rho vN \quad (15)$$

Where ρ: Exit gas density (kg/m3),

v: Exit gas velocity (m/s), N: Number of columns

In the fresh water condenser, the amount of condensed water is calculated from the inlet humidity of humid air and its saturated humidity after being cooled.

$$Cond.Water \text{ (PW)}=qa(W_{A2}-W_{As}) \quad (16)$$

The amount of seawater used for cooling is calculated from the enthalpy difference between the inlet and the outlet air, given the inlet seawater temperature and assuming its outlet in order to maintain a specific temperature approach.

$$Qsw=H_{A2}-H_{A1}C(T_{w1}-T_{w2}) \quad (17)$$

The heat transfer area is calculated from

$$Area=H_{A2}-H_{A1}Uc\Delta Tm \quad (18)$$

Where

$$\Delta Tm = ((T_{A1}-T_{w1})-(T_{A2}-T_{w2}))/\ln((T_{A1}-T_{w1})(T_{A2}-T_{w2})) \text{ (°C)} \quad (19)$$

Uc: Overall heat transfer coefficient (kcal/m2.°C.h)

5. Input Conditions

4.1. Flue Gas

For flue gas generated from the combustion of Fuel Oil, a basis of 400,000 kg/h will be used at a temperature of 180°C [6]. Based on typical fuel oil composition, combusted with 15% excess air, the flue gas will have a humidity of 0.060185 kg water/kg dry gas, SO_2 concentration of 0.0994% by weight, and an average molecular weight of 29.13135.

While in the case of power plants operating on Natural Gas, the basis for the generated flue gas will be 200,000 kg/h at 150°C. Based on its typical composition, combusted with 5% excess air, it will have a humidity of 0.12413 kg water/kg dry gas, it will be SO2free, and will have an average molecular weight of 27.75788.

The temperature of seawater is assumed to be 30°C, which should be the maximum temperature in summer. The concentration of salts is taken as 35 ppt (parts per thousand).

4.2. Physiochemical parameters

Since the process involves a change in the salt concentration in the seawater, seawater properties such as vapor pressure and specific heat capacity will be related to both temperature and concentration using suitable correlations[1].

The specific heat capacity of dry air (Cg) is taken as 0.24 kcal/kg.°C, while that of water vapor (Cw) is equal to 0.45 kcal/kg.°C. The latent heat of vaporization of water (λ) is equal to 597.33 kcal/kg at the reference temperature.

4.3. Transport parameters

The heat transfer coefficients in the gas-seawater heat exchangers (Ue) and in the scrubber filled with wooden lath packing (Kp) are taken as follows[7]

Ue= 137.5 kcal/h.m2.°C, kp= 875 kcal/h.m3.°C

6. Results

The calculations were made in the two cases discussed earlier; using Fuel Oil or Natural Gas Flue Gas. The previous equations were used to get the process data and the design data in each case. Then the cost of producing fresh water was calculated. The cost is mainly divided into two parts: Fixed Cost and Operating Cost. Fixed Cost includes the costs of the heat exchangers, condensers, humidifiers, packing, pumps, and fans based on the cost index of 2018[8]. While the operating cost includes the costs of pumping the water and circulating the gases. The annual total cost is calculated by adding the annualized fixed cost of the various equipment, assuming a twenty year service life, to the annual operating cost[9]. The currency conversion rate was taken at $1=EGP17.8.

5.1. Using Fuel Oil Flue Gas

Figures 2-5 show the variation of the design data of the different equipment, and the variation of seawater requirements with the variation of the air circulation rate for the same hot seawater consumption.

5.2. Using Natural Gas Flue Gas

Figures 6-9 show the variation of the design data of the different equipment, and the variation of seawater requirements with the variation of the air circulation rate for the same hot seawater consumption.

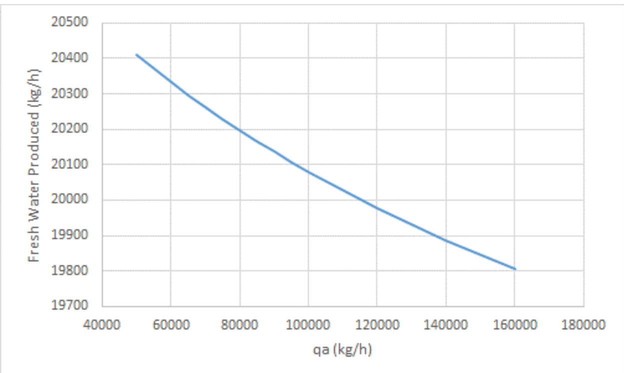

Fig. 2 *Fresh Water Produced vs. Air Circulation Rate – F.O. Flue Gas*

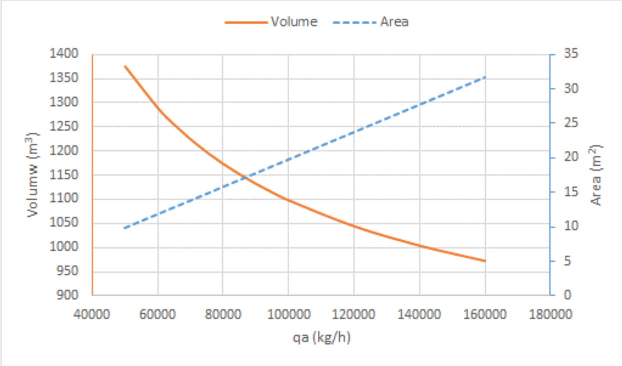

Fig. 3 *Humidifier Area and Volume vs. Air Circulation Rate –, F.O. Flue Gas*

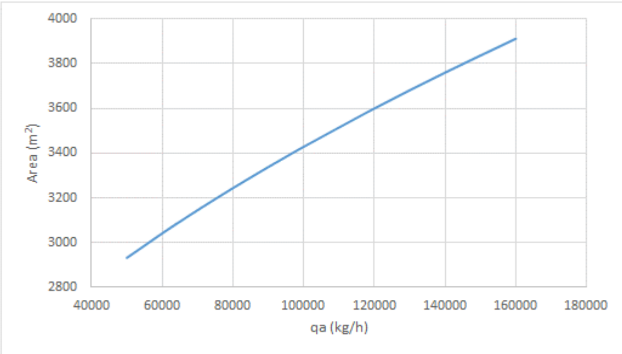

Fig. 4 *Condenser Area vs. Air Circulation Rate – F.O. Flue Gas*

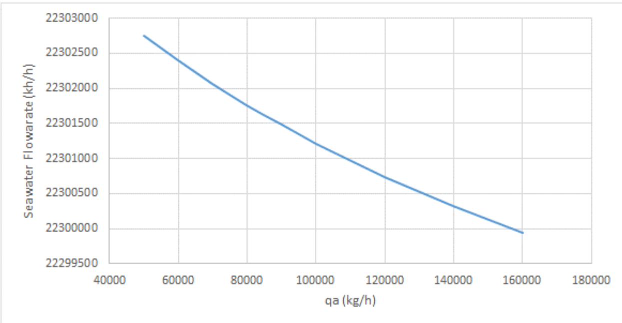

Fig. 5 *Seawater Requirements. Air Circulation Rate – F.O. Flue Gas*

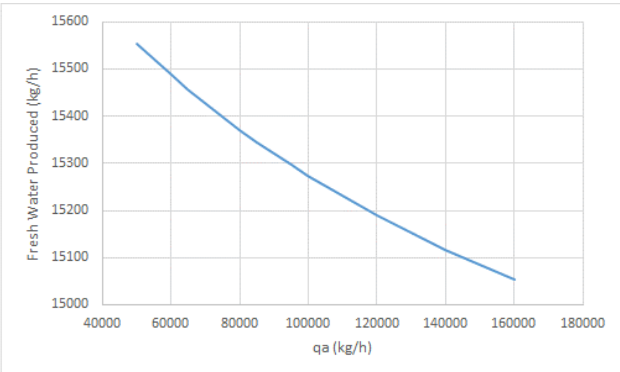

Fig. 6 *Fresh Water Produced vs. Air Circulation Rate – N.G. Flue Gas*

5.3. Total Production Cost

The only variable in this scheme was the flow rate of the circulating air. It was found that the fixed cost of the heat exchanger will remain constant, while all the other fixed and operating costs will increase with the increase in the circulation rate except for the fixed cost of the empty columns, the packing, the pumps, and the pumping operating cost. The cost of packing decreases as the volume of the packing decreases on increasing the circulation. The other costs will vary with the total number of columns that depend on the height and diameter limitations.

It was found that the recommended scenario, with the least value of the total cost, is at the smallest air circulation rate.

Figure 10 compares between the variations of the total annual cost per m3 of produced water with the air circulation rate in both cases.

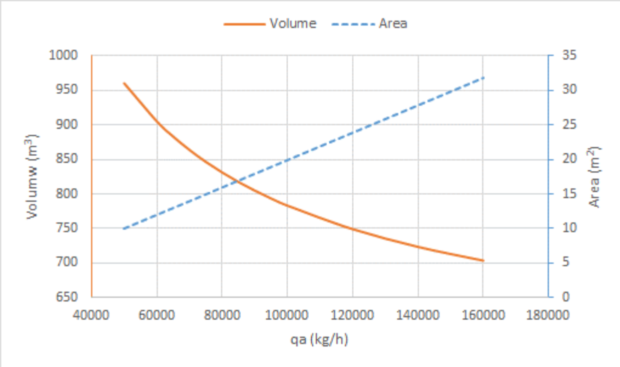

Fig. 7 *Humidifier Area and Volume vs. Air Circulation Rate –, N.G. Flue Gas*

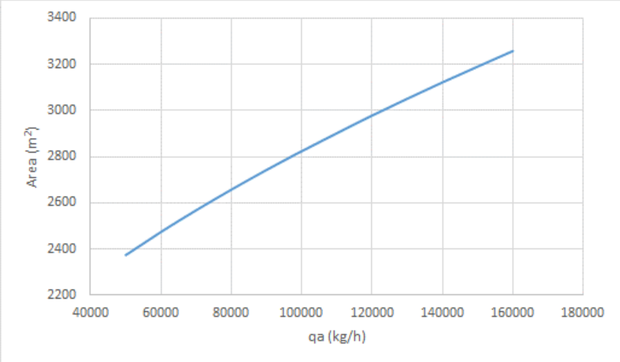

Fig. 8 *Condenser Area vs. Air Circulation Rate – N.G. Flue Gas*

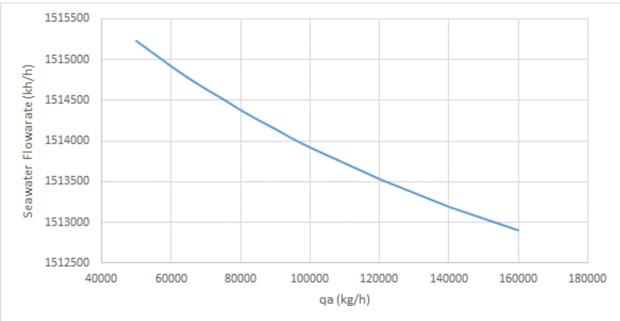

Fig. 9 *Seawater Requirements. Air Circulation Rate – N.G. Flue Gas*

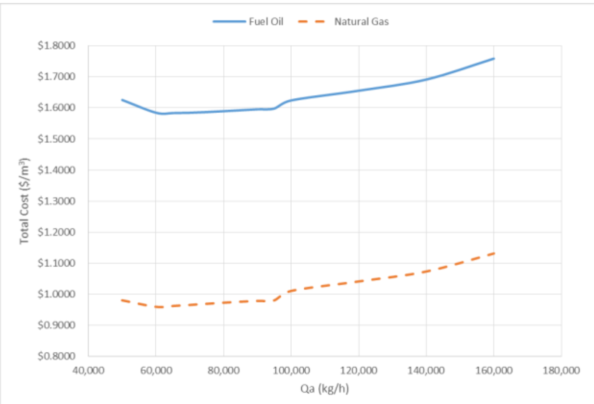

Fig. 10 *Total Production Cost of Fresh Water vs. Air Circulation Rate*

7. Conclusion

This work is concerned with the utilization of waste heat from power stations' flue gases in seawater desalination. The flue gases used in the process are produced from electric power stations that operate on either heavy fuel oil or natural gas. The type of fuel affects the composition and the quantity of the produced flue gases. A process scheme was proposed to desalinate seawater by the humidification-dehumidification technique utilizing the flue gases. The scheme include the following processes: indirect preheating of seawater using hot flue gases, humidification of an air stream by direct contact with seawater, dehumidification of the same stream by indirect cooling in a surface condenser using cold seawater, and an absorption step to desulphurize the flue gases in case of using fuel oil flue gases.

The results were compared with respect to the cost of the produced fresh water. The cost was calculated based on material balance, energy balance, and equipment design equations. The cost includes the fixed cost of the exchangers, condensers, humidifiers, packing, pumps, and fans based on the cost index of 2018. It also includes the operating cost of pumps and fans based on the current cost of electricity.

Results have shown that using the flue gases produced from natural gas power stations will produce fresh water with less total cost than the case of fuel oil flue gases. A significant amount of water will be condensed on cooling the flue gases ensuing from burning natural gas owing to their high humidity ratio, which will result in increasing the total amount of fresh water produced.

For future work, it is recommended that more parameters should be varied to study their effect on the cost and rate of water production such as the minimum temperature approaches in the exchangers or the humidifiers.

8. References

1] A. O. Ghallab and M. H. Elnahas, "Determination of the Physical Properties of Saline Water at Different Temperatures and Concentrations," *International Scientific Journal SCIENCE.BUSINESS.SOCIETY,* no. 1, 2017.

2] E. Chafik, "A New Seawater Desalination Process Using Solar Energy," *Desalination,* vol. 153, pp. 25-37, 2002.

3] S. Parekh, M. M. Farid, J. R. Selman and S. Al-Hallaj, "Solar Desalination With a Humidification-Dehumidification Technique - A Comprehensive Technical Revie," *Desalination,* vol. 160, pp. 167-186, 2004.

4] "Calorific values of solid, liquid and gaseous fuels 3.11.4," [Online]. Available: http://www.kayelaby.npl.co.uk/chemistry/3_11/3_11_4.html. [Accessed 2018].

5] D. K. Bellman, "Electric Generation Efficiency," *NPC Global Oil & Gas Study,* July 2007.

6] "Wikispaces," [Online]. Available: https://chemengineering.wikispaces.com/Acid+dewpoint. [Accessed 2015].

7] N. F. A. Àttia, "Simultaneous Flue Gas Desulphurization and Seawater Desalination," PhD. Thesis, Faculty of Engineering, Cairo University, Giza, Egypt, 2010.

8] "CEPCI-8-2018," 2018. [Online]. Available: https://www.che.utah.edu/~ring/Design%20II/Homework/CEPCI-8-2018.pdf. [Accessed 2018].

9] R. Smith, Chemical Process Design and Integration, 2005.