PROSPECTS OF IMPROVING ENERGY CONSUMPTION OF THE MULT-STAGE FLASH DISTILLATION PROCESS[1]

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ABSTRACT

The multi-stage flash (MSF) distillation process in the Arab Gulf Region is superceding other conventional desalting processes. Although the MSF process was introduced more than forty years ago, the development of the process has been evolutionary rather than revolutionary. Research and development efforts were mainly directed towards the control of scale formation on heat transfer tubes by developments and dose rate optimization of scale inhibiting chemicals and adoption of on-line sponge ball cleaning. Other areas of R&D are selection of appropriate construction materials, increase of unit capacity and improvements of the quality and variety of control and instrumentation.

The MSF process is an energy intensive process that is associated with high irreversibility. Although coupling the water production with power generation in a dual purpose arrangement reduces the specific fuel energy consumption for water production to around 60 kWh/m^3 which is 50 percent less than that required by single purpose water production desalting plant, it is still much larger than that required by an ideal reversible desalination process. The specific energy consumption of the MSF process can be reduced either by the use of innovative modifications in conventional power cycles and/or by reducing the irreversibility of the MSF process through the improvements in the design and operating features of the distiller.

Accumulated design and operating experiences of the MSF process are effectively utilized for the quest of an improved process design and operation. MSF configurations

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with improved energy consumption and operating at a wide range of top brine temperatures with less scaling potential will be discussed in this paper. Opportunities for designs of water/power co-generation cycles with improved thermal efficiencies such as a gas power cycle topping a vapor power cycle will also be highlighted.

Keywords : MSF, co-generation, energy consumption

INTRODUCTION

The multistage flash distillation process is currently producing around 64% of the total world production of desalinated water. Most of the MSF plants are located in the Arab Gulf region where 82% of the total MSF world production is achieved (Wangnick 1998). The Saline Water Conversion Corporation of Saudi Arabia (SWCC) is the world largest producer of desalinated water. It owns and operates 13 large MSF plants which are located along the Arab Gulf and Red Sea Coasts and with a total installed base load capacity of 658 MIGD which represents 20.6% of the total world desalinated water production. The popularity of MSF is due to its simplicity, robustness and inherent reliability. Although the production capacity of MSF plants world-wide increased from 3.7 MIGD in 1962 to 2042 MIGD in 1998, there is no change in the basic technology and process configuration. However, remarkable evolutionary improvements have been achieved with respect to scale and corrosion control, tendency to build larger plants to reduce the cost of produced water and utilisation of energy efficient dual purpose water/power production plants.

Although the MSF process is the most reliable source for production of fresh water from seawater, it is considered as an energy intensive process, which requires both thermal and mechanical energy as shown in Figure 1. Thermal energy in the form of low pressure bleed steam from a steam turbine at a pressure range of 1 to 3 bar is required for heating recycle brine in the heat input section (brine heater), while medium pressure steam from higher pressure extraction point in a steam turbine is passed to the ejectors to generate the required vacuum in the different sections of the distiller. Mechanical energy is also required for driving the various MSF pumps.

Different methods are normally used to rate the energy consumption of MSF desalting plants (Darwish et al. 1997) such as gain output ratio, performance ratio and specific thermal ener

consider the consumption of auxiliary energy such as energy consumption of venting systems although it demands steam of high energy quality and high quality pumping power. Meanwhile the available energy (exergy) method has the capability to overcome these difficulties and harmonise the thermal and mechanical energy consumption.

In this paper the prospects of improving the energy consumption of the MSF process will be discussed at length. The impact of different design and operating conditions, energy efficient cogeneration and hybrid arrangements, selection of effective control strategy and operational malfunctions on process energy consumption will be evaluated and discussed.

IMPACT OF DESIGN AND OPERATING PARAMETERS

Energy consumption of the MSF distiller can be reduced by increasing the performance ratio through the increase of top brine temperature, number of stages and heat transfer surface area. Increase of TBT increases the flash range which in turn will increase distillate production and improves the thermal performance. Figure 2 shows that increase of TBT increases the performance ratio and reduces the specific surface area. However selection of TBT is limited by the temperature to which the brine can be heated before serious scaling occurs.

Most of the MSF plants are currently operating with a TBT range of 90 to 112^{o}C using high temperature additives treatment (such as polyphosphonate , polymaleic and polycarboxylic acids) with on-line sponge ball cleaning (Al-Sofi 1987). Acid dosing which removes bicarbonate from seawater feed, allows evaporators to operate at an increased top temperature of 120^{o}C close to solubility limits of calcium sulphate . The use of acid, however while enhancing the thermal efficiency of evaporators and possibly reducing capital cost (low heat transfer surface area requirement),needs careful control and monitoring of acid dose level to minimise the risk of corrosion and scale formation and ensure a reasonable plant life (Finan et al. 1989).

Recently a promising approach for pre-treatment of seawater using nano-filtration membrane has been successfully tested to offer a viable alternative to escape from the top brine temperature limitation (Hassan et al. 1998, Al-Sofi et al.,1998). By removing calcium, magnesium, bicarbonate and sulphate ions in the raw seawater by nano-filtration opens the possibility to safely increase TBT above 120^{o}C, which will materialise in significant reduction of energy consumption. Increase of TBT will increase the performance ratio which will consequently decrease the heat added to brine heater and will also reduce the heat exchange surface area. High TBT will also lead to better designed dual-purpose plants of higher overall efficiency at increased production of both water and power at reduced costs (Al-Sofi et al. 1999).

Another factor, which influences the energy consumption of the MSF process, is the number of stages. As shown in Figure 3 increasing the number of stages will increase the performance ratio. This is due to improvement in the efficiency of heat recovery during flashing in each stage but slightly more heat transfer surface area is required due the reduction of the temperature difference over the heat exchangers. The maximum performance ratio obtained for a distiller of 40 stages and a TBT of 120^{o}C is 13 kg/2326kJ as shown in Fig.3. Such expansion of cascading form 16 to 40 stages could improve performance by a factor of 1.5 only. However, the maximum number of stages is limited by the available pressure difference between the stages (especially the Bottom stages) to move brine from one stage to another (Darwish et al. 1995). Moreover, boiling point elevation also restricts the maximum number of stages. That is to say that the minimum interstage temperature drop must be greater than the boiling point elevation for flashing to occur.

An innovative MSF design has been reported (Sommariva et al. 1999) where a brine distillate heat exchanger is to be installed in between brine recycle pump and the recovery section to transfer the residual heat of distillate to the recycle brine. Such arrangement will avoid the irrevesibilties associated with multiple condensation of vapour already condensed as is normally practised in conventional MSF distillers and will bring about a substantial improvement of the plant performance ratio.

ELECTRIC POWER CONSUMPTION

MSF plants incorporate a number of pumps such as recycle, cooling water, blowdown, product and condensate pumps as well as other small pumps for chemicals dosing, which normally consume electric energy. The specific electric energy requirements of an MSF distiller depends mostly on number of stages, top brine temperature, tube velocity and diameter and the design terminal temperature approach (El-Nashar 1994).

The total specific fuel energy consumption of a cross-flow MSF distiller coupled to a back pressure turbine is shown in Fig.4 for two top brine temperatures .The total fuel energy is the summation of the fuel energy consumed to supply the thermal energy requirements of the brine heater and ejector system as well as the fuel energy requirements to generate mechanical energy for driving the various pumps. Fig.4 shows that the pumps fuel energy requirements represent around 14.6 and 15.7 percent of the total fuel energy consumption for TBT of 112.8 and 90.6^{o}C respectively. The breakdown of electrical power consumption among the major pumps is shown in Figure 5. It shows that the brine recirculation pump consumes more than 66 % of the total electrical energy consumption. Fig. 5 also shows operating at high TBT consume less electrical energy and this is due to the fact that operation at high TBT reduces brine recirculation flow and consequently its pumping power requirements.

It has been reported that if large MSF plants are equipped with back-pressure steam turbines as drive for the main pump, the electrical energy consumption will be reduced significantly such that the consumption of electrical energy will be lower than 1 kWh per m^3 (Ialimpianti 1998). Power consumption can also be reduced by specifications of pumps with very high efficiency and reduction of the pipe work and equipment friction losses through optimal routing and proper selection of the equipment geometry (Sommariva et al. 1996).

EFFECTIVE CONTROL STRATEGY

Efficient thermal operation of the MSF distiller is dictated by an effective control strategy. MSF control started with local manual controls where setpoints are normally fixed by plant operators based on previous operating experience and improved to local automatic control with pneumatic controllers. Remote automatic control of MSF actuators through pneumatic controllers and manual set point adjustment will not necessarily result in optimum running condition of the MSF plant (ELNashar 1998). The use of process computer system in process automatic control gives the facility of improving the control of process by obtaining all necessary field data and facilitates energy balances for the process to achieve the set point adjustment based on computed optimal set point for the closed loop controls (El-Saie 1992).

Online set point optimisation is another realistic application where the digital computer will vary the necessary operating variable to accomplish optimum conditions (EL-Nashar 1998). The process measurements are supplied to the computer and form the input to its optimisation program, which carries out a search to find the optimum set point values which minimises the operating cost. The output of the computer will be the optimal values of the set points which are directly implemented by the control loops. However, it has been argued that over instrumentation and control would be unnecessary if an MSF plant is well designed where it will be consistently stable in operation and the plant lends to run for long periods of time with minimum change in operating conditions (Morris 1992).

ENERGY EFFICIENT COGENERATION AND HYBRID CYCLES

MSF distillers are usually combined with power generating cycles to make the best use of low-grade heat that would otherwise be rejected by the generating plant cycle. Selection of the most appropriate cycle depends on the relative demands for power and water and on the variation between summer and winter power water loads (Wade 1992). A recent comparative study between a back pressure and extraction condensing power/water cogeneration cycles revealed that the cycle with back pressure turbine is exhibiting relatively higher thermal efficiencies (Hamed et al. 2000). The study also showed that the fuel energy allocated to water production of the back pressure turbine arrangement using the available energy method (dividing the boiler fuel consumption between power and water according to the available energy consumption of each product) is around 60 kWh/m^3 which is 50 percent less than that required by a single purpose water plant.

Combined gas-vapour cycles in which a gas power cycle (Brayton) topping a vapour power cycle (Rankine) are reported to have higher thermal efficiencies than either of the cycles executed individually and thus be considered as a good alternative to conventional power cycles. Combined cycles with efficiencies more than 40 percent were reported (Cengel and Boles 1994). Since power/water combined cycles are characterized by high power to water ratio, excess power production from the cogeneration plant can be reduced by including an RO unit as shown in Figure 6 (Awerbuch 1997,Darwish and Al-Najem 2000). Prospects of application of gas turbine hybrid all-water systems have been reported (EL-Sayed 1999). The hybrid incorporates gas turbine steam turbine, MSF and mechanical vapour compression distillers. Thermo-economic analysis of the hybrid system revealed that the production cost of water could be reduced by as much as 30% .

Topping conventional Ranking cycle power plants with fuel cells which convert chemical energy of fuel directly into electricity, have been reported (Dunbar and Lior 1991) to increase the efficiency of fuel-celltopped plant to 62%. The improvement stems from the improved exergetic efficiency of fuel oxidation in the topping power plant as contrasted with the highly dissipative combustion process in conventional fuel-fired ones.

The advantages of hybrid triple Power-MSF-SWRO over the dual Power-MSF and single purpose plants were reported by Al-Sofi et al. (1995). The RO plant during cooler seasons (mainly in winter operation) will be fed with preheated water rejected from the MSF heat rejection section and this will result in the increase of plant productivity and reduce energy required by the RO process. Such combination could also lower the cost of intake systems and reduce chemical consumption due the high recovery ratio of the hybrid system . The brine discharge from the RO plant can also be combined with the brine recycle in the MSF plant. The blending of the products from MSF and SWRO allows for the use of a 1-stage SWRO plant instead of the two stage SWRO plant normally employed in single purpose SWRO plants. All these factors should contribute to the lowering of the cost of desalinated water. Moreover, excess power production from the hybrid system will be reduced which will consequently result in a low power to water ratio.

OPERATIONAL MALFUNCTIONS

Improper functioning of components and subsystems of the MSF distiller will result in an increase of energy consumption. Formation of scale on heat transfer surfaces due to ineffective performance of scale inhibitors or cleaning balls, will increase the resistance of heat transfer and deteriorate the heat transfer coefficients which will subsequently decrease the performance ratio. MSF plants are thus frequently acid cleaned to maintain clean heat transfer surfaces and to restore the design performance ratio.

Although over-venting increases the heat transfer coefficient but it also increases the quantity of vapour extracted from the stage without condensation along with the non-condensable gases (Bodendieck and Genether 1999). Such situation will result in the reduction of stage efficiency and performance ratio. Conversely, under-venting decreases the heat losses from the stage, but the possibility of the formation of a blanket of non-condensable gases on heat transfer surfaces will be high and will ultimately lead to low heat transfer coefficients and performance ratio.

Supplying steam to the heat input section with a superheat temperature higher than that required will increase the specific exergy losses and reduce the performance ratio. This attributed to the fact that the thermal energy supplied to the brine heater will have a high exergy value which is eventually dissipated (Hamed et al. 2000).

Brine gates transfer brine from a higher temperature stage to the next which is at a lower temperature stage and they are normally designed and fixed to obtain reasonable approach to equilibrium in the stage (Hornburg and Watson 1993). Unexpected change in the stage flash range and saturation temperature, shell load or brine level may be reflected in the increase of the non-equilibrium losses and accordingly in stage thermal efficiency. If the recycle brine flow is reduced and the brine transfer devices are not properly adjusted to accommodate this change, sealing between the stages may no be adequate and vapour will blow through successive stages and operation be thermally inefficient.

CONCLUSIONS

1. Due to relatively high specific exergy consumption of the MSF process compared to other competing desalination processes, efforts should be directed to reduce specific energy consumption of the process.

2. Most of MSF plants in the Middle East are currently designed with PR of around 8 kg/2326kJ. With the present high energy cost, it is essential that design specifications for future plants have to be changed to reduce energy consumption by selecting an optimised PR which could be in the range of 10 to 11 kg/2326 kJ.

3. To reduce energy consumption and escape from the TBT limitation, it is necessary to further develop seawater pre-treatment methods such as development of high temperature additives or utilisation of nanofiltration membranes, which will prevent the precipitation of calcium carbonate and calcium sulphate scales.

4. Power requirements of MSF plants represent around 13 to 17 percent of the energy consumption and thus optimising power consumption is an important factor in keeping the water cost low.

5. For low energy consumption and low power to water ratio, it is recommended to employ power/water cogeneration cycles with back-pressure turbines.

REFERENCES

1. Al-Sofi, M. AK., Al-Hussain, M.A. and Al-Zahrani, S., (1987), Additive scale control optimization and operation modes ,J.Desalination, 66,11-32.

2. Al-Sofi, M. AK., Hassan, A.M. and El-Sayed, E.F., (1995), Integrated and non-integrated power/MSF/SWRO plants, J. Desalination & Water Reuse, Vol. 2/3,10-16.

3. Al-Sofi, M. AK., Hassan, A.M., Hamed, O.A., Mustafa, G.M., Dalvi, A.G. I. And Kither, M.N.M., (1999), Means and merits of higher temperature operation in dual purpose plants, J.Desalination, 125, 213-222 .

4. Al-Sofi, M. AK., Hassan, A.M., Mustafa, G.M., Dalvi, A.G. I., Kither, M.N.M., (1998), Nanofiltration productions (NFP) or NF-$SWRO_{reject}$(NF-RO_R) as make-up to MSF, Membrane Conference, Amsterdam, Holland, Sept.21-24, 118, 123-129 .

5. Awerbuch,L., (1997), Power-
Proceedings of IDA World Conference, Madrid , Spain , Vol. IV ,181-192.

6. Bodendieck, F., Genthner, K., (1999), The effect of different venting and deareation concepts on the performance and energy consumption of MSF distiller, IDA proceeding, San Diego, USA Vol. 1, 181-192.

7. Cengel, Y.A. and Boles, M.A., (1994), Thermodynamics, An Engineering Approach, 2nd Edition, McGraw-Hill Inc., New York, 987p.

8. Darwish, M.A., (1991), Thermal analysis of Multistage Flash Desalting Systems, J.Desalination , 85, 59-79 .

9. Darwish, M.A., and Al-Najem, N.M., (2000), Cogeneration power desalting plants in Kuwait:a new trend with reverse osmosis desalters,J.Desalination,128,17-33.

10. Darwish, M.A.,El-Refae,M.M. and Abdel-Jwad,M., (1995), Developments in the multi-stage flas desalting system, J.Desalination,100,35-64. .

11. Darwish, M.A., Yousef, F.A. and Al-Najem, N.M., (1997), Energy Consumption and Costs with a Multi-stage Flashing (MSF) Desalting System, J.Desalination, 97, 285-302 .

12. Dunbar, W.R. and Lior, N., (1991), Combining fuel cells with fuel fired power plants for improved exergy efficiency, J.energy, Vol. 16, No. 10, 1259-1274 .

13. El-Nashar, A.M., (1994), An MSF evaporator for the UANW 9 and 10 power station design consideration based on energy and exergy, Desalination, 97, 253-279 .

14. El-Nashar, A.M., (1998), Optimization of operating parameters of MSF plants through automatic set point control, Desalination, 116, 99-107.

15. El-Saie, M.H.A.,(1992), Technical developments of the MSF process desalination process and its prospects for the future, Proceedings of Desal 92 Arabian Gulf Regional Water Desalination Symposium, Al-Ain, U.A.E., Vol. 2, 579-596.

16. El-Sayed, Y.M., (1999), Thermoeconomic of some options of large mechanical vapor-compression units, J. Desalination,125, 251-257.

17. Finan, M.A., Smith, S, Evans, C.K., and Muir, J.W.H. (1989) Belgard EV-15 years experience in scale control, Proc. Fourth World Congress on Desalination & Water Reuse, Kuwait, November 4-8,1989,Vol.1, 341-357 .

18. Hamed,O.A., Al-Sofi M.AK., Imam M., Mustafa, G.M., Ba-Mardouf, K., Al-Wshmi, H., Al-Olyani, A., Al-Ameri, N., and Al-Zahrani, A., (2000), Thermo-dynamic analysis of Al-Jubail Power/Water cogeneration cycles, report published by Dept. of Research & Development, SWCC, Saudi Arabia, Report No. TR 3808/APP 98002.

19. Hamed, O.A., Al-Sofi, M. AK., Imam, M., Mustafa, G.M., Bamardouf, K. and Al-Washmi, H., (2000), Thermal performance of multistage flash distillation plants in Saudi Arabia, J. Desalination ,128, 281-292.

20. Hassan, A.M., Al-Sofi, M. AK., Al-Amoudi, A., Jamaluddin, A.T.M., Mohammad, N.K., Mustafa, G.M. and Al-Tisan, I., (1998), A nano-filtration

(NF) membrane pretreatment of SWRO feed and MSF makeup- Part, Desalination & Water Reuse, 8/1,54-59.

21. Hassan, A.M., Al-Sofi, M. AK., Al-Amoudi, A., Jamaluddin, A.T.M., Mohammad, N.K., Mustafa, G.M. and Al-Tisan, I., (1998), A nanofiltration (NF) membrane pretreatment of SWRO feed and MSF makeup-Part 2, Desalination & Water Reuse, 8/2,35-45.

22. Hornburg, C. D. and Watson, (1993), Operation optimization of MSF systems, J. Desalination, 92, 333-351 .

23. Italimpianti, F. (1998) Exposition of the advantages of MSF desalination for the years (2000), private communication prepared by Wangnick Consulting Engineers,Germany,8p.

24. Morris, R.M., (1992). The development of the multistage flash distillation process A designer Viewpoint, Proceedings of Desal 92 Arabian Gulf Regional Water Desalination Symposium, Al-Ain, U.A.E., Vol. 2, 881-890.

25. Sommariva, C Baorsani, R, Butt, M.I. and Sultan, A.H., (1996), Reduction of power requirement for MSF desalination plants: The example of Al-Taweelah B, J.Desalination, 108, 37-42 .

26. Sommariva, C., Pinciroli, D., Sciubba, E and Lior, N., (1999), Innovative Configuration for multistage flash desalination plant, Proceeding of IDA World Conference, San Diego, USA, Vol.-I, 65-80.

27. Wade, N.M., (1992), Technical and economic evaluation of distillation are reverse osmosis desalination process, Proceedings of Desal 92 Arabian Gulf Regional Water Desalination Symposium, Al-Ain, U.A.E., Vol. 2, 637-660.

28. Wangnick Consulting & GmbH, (1998), IDA Wordwide Desalting Inventory Report No. 15 Germany, 300p.

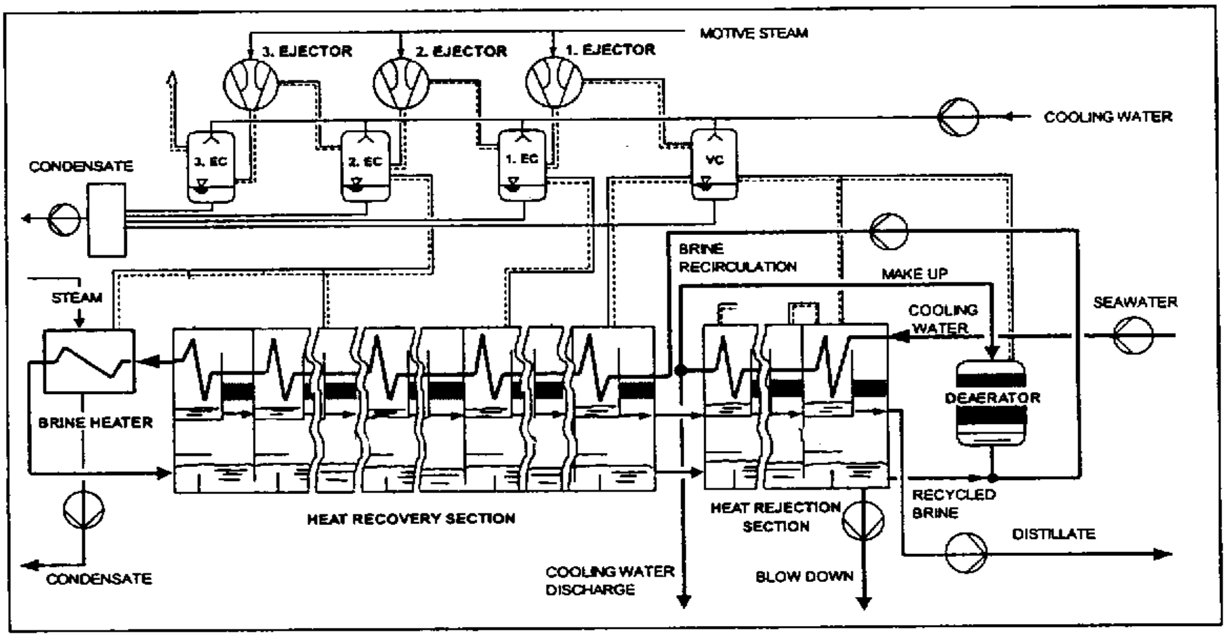

Figure 1. Process flow diagram of a multistage flash distiller

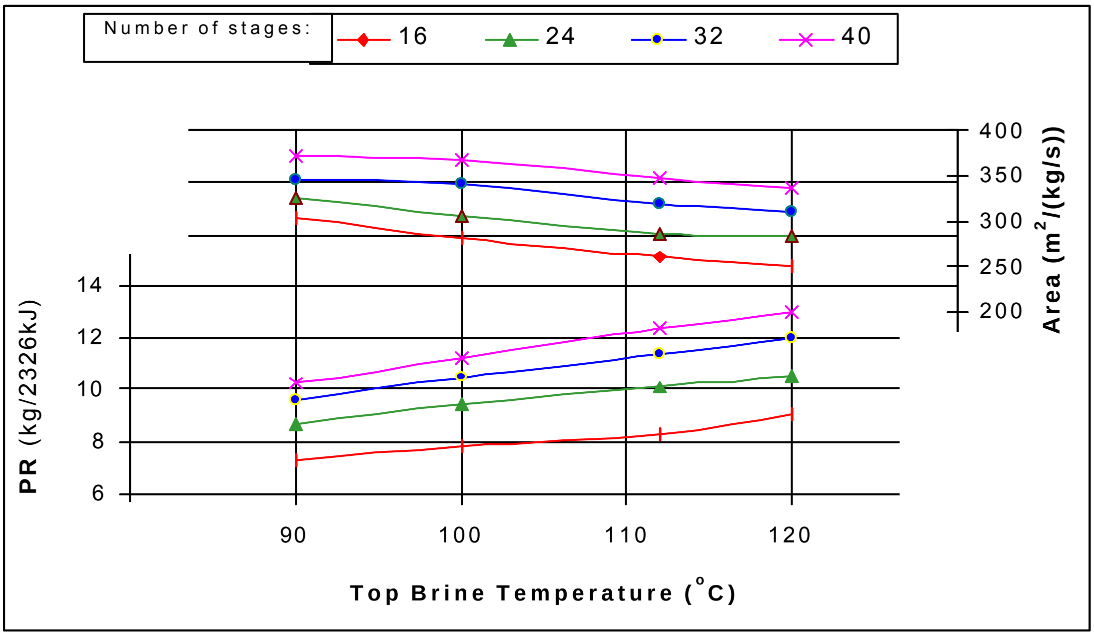

Figure 2. Impact of variation of top brine temperature on performance ratio and specific condensing area.

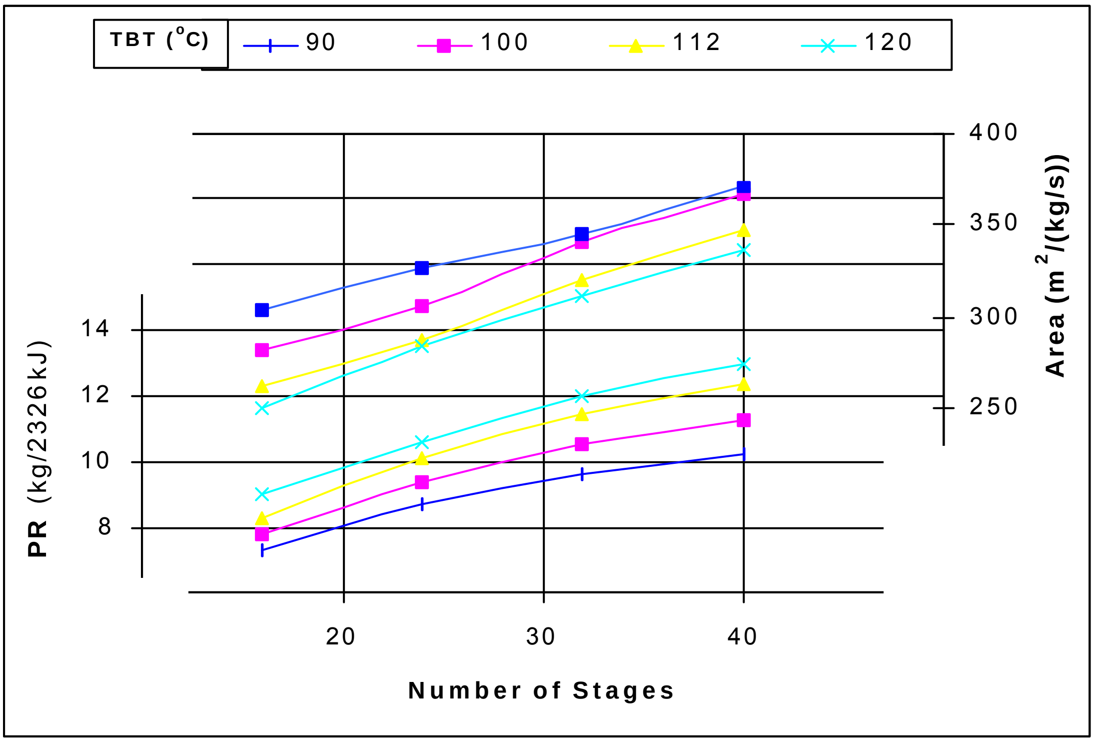

Figure 3. Impact of variation of number of stages on performance ratio and specific condensing

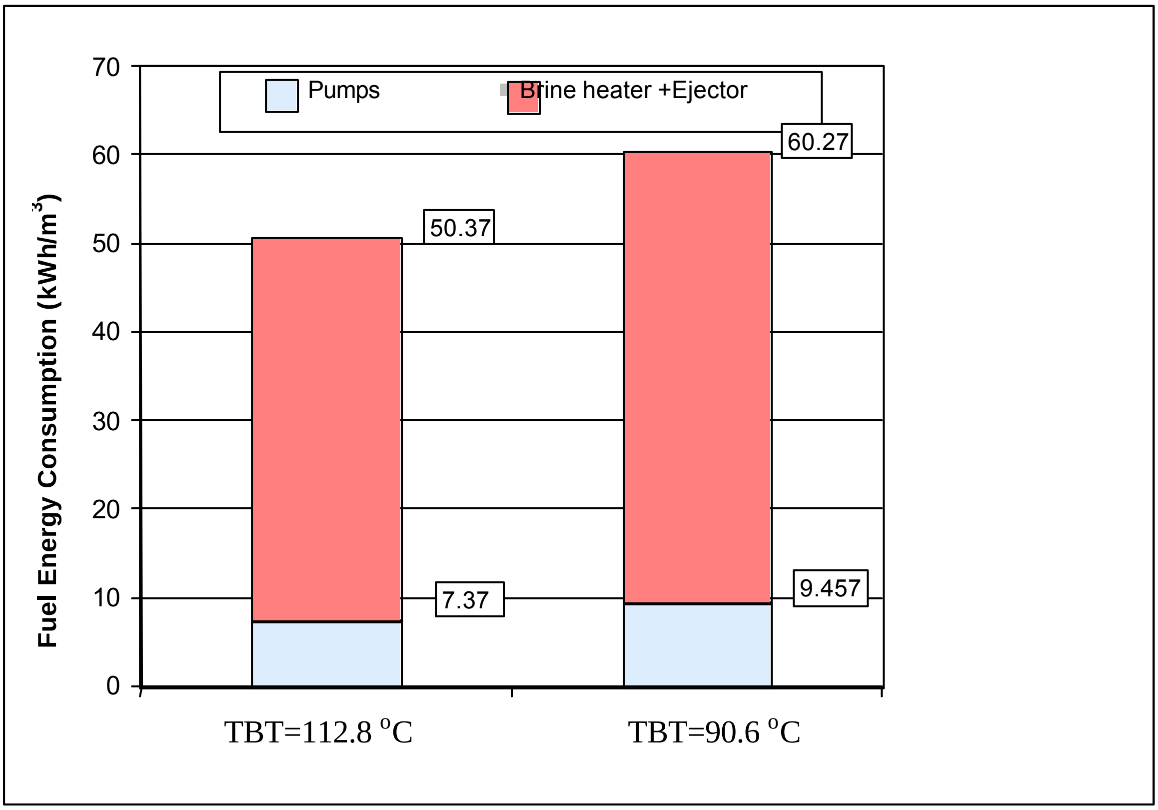

Figure 4. Fuel energy consumption of an MSF distiller coupled to a back-pressure power generation plant.

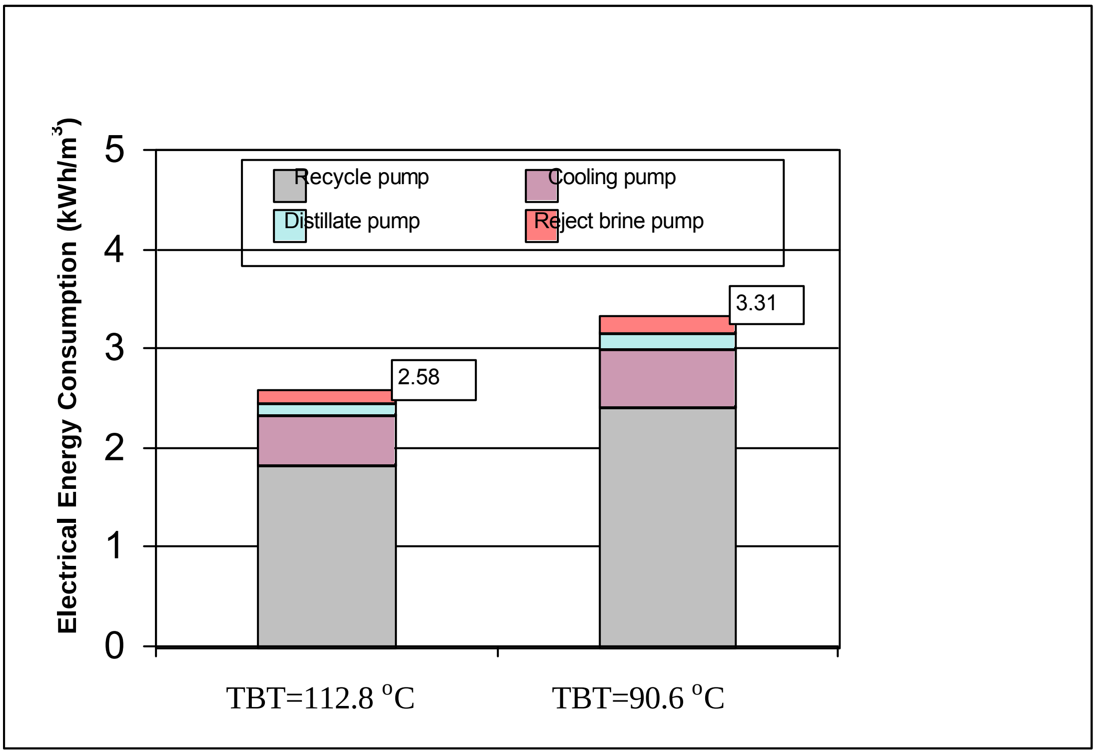

Figure 5. Breakdown of MSF electrical energy consumption.

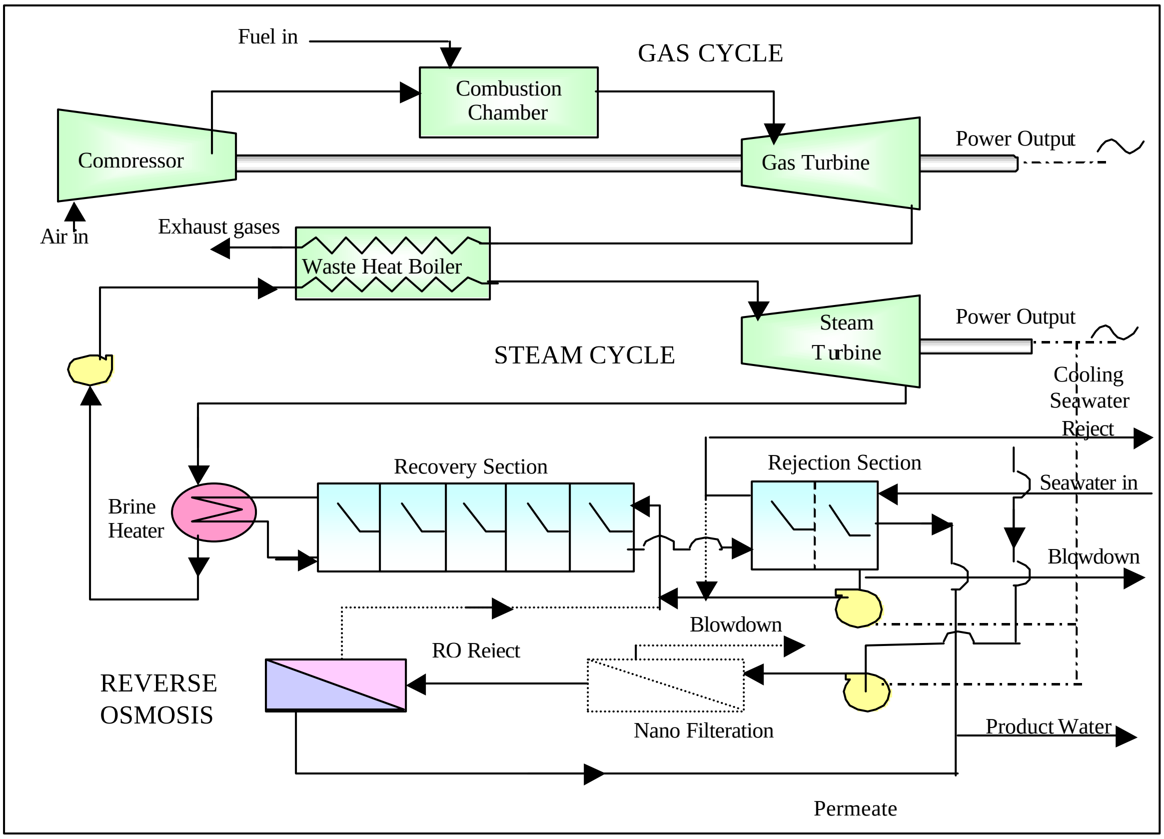

Figure 6. Gas-vapor power generation cycles coupled with MSF/RO desalination plants.