Multi Stage Flashing Small Scale Plant Combined CHP Plant Driven by Biogas Plant

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Abstract

This paper presents a technical and economic study of a small scale of Multi-Stage Flash - Recycle Brine (MSF-BR) desalination plant, which is driven by the waste heat energy of Co-generator CHP (1.6 MW_{el}), it provided about 1.6 MW_{th} to produce 383 m³/day. Applied with a simple mathematical model to layout MSF-BR, that has performance ≈ 8. The plant consists of 24 small-stages with BR rate about 48 kg/s and stage length vary from1.7 to 2.3 m, where the unit product cost in term of production is about 2 €/m³ and investment cost 1.4 millions €. These design features provided a great opportunity to combine a twofold purpose. The thermodynamic diagnosis is identified the design restrictions and an improved feature of different small scales of MSF-BR, those can be effectively used for small and island towns in the Middle east.

Keywords

MSF- BR desalination,Co-generator, Co-generator; Desalination plant cost, MSF dimension

Nomenclature			
MSF	Multi stage flashing	**MED**	Multi effect desalination
MSF-BR	Multi stage flashing -Brine recycle	**GE**	Geothermal energy
MSF-OR	Multi stage flashing –Once through	**SE**	Solar energy
MSF-M	Multi stage flashing- Mixing	**O & M**	Operation and maintenance
RO	Reverse osmosis	**BH**	Brine heater
FW	Fresh water	**HE**	Heat exchanger
ICE	Internal Combustion Engine	**ME**	Middle east

1. Introduction

As Middle East (ME) population grows, water scarcity, increases energy demand, energy price oscillation and global agreement for climate change mitigation. According to the world bank, ME is considered as amain region of water-scarce after Africa, per capita water availability is expected to fall by more than 50 % by 2050 [1]. So that, In ME countries, the major challenge is the ability to access a clean water supply. The sea water has become a main FW resource through different treatment processes by separating dissolved salts from seawater or brackish water, among these different desalination processes, the MSF and Revers Osmosis (RO) are mostly used. Most countries of the ME and especially the Arabian Gulf countries are using MSF technologies[2, 3].The Combined power - water production is the main economical way to overcome both demands for FW and energy at the same time. The necessary thermal energy to drive MSF desalination plant can be derived from cycle power of a gas turbine[4], steam turbine [5] and Internal Combustion Engine (ICE).Water and energy are closely interconnected in the terms of adaptation and mitigation choices.

Conventional desalination technologies consume intensive energy, as well as a potentially high negative environmental impact through side-products and CO2 emissions those led to turning the research to produce Fresh Water (FW) by renewable energy sources [6, 7]. About 87% of MSF desalination plants powered by fossil fuels, while the remaining 13% are powered by renewable energy.As early, a micro desalination plant was set, wind turbine was used to supply electrical power to drive a micro- Vapor Compression (VC) desalination unit [8]. A market – available wind/RO desalination plant was installed to treat seawater without storage batteries [7], also a hybrid system of wind/PV is used in remote areas to drive both RO and VC desalination technology. Karytsas et al [9] evaluated technical and economical analysis of Geothermal Energy (GE) coupled to the small MED unit (80m^3/d), showed that GE could be a good application with high temperature geothermal desalination.Recently, Loutatidou et al. [10] presented a techno-economic evaluation of coupling a low-enthalpy GE, Showed that GE/RO cost, higher than GE/MED, and GE/RO system not an economically viable alternative to conventionally powered RO desalination. Sharon and Reddy [11] investigated the possibility to produce the FW through different desalination technology combined with renewable Solar Energy (SE), that hence to choose the suitable desalination process for further development.

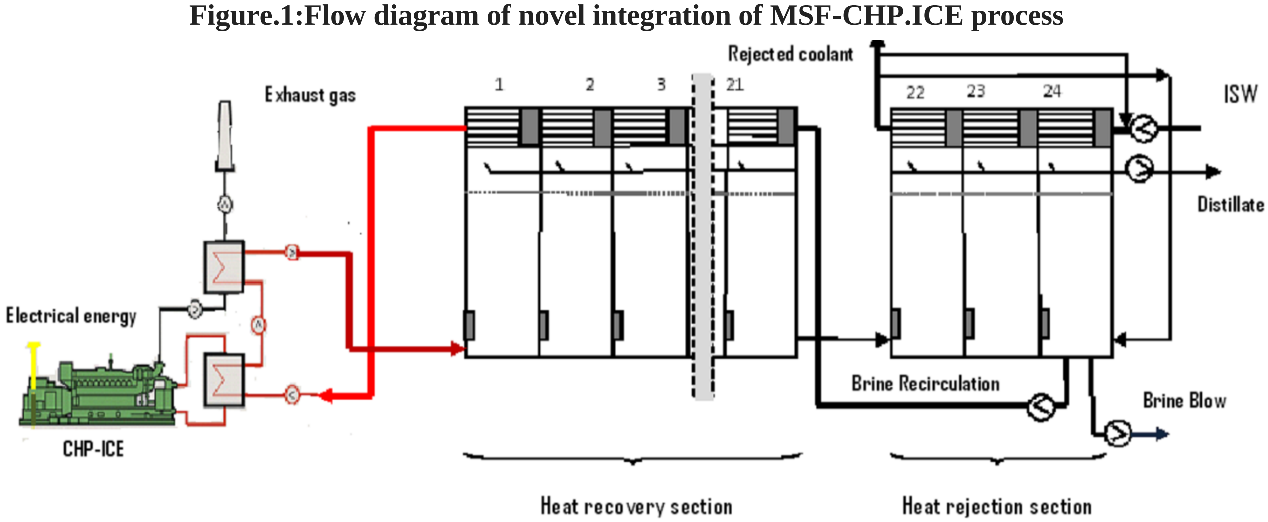
The MSF with brine circulation technology has many more attractive features than other desalination technologies such as the brine mixing system "MSF-M", and the once- through system "MSF-OT" [12, 13].Investigating economic effects for seawater desalination can help the investors make appropriate decisions on investment. The investment cost of MSF desalination plant depends mainly on energy type which drives the process, the plant scale [14], production capacity andplant lifetime.In fact the main impediment for the MSF desalination plant is high costs of constructing, operating facilities which affect on the distillate water cost. According to Gude et al. [14] the desalinated water prices range between 0.3 to 3.2 \$/ m^3 [15].The aim of this study is investigating techno-economical analysis of MSF-BR plant combined with a Co-generator type of CHP-ICE, its new application of renewable energy coupled with desalination technology. Aims to capture the untapped waste heat of ICE and using it to a desired thermal energy to drive MSF-BR plant by incorporating power generation and desalination process.In this paper, a CHP-ICE combined-cycle power plant with MSF-BR desalination plant was modeled. Analyzed by a mathematical model, it covers energy, exergy system, geometrical dimensions of all stages, estimated the economic and environmental issues.

2. Methodologyand Process description

2. 1. Configuration of MSF-BR combined CHP-ICE

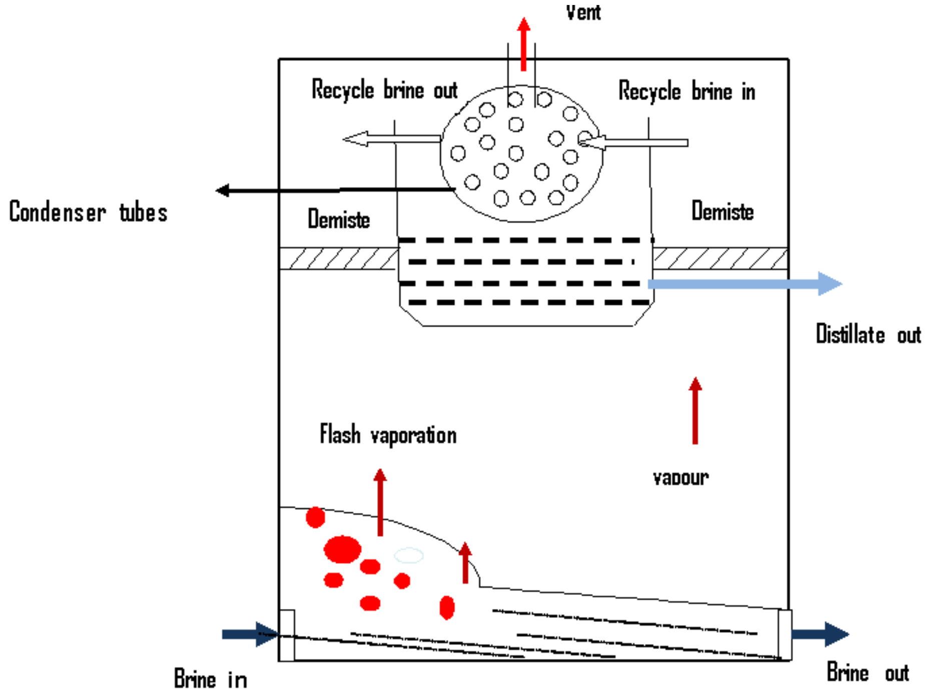
The studied plant consists of CHP-ICE driven by biogas generated from co-digestion of biodegradable waste (sewage sludge and organic waste) ≈ 1,436,49 ton biogas/year collected from medium town (130,000 inhabitants), thus generate about 4,393,797 Nm3/year (68 % CH4) through the Anaerobic digestion plant that powered CHP-ICE (7,500 annual operational hours). The thermal energy extracted during power generation to drive MSF-BR desalination plant, with respect to the allowable salinity of blowdown in the range of 50,000 to 80,000 ppm. The schematic diagram of the proposed MSF-BR combined CHP-ICE plant configuration is shown in Fig. 1.

Figure.1:Flow diagram of novel integration of MSF-CHP.ICE process



The proposed MSF-BR plant consists 24 small flashing stages, stages 1-21 are considered as a section of heat recovery “denoted with HRSR” while stages 22 -24 are the heat rejection section “denoted with HRSJ”. As usual, all the stages in the system have a similar configuration (see Fig. 2); chamber(rectangular shape),consider (preheated tubes- tube bundle), venting line, demister, portion wall and brine orifices [13, 16].

Figure.2:Schematic diagram of the stage



2.1. Energy generated

The source of thermal energy in this model is generated in The Brine Heater (BH) section, it operates as a shell and bundle of tube heat exchanger and it connected to the stage 1.The recycled brine leaves the condenser of stage 1 then passes through tubes of BH which allows to increase its temperature to reach a maximum allowable temperature.In this present work, the BH consists of two heat exchanger in series, those to capture the waste heat produced during the electricity production. The first heat exchanger (HEC)is used to cover untapped waste heat of the cooling system of ICE, that is caused to increase brine recycle temperature from tr1 to T'.While the second heat exchanger (HEF) is used to cover untapped waste heat of the exhaust fume and is allowed to increase the temperature from T' to T0.

The installed power of CHP-ICE can be estimated by the following equation:

$Q = [biogas \times LHVbiogas] / [operationhours \times 3600]$ 1

Considering the thermal energy produced during power generation process by ICE(the generator has 6 reciprocating gas engines) which is characterized as presented in Table 1. The amount of recycled brine($\acute{m}_r$) depends onspecific thermal energy consumption by the process, HE efficiency, terminal temperature difference in the brine heat (ΔT_{HE}) and brine specific heat is defined as Eq. 2 where the brine specific heat depends on the salinity and temperature of brine [13, 17]

Table. 1: Characteristics of CHP-ICE

Technical data	System	Q(KW)	ή (%)
Useful thermal output	Exhaust gas	712	18.3
	Hot water of cooling system	817	21
Electric power		1633	42.2

$Q_{th} \times \acute{\eta} = \acute{m}_r \times Cp \times \Delta T_{HE}$2

2. 2 Evaporator

The model of the MSF-BR is based on the balance of energy and mass, pressure drops across the stages and the heat transfer equations [12, 13, 17].

Individual effects (with denoted i) are varying from 1 to 24, the values of pressure inside the flashing chambers are equal to the pressure of saturation vapor. Considering the top brine temperature (T0), intake seawater (Tsw) temperature and blow down temperature (Tn) are 92°C, 26°C and 40°C, respectively. Accordingly, the value of temperature drop in each stage is2.17°C. The amount of distillate produced in each effect is obtained by:

$$\acute{m}_{di} = \frac{\acute{m}_r \times \boldsymbol{C_{pi}} \times \Delta \boldsymbol{t}}{\boldsymbol{\lambda_{vi}}} \quad 3$$

Where λ_{vi} is the latent heat of evaporation at saturation temperature in stage i.The salt concentration of streams (X_i) Isvarying from stage to another and the quantity of increase in brine salinity depends on the flow rate ($\acute{m}_{bi}$) and the salinity in the previous stage, it is obtained by performing balance of salt (Eq.4).

$$X_i = \frac{\acute{m}_{b(i-1)}}{\acute{m}_{bi}} X_{i-1} 4$$

The total mass flow rate of feed stream ($\acute{m}_f$) and cooling water flow rate ($\acute{m}_{cw}$) are determined by the energy and mass balance equation (Eq. 5 & Eq.6).

$$\acute{m}_f = \acute{m}_d + \acute{m}_b \quad 5$$

$$\acute{m}_{cw} = \acute{m}_{sw} - \acute{m}_f 6$$

2.3 Brine heater and condensers heat transfer area

The thermal energy provides heat exchanges of brine heater unit to increase the recycle brine temperature fromtr1 to T0as required by the process, brine heater. Therefore, the heat transfer area depends on the temperature difference in each heat exchange and given by:

$$A_{BH} = \acute{m}_r \times Cp_r \times \left(\frac{T' - t_{r1}}{U_{HE_C} \times LMTD_{HE_C}} + \frac{T_0 - T'}{U_{HE_F} \times LMTD_{HE_F}}\right) \quad 7$$

The heat transfer area for each condenser in HRSR and HRSJ stages is defined as:

$$A_{Ri} = \acute{m}_{ri} \times Cp_{ri} \times \left(\frac{t_{ri-1} - t_{ri}}{U_{ri} \times LMTD_{ri}}\right) \quad 8$$

$$A_{Ji} = \acute{m}_{SW} \times Cp_{SW} \times \left(\frac{t_{Ji} - T_{cw}}{U_J \times LMTD_J}\right) 9$$

Where

$$LMTD_{ri} = \frac{(T_{vi} - T_{ri}) - (T_{vi} - T_{r(i+1)})}{\ln\left(\frac{T_{vi} - T_{ri}}{T_{vi} - T_{r(i+1)}}\right)} \quad 10$$

$$LMTD_{Ji} = \frac{(T_{vJi} - t_{Ji}) - (T_{vJi} - T_{cw})}{\ln\left(\frac{T_{vJi} - t_{Ji}}{T_{vJi} - T_{cw}}\right)} \quad 11$$

2.4 Brine heater and stage dimensions

The BH is shell and tube heat exchanger. The dimensions of BHdepend on the heat transfer area, total heat transfer coefficient (U) and LMTD. The U based on the tubes number (nt), the length of tube and outside diameter of tube for stream flow inside tube (brine)or equivalent diameter for stream flow outside tube (hot water/exhaust gas).

$$A \times U \times LMTD = \pi n_t L d_t \ 12$$

$$U = \left(\frac{1}{h_{xi}} + \frac{1}{h_{xo}} + \frac{s}{\mu_m} + R_{xi} + R_{xo}\right)^{-1} 13$$

$$h_{xi} = \frac{N_{uxi/o} k_{xi/o}}{d} 14$$

Nusselt number for stream inside/outside (i/o) tube is defined as Eq.(15), where thevalue of a, b and c depends on the type of internal-flow (laminar / turbulent).

$$N_{uxi/o} = cR_{xi/o}{}^{a} P_{xi/o}{}^{b} \quad 15$$

The area of the stage can be determined by using Eq. (16), where the width of the stage is determined from a brine Shell Load (SL_b) and flow rate of recycled brineEq.(17).

$$A = w \times l 16$$

$$w = \frac{\acute{m}_r}{SL} \quad 17$$

Where the SL of brine is assumed that as:

SL_b= 53.43$\acute{m}_d$ + 457.2 18

The length of MSF-BR effect (l) is determined from density of steam (ρ), vapor velocity, distilled water and the effective width (w). The vapor velocity and density are varied through the first to last one. The Brine Depth (BD) is typically higher than the gate height (GH) by 0.2 m. The Hg based on the orifice discharge coefficient “Cd” which is ranging from 0.45 to 0.603 [18], density and mass flow of steam as well as the stage width and distillate production, it is obtained by Eq. (20) . The shape of the stage gate is rectangular shape, its width based on the brine discharge (volume/unit time) and GH and itis givenby Eq. (21).

$$l = \frac{\acute{m}_d}{\rho_v V_v w} \quad 19$$

$$GH = \frac{\acute{m}_r}{C_d w}(2\rho\Delta p)^{-0.5} \quad 20$$

$$GW = 0.2\, GH + \left(\frac{D}{1.84\, GH^{\frac{2}{3}}}\right) \quad 21$$

3. Economic analysis

The distillate water cost varies considerably from country to another as well as from region to region, that based on socio- economic, geographical and environmental conditions. The costs of MSF-BR plant are function of Capital Costs (CC) which is occurring at once- time investment (plant construction) and the Operational and Maintenance (O&M) cost.

3. 1 plantCapital costs and annual cost

Due to the lack of detailed data for the cost estimation of desalination plant coupled power cycle CHP-ICE, which powered by biogas, as well as the typical economic model, so that CC is estimated by using a capacity scaling factor. We adopted the capital cost of small MSF plant (3875 m^3/d) about 19,264,136 $ which consist direct and indirect capital cost [18],the CC is determined by Eq. 21.The expenditures incurred during the annual operation arethe annual fixed charges (Eq. 23), chemical treatment materials, labor, energy, O & M. Where the annual fixed charges are based on the annual interest payments of capital cost, considering the plant lifetime (n)is 30 years and interesting value (i) is 5%. The financial analysis such as the Internal Rate of Return (IRR), Net Present Value (NPV), Return on investment (ROI) in addition to the Payback Period (PP)were used to evaluate the viability, profitability and stability of the small MSF-BR desalination plant. The equations of all financial indicators are present in Table 2.

Table 2. Equation used for economic calculation.

Capital cost (21)	$CC_{MSF} = \text{E\&F}_{\text{known}} \times (\frac{\acute{m}_{dknown}}{\acute{m}d_{MSF}})^x + 0.2\ (E\&F_{MSF})$	
Amortization factor (22)	$f = \frac{i(1+i)^n}{(1+i)^{n-1}}$	
Annual fixed charge (23)	$A_F = f \times CC_{MSF}$	
Annual cost	$A_c = (D \times ((S_{EL} \times W) + S_{TH} + S_C + S_L)) + A_F$	(24)
Net Rate of Return (25)	NPV = $\sum_{n=1}^{N} \frac{C_n}{(1+r)^n}$ - C_0	
Return On Investment	ROI = $\frac{Gainfrominvestment \quad -costofinvestment}{costofinvestment}$	(26)

Nomenclature

X= Cost exponent C_t = Net cash inflow during the plant life, €
r = Discount rate C_0 = total initial investment cost, €
n = Plant life, yrw = Specific consumption of electrical power, kWh/m^3
I = Interest rate S_{TH} = Specific thermal energy cost, €/kWh$_{th}$
D= Operation days S_C = Specific chemicals cost, €/m^3
S_{EL} = Specific electrical power cost, €/kWh$_{el}$$S_L$ = Specific labor cost, €/m^3

4. Results and discussion

4.1 Technical evaluation

The small MSF-BRddesalinationplant techno-economic performance characteristics were predicted using pre-mentioned models in theMethodology. The parameters of operation are investigated. The performance of MSF-BR plant is indicated by the efficiency of CHP powered by biofuel,the fraction of heat waste energy, specific energy consumption and the output gain of the system. The plant is scheduled to operate continuously, and its production is designed to produce about 383 m^3/day.Table 3 presents the main characteristics of the streams flow in both the heat exchangers of the brine heater section, the efficiency was considered 90 % for both heat exchangers. According to the accomplished calculation, the calculated dimensions and manufacturing parameters are presented in Table 4.1 for the brine heater section.

Table 3. The characteristics of the streams flow in the brine heater section

Parameter	**HE_C**		**HE_F**	
	Recycle brine	Hot water	Recycle brine	Exhaust gas
$\dot{m}$(Kg/s)	47.73	43.91	47.7	2.21
T_{in} (°C)	85.5	90	88.5	450
T_{out}(°C)	88.5	86	92	180
C_P (KJ/KgK)	3.9	4.186	3.904	1.074

Table. 4. 1 Specification of a brine heater section of small MSF-BR coupled CHP-ICE.

Specification	HE_C	HE_F
Number of tubes	171	17
Tube diameter (mm/in)	50.8 / 2	31.7 / 1 $^1/_4$
Thickness (mm)	2	3
Intercooler water inlet - outlet connection (mm/inch)	100 / 3$^{15}/_{16}$	
Exhaust gas outlet connection	508 / 20	
Overall BH dimensions		
Width (mm)	1800	
Height (mm)	4158	
Length (mm)	5600	

In this study the width of all flashing chambers is constant0.2 m.The calculated dimensions of the stage, gate and distillate (number of tubes, tube length and heat area)as well as brine depth is listed in Table 4. 2, where the tube diameter in the heat recovery section and heat rejection section is considered 31.8 mm and its thickness is 2.5 mm.Based on those values, the distance between demister and brine level and the space height above the demister are assumed 0.8 - 1 and 0.6 - 1 m, respectively. Thus, the total stage height in both heat recovery and heat rejection section is considered in the range of1.7 to 2.3 m.

Table 4.2. Values of stage, condenser and gate dimension, brine depth and heat area.

Stage .N°(i)	l_i(m)	n_t	GH_i (m)	GW_i (m)	BD_i(m)	A_i (m^2)
1	2.314	281	0.091	0.146	0.291	64.8
2	2.275	293	0.151	0.121	0.351	66.5
3	2.145	309	0.130	0.126	0.330	66.3
4	2.135	314	0.150	0.120	0.350	67.0
5	2.117	316	0.116	0.130	0.316	66.8
6	2.115	322	0.142	0.122	0.342	67.9
7	1.946	348	0.118	0.128	0.318	67.5
8	1.903	363	0.150	0.119	0.350	69.0
9	1.961	354	0.147	0.119	0.347	69.4
10	1.945	361	0.151	0.118	0.351	70.1
11	1.900	377	0.170	0.115	0.370	71.6
12	1.854	387	0.155	0.117	0.355	71.6
13	1.838	404	0.186	0.113	0.386	74.0

14	1.802	412	0.171	0.114	0.371	74.1
15	1.786	426	0.184	0.112	0.384	75.9
16	1.782	451	0.224	0.111	0.424	80.3
17	1.753	439	0.165	0.114	0.365	76.8
18	1.744	485	0.232	0.110	0.432	84.4
19	1.734	574	0.313	0.115	0.513	99.4
20	1.726	493	0.204	0.110	0.404	85.0
21	1.732	523	0.229	0.110	0.429	90.4
22	1.955	356	0.252	0.110	0.452	69.5
23	2.147	373	0.285	0.112	0.485	79.8
24	2.352	343	0.285	0.112	0.485	80.6

As shown in the Table 4.2, the stage length is decreasing from stage 1 to 21 of the heat recovery section and then increasing from stage 22 to 24 that referred to the decreasing of density of steam and pressure.The pressure variations inside the stage, brine salinity andcalculated temperature values for all the streams flow inside chambers are given in Table 5.The pressure is processed by the vacuum condition along the stages. Where the first stage has the maximum shell pressure while the last stage has the lowest pressure, since the pressure decreases, portion of brine will evaporate which leads to increase salt concentration. The salinity of recycled brine is 63,723 ppm and the brine discharges from the last stage with high salinity 69,953 ppm. By increasing the number of stage the brine salinity increased and the temperature decreased, those are led to partial decrease of specific heat capacity.

Table 5. Temperature profile, brine salinity, pressure and brine and distillate flow rate for all stages.

Stage °N	Pressure (bar)	Brine salinity (ppm)	Temperature of IRB (°C)	Temperature of ERB (°C)	Temperature of IB (°C)	Temperature of EB (°C)	Flow rate of Brine (Kg/s)	Flow rate of distillate (Kg/s)
1	0.644	63,970.71	83.33	85.50	92.00	89.83	47.54	0.185
2	0.590	64,219.83	81.17	83.33	89.83	87.67	47.36	0.184
3	0.542	64,469.93	79.00	81.17	87.67	85.50	47.18	0.183
4	0.496	64,721.00	76.83	79.00	85.50	83.33	46.99	0.181
5	0.455	64,973.06	74.67	76.83	83.33	81.17	46.81	0.180
6	0.415	65,226.10	72.50	74.67	81.17	79.00	46.63	0.180
7	0.379	65,480.13	70.33	72.50	79.00	76.83	46.45	0.178
8	0.345	65,735.15	68.17	70.33	76.83	74.67	46.27	0.177
9	0.314	65,991.18	66.00	68.17	74.67	72.50	46.09	0.179
10	0.285	66,248.20	63.83	66.00	72.50	70.33	45.91	0.178
11	0.256	66,506.22	61.67	63.83	70.33	68.17	45.73	0.177
12	0.234	66,765.26	59.50	61.67	68.17	66.00	45.55	0.177
13	0.211	67,025.30	57.33	59.50	66.00	63.83	45.38	0.176
14	0.191	67,286.37	55.17	57.33	63.83	61.67	45.20	0.175
15	0.172	67,548.45	53.00	55.17	61.67	59.50	45.85	0.175
16	0.154	67,811.56	50.83	53.00	59.50	57.33	44.85	0.174
17	0.140	68,075.70	48.67	50.83	57.33	55.17	44.68	0.173
18	0.124	68,340.87	46.50	48.67	55.17	53.00	44.50	0.173
19	0.110	68,607.08	44.33	46.50	53.00	50.83	44.33	0.172
20	0.100	68,874.33	42.17	44.33	50.83	48.67	44.16	0.171
21	0.089	69,142.62	40.00	42.17	48.67	46.50	43.99	0.171
22	0.079	69,411.97	35.33	40.00	44.00	44.33	43.82	0.171
23	0.069	69,682.36	30.67	35.33	39.33	42.17	43.65	0.170
24	0.061	69,953.82	26.00	30.67	34.67	40.00	43.48	0.169

- IRB: Intake Recycle Brine; ERB : Effluent Recycle Brine;
- IB: Intake Brine; EB: Effluent Brine.

Table 6 illustrates the main calculated performance of the small MSF-BR plant. As shown, the total thermal energy drives the MSF-BR plant is 117.5 kWh/m3 while the total distillate capacity is 382.8 m^3, this quantity of production depends on the biogas plant production, top brine temperature and flashing chamber pressure.

In addition, calculated heat transfer area for each section, that shows the heat transfer area of the heat rejection section is higher than heat rejection section (see Table 6).

Table 6. The main calculated performance of desalination MSF-BR plant.

Parameter	Value
Capacity of distillate, m^3/d	383
GOR	8
Rejected coolant flow rate, m^3/d	854
Recycle brine flow rate,m^3/d	4.123
Blowdown flow rate,m^3/d	615.58
Heat transfer area for heat recovery section, m^2	1558.7
Heat transfer area for heat rejection section,m^2	229.9

4. 2Economic evaluation

The economic analysis of this work is performed using an annualized life cycle cost model. The cost model includes capital, O&M costs for all aspects. The thermal energy supply price is calculated using a baseline cost of 0.016 $\$kWh^{-1}$that which correspond with REN21[19], which based on the direct and indirect cost of biogas plant.The specific values of annual costs are included in Table 7. 1

Table 7.1.Specific costs of operating parameters of small MSF-BR plant [25, 26].

Parameter	Value
Thermal power cost, €/kWh	0.016
Electrical power cost, €/kWh	0.056
Operation and maintenance, €/m^3	0.02
Operating labor, €/m^3	0.1
Chemical cost, €/m^3	0.025
Specific consumption of electrical power, Kwh/m^3	3.5

Table 7.2. Annual cost of small MSF-BR desalination plant.

Annual cost	Value (€)
Fixed charge	225,336.0
Thermal energy	179,531.0
Electric power	20,945.0
Operation and maintenance	11,969.0
Labor	3,591.0
Chemical materials and cleaning	2,992.0
SUB-TOTAL	444,364.0

5. Conclusion

A MSF-BR desalination plant combined CHP-ICE derived by the biogas plant of 1.6 MW, which providing only 383 m^3/ day of distillate water and the plant performance of 8. MSF-BR plant has 24 stages (21-heat recovery section and 3- heat rejection section) with dimension (4100 mm * 200 mm).An economic analysis was implemented on MSF-BR small scale plant carried out with 2 € / m^3. The rate of the total cost was considered as the objectives and the initial investment costs are paid back from selling the electricity to the main grid and from distillate fresh water. This study, carried out with a small scale plant of MSF- BR which is suitable for medium town or for the island.

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