SECOND LAW-BASED ANALYSIS AND OPTIMIZATION OF SEAWATER DESALTING SYSTEMS

Y.M. El-Sayed
President, Advanced Energy Systems Analysis, Fremont, CA 94539-4613, USA

Keywords : Preliminaries, Characterizing quantity, Cogeneration, Decomposition, Decision variables, Dissipative process, Thermoeconomics

Contents

Summary

This article introduces the numerical techniques of second law-based analysis and optimization of energy-intensive systems to the design of systems of interest to desalination. The analysis is known as *exergy* analysis and the optimization is known as *thermoeconomics*.

The techniques, developed over more than 30 years, are surveyed. A powerful tool for optimal system synthesis and design is highlighted. The tool allows intensive analysis of conveniently generated system design concepts.

System complexity is managed by a two-level decomposition strategy using the relatively new concept of costing equations at the level of the disciplines of knowledge and the known Lagrange concept at the device level.

A journey of system improvement is demonstrated as an application example. An accompanying software applies the tool to the systems involved in the improvement journey.

Finally a continuity is created from optimal design to optimal operation.

Beyond the introduction, it is assumed that the reader is familiar with introductory courses in thermodynamics, heat transfer, and fluid mechanics. Appendix (A) is included to the readers who may wish to refresh their memory regarding these courses.

1. Introduction

Man is by nature an exploiter of resources. In time, it became apparent that there is a constraint on the rate of his exploitation since it is not practical to accelerate the renewal rate of resources set by nature and that human developments have to be sustainable. The depleting fuel resources, the depleting ozone layer, and the increasing carbon dioxide in the atmosphere offered the sufficient evidence that man has to live within nature's recycling rate of the essential life support elements. This is a basic law of life and is *embodied* in the laws of *thermodynamics*.

In simple but less accurate terms, the first law of thermodynamics states that energy is changeable to various forms (mechanical, thermal, chemical, …) but in total is conserved. It can neither be created or destroyed. The second law states that all processes proceed to states of higher disorder. So while the first law means that the total energy of the universe is constant, the second law implies that the useful part of energy is diminishing and the universe may be running downhill. In further simpler terms, the first law says to those trying to exploit energy that they cannot win and the second law says that they always lose. The exploiter must be aware of minimizing the inevitable disorder.

The separation of pure water from salt-water will not occur spontaneously. It is necessary to create a device in which the separation of salt from water is forced to occur by an energy resource. The creation of the device requires materials and energy to process and shape them. The form of the needed energy is usually work or heat or combination. Economics comes into play with thermodynamics when the device and its driving energy are valued in monetary units as costs.

The combined application of the first and second laws of thermodynamics gives the least amount of work essential to effect separation by assuming the process used to proceed under constant order producing no increase in the disorder. This least work depends on temperature and salt content. For seawater it is in the neighborhood of 1 kW for each hourly production of one ton of pure water, or 5 kJ kg^{-1} (1.5 Btu lb^{-1}).

A device producing no disorder would have 100 per cent efficiency and would require the least work but unfortunately such device does not exit. On one hand, a device producing little disorder will have high efficiency less than 100 per cent and will need work somewhat higher than the least work but its cost will be very high. On the other hand, a crude cheap device producing very high disorder will have very low efficiency but would require a great deal of work. In either case, the cost of separation, which is the sum of the device's cost and its driving energy, is large. In the first extreme, the device cost shoots high. In the second extreme the cost of the driving energy shoots high. In between these two extremes, there exists an efficiency where the cost of separation is minimum or within a minimum cost band.

This article is devoted to the identification of this minimum cost or band as function of alternative system designs and as function of the economic environment in which the various alternatives happen to be embedded. Of course there are other desirable criteria such as flexibility, safety, reliability and availability. In seeking the minimum cost these criteria are always in the background qualitatively to make sure that none of them falls below acceptable levels. In the design phase of a desalination system, the minimization of the cost of materials and energy as leading criterion is appropriate.

Achieving a minimum cost in desalination is most important since historically water has been taken for granted to be a cheap commodity. Although industry knows no manufactured chemical that sells for less than 1$ per ton, when it comes to water, this price is high.

To find out a minimum cost, a number a scientific disciplines have to be invoked, beside thermodynamics and economic principles. These are the principles and practices of the design and the manufacture of the devices of a sought system and the mathematics of optimization which help searching for a minimum or a maximum.

The outcomes of communicating mathematically among the disciplines of thermodynamics, design, manufacture and economics are far reaching. Design concepts of desalination systems are generated and eliminated without early commitment to any system until the competing ones are discovered. Not only competing alternatives are identified, but also innovative alternatives are inspired and new avenues of research and development are discovered. Good innovative alternative solutions should reduce capital cost for a given system efficiency. This shifts the minimum cost towards less fuel consumption and a double benefit to cost is gained.

This kind of intensive analysis done before being committed to the detailed analysis of a particular system's alternative may have been difficult, or even impossible, before the computer age. Now number crunching costs little. All that is needed is modeling the cost and the performance of the ideas of the system's concepts and observe the interpretations of their minimized costs.

The competing alternatives may now be treated as projects worthwhile detailed cost analysis for complete project management. Usually other cost factors come into play such as factors associated with reliability, availability, and mostly uncertainty. These factors may reduce the number of the competing alternatives or even force the seeking of new ones. Costs not directly involved in the separation process such as the costs of the procurement of the raw seawater, of the disposal of concentrated brine, of pretreatment, of product after-treatment, and of product storage, are not likely to affect the choice of the recommended alternatives.

Conceptual system design driven by intensive analysis would promote a wiser use of energy, create a new generation of lower cost higher efficiency energy systems and enhance sustainable development.

Beyond this introduction, it is assumed that the reader is familiar with introductory courses in thermodynamics, heat transfer, and fluid mechanics. Appendix (A) is included to the readers who may wish to refresh their memory regarding these introductory courses.

2. Preliminaries

This section is an extended introduction to readers having an engineering background and are interested in cost-effective energy savings. The appendix (section 11) is a refreshing review of some relevant aspects of mechanical engineering science. Here in this section system design practice is reviewed. The complexity of the design space is illustrated. The interaction of energy and materials is brought into focus followed by the essentials of the design analysis of energy systems. Second law-based analysis and optimization is then introduced.

2.1. The Emerging Concerns

Design synthesis and design analysis are mental concepts for design innovation and are as old as man's recognition of the need for tools. The traditional approaches to the synthesis and design analysis of energy intensive systems relied on the intuition of experienced designers and engineers. Modest concern was given to fuel economy and no concern was given to the environment.

For the last two decades, the concern regarding depleting fuel resources, waste reduction and cleaner environment has posed a hard challenge to the designers and the operators of energy intensive systems and the challenge is almost international. Cost-effective fuel saving became a focus of attention in the design and in the operation of energy intensive systems. The design process became more complex and required the bases of many disciplines and specialized knowledge in each discipline. The operation became more involved with the strategies of energy management, emission control, and waste disposal. Many R&D projects, targeting a new generation of energy systems which meet the challenge, at both the producer and consumer ends, are at work in both private and governmental sectors. The guide to further study lists examples of the changing attitude towards the use of energy that supports the current work on the Encyclopedia of Life Support Systems. It shows examples of the projects of the Small Business Innovation Research Program supported by US department of energy, and of the activities on improved methodologies supported by the symposia of the Advanced Energy Systems Division of the American Society of Mechanical Engineers since 1985 and by the International Conferences sponsored by the Society since 1987.

These activities did accelerate and disseminate the development of improved methodologies of system synthesis, analysis and optimization to assist the intuition of a designer towards the target of a new generation of energy systems. The low cost of number crunching nourished the development of the methods of analysis. All methods imply optimization and seek innovation through analysis and their common tools are modeling and computational algorithms. However, the facts that models involve assumptions and that they may view the same system from different angles and with different zooms, created variations in the quality and reliability of the developed models. It is, therefore, important that models be verified and it is important that one should be clear about the purpose of the models of interest and their limitations.

Unfortunately the US government support today for large scale seawater desalination is much less than it was in the early sixties. It is hoped, however, that this article may help in transferring some of the improved methodologies to the benefit of desalination.

2.2. The Complexity of the Design Space

One of the main challenges to any methodology dealing with system design is the complexity of the design space. The design space of an energy system may be described in a simplified way by three multi-dimensional coordinates as shown in Figure 1. For a given objective function (efficiency, cost, emissions, safety, … or combinations), an optimal design has both an optimal structure (a connectivity of devices) and an optimal design point (a decision vector of thermodynamic variables and devices' design and manufacture variables). Because structural changes are evolutional and design point changes are multi-dimensional, the topology of the design space is indeed complex and not homogeneous. With desalination systems cogenerating power and water, a desired power:water ratio is an added complexity influencing structural changes.

Means of enhancing the search in both directions of design point and structural changes are needed, though one should not expect a unique optimal solution. Usually there is no single significantly superior solution and more than one solution may share the same objective within narrow differences. The search is, therefore, a search for *an* optimum solution rather than *the* optimum. Moreover, there is no optimization method yet which guarantees global optimum for a multi-variable problem.

All recent energy analysis methodologies are outcomes of the challenge to handle such complex space and the challenge is continuing.

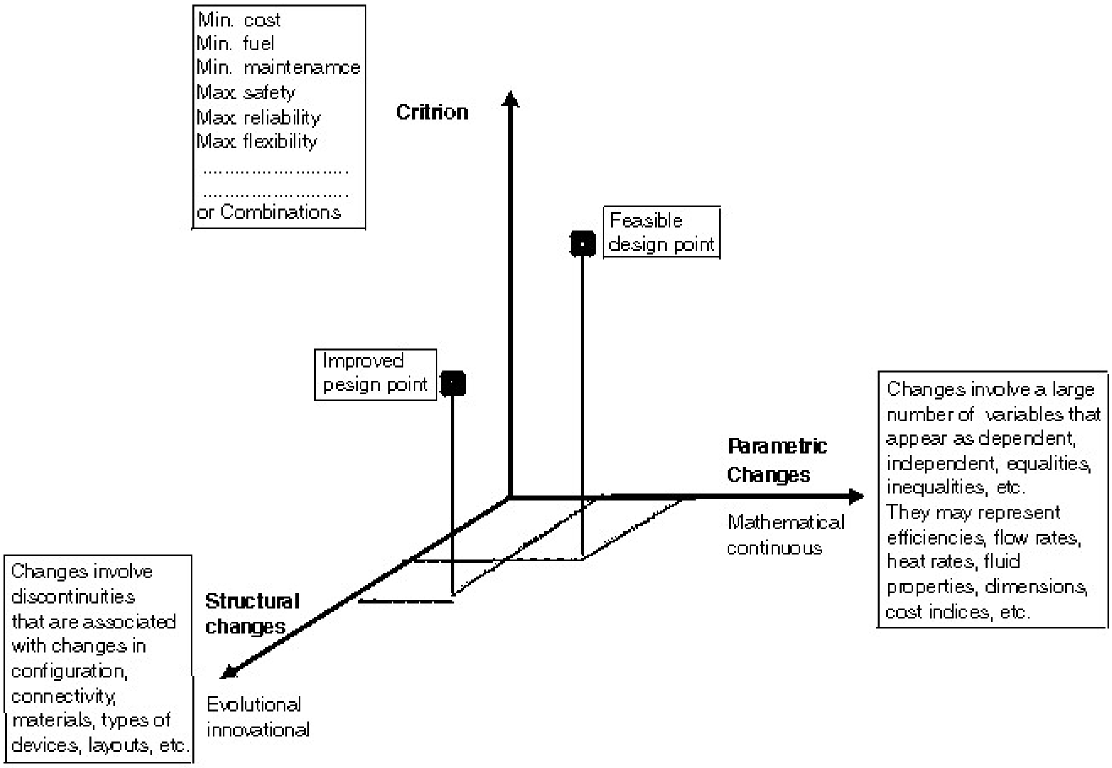


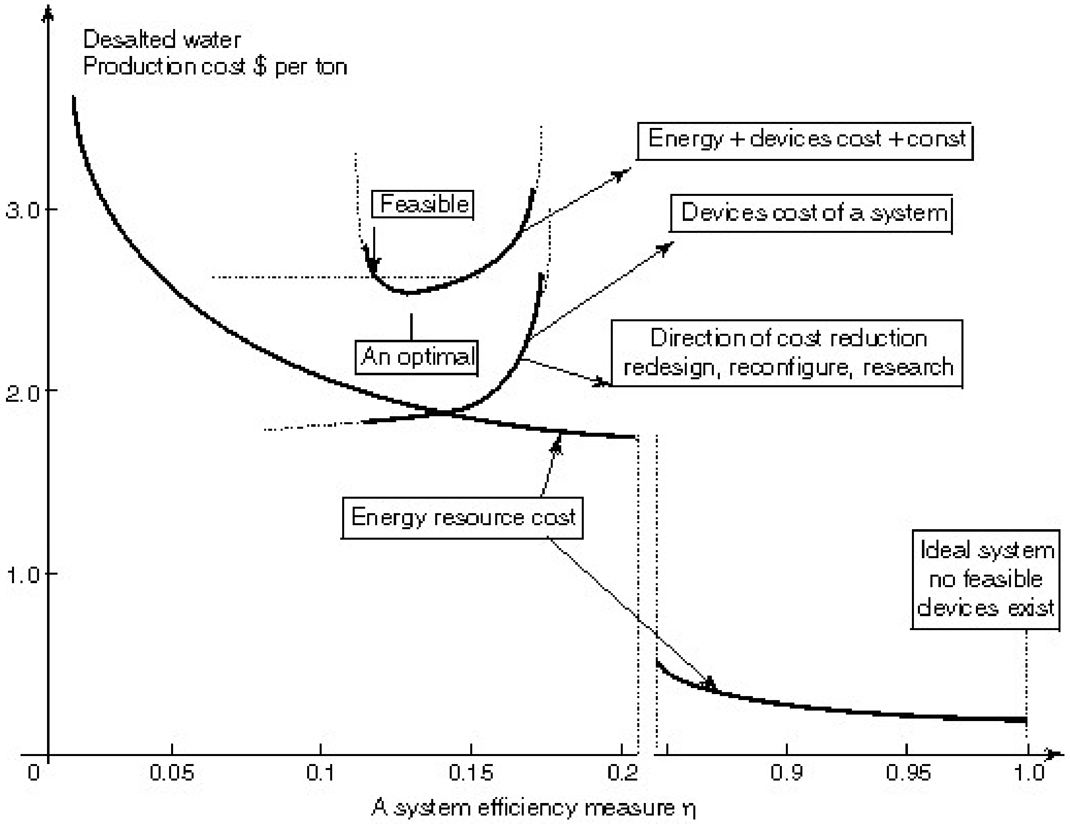
Figure 1. The Complexity of the design space.

2.3. The Interaction of Energy and Materials Requirements

In many energy intensive systems and in particular desalination systems, the requirements of energy and materials processed and shaped as the devices of a system are in strong conflict. The first manifests itself mostly as fuel and the second as a capital cost. In desalination processes, the required surfaces for desalting are a major part of the capital cost.

Consider for illustration a system that produces only water. A system may co-produce power but the power is used solely to produce water. The system therefore starts with fuel and ends with a specified rate of desalted seawater. Figure 2 shows, qualitatively, the fuel cost, the capital cost of the system and their sum per unit water product on a cost-efficiency plane. Obviously the optimal solution provides a lower water cost than any other feasible solution. An innovative design shifts the optimal cost to lower cost and higher efficiency. This is usually associated with an added capital cost to the present design and, in the same time, a significant increase in water production that leads to lower capital per unit product. The road to innovative shift is redesign, restructuring and research. The complexity of cogenerating power and water may force, for some system configurations, an optimum power:water ratio different from the desired ratio.

Using as a measure of efficiency the ratio of actual work to ideal work for power production and the ratio of ideal work to actual work for water production, the ratio varies from 0.25 to 0.55 for power and, as shown in Figure 2, only up to 0.15 for water. The bad news is such low efficiency is not limited only to water but is shared by a large number of energy driven industrial processes. The good news is that there is ample room for future improvement if not breakthroughs.



A unified measure of efficiency:
Desalination: $\eta = W_{ideal}/W_{actual}$, Efficiency band: 2% to 15% (same as many other processes);
tower production: $\eta = W_{actual}/W_{ideal}$, Efficiency band: 25% to 55%;
where $W_{ideal} = (\Delta G)_{Po,To}$ for the process or the fuel.

Figure 2. The cost-efficiency plane.

-
-
-

Bibliography and Suggestions for further study

El-Sayed Y (1997) Radial Inflow Compressor for large Volumetric flows, United States Patent Number 5 676 801, October 1997.

El-Sayed Y and Evans R (1970) Thermoeconomics and the Design of Heat Systems. *Journal of Engineering for Power*, January 1970, 27-35.

Gaggioli R and Petit P (1977) Use of Second Law First. *Chemtec* 1977, 496-506.

Gibbs J (1878) On the Equilibrium of Heterogeneous Substances, *The Collected Works*, Yale University Press, Vol. 1, 1928, p. 77.

Lennox F and Stauffer T (1996) The Efficiency of Inefficiency: Optimizing Power and Water Production under Gulf Conditions. *The International Desalination and Water Reuse Quarterly*, 6/3, 32-39.

Tribus M and Evans R (1962) Thermoeconomics of Seawater Conversion. *Report No 62-63*, University of California Los Angles.

Guide for Further Study

Books on Exergy and Related Topics

Gaggioli R (1980) *Thermodynamics: Second Law Analysis,* ACS Symposium Series 122, American Chemical Society, Washington D.C.

Gaggioli R (1983) Efficiency and Costing, ACS Symposium Series 235, American Chemical Society, Washington D.C.

Kotas T J (1984) The Exergy Method of Thermal Plant Analysis, Butterworth, 1984.

Moran M J (1982) Availability Analysis, A Guide to Efficient Energy Use, Prentice Hall, 1982.

Reid R, Pruasnitz J and Poling B (1987) *The Properties of Gases and Liquids,* 4th edition, McGraw Hill, 1987.

Szargut J, Morris D, and Steward F (1985) *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*, Hemisphere Publishing Corporation, 1985.

The changed Attitude towards Energy Use

Florence World Energy Research Symposium, (FLOWERS'90), Stecco S and Moran M, Editors, Florence, Italy May 28-June 1 1990.

Fourth International Symposium on Second Law Analysis of Thermal Systems, Moran M, and Sciubba E, Editors, Rome Italy, May 25-29 1987.

International Conference on the Analysis of Thermal and Energy Systems, (Athens'91), Athens Greece.

International Symposium on Efficiency, Costs, Optimization, and Simulation of Energy Systems (ECOS'92), Valero A and Tsatsaronis G, Editors, Zaragoza, Spain, June 15-18 1992.

International Symposium on Efficiency, Costs, Optimization, and Simulation of Energy Systems (ECOS'95), Istanbul, Turkiye, July 11-14 1995.

International Symposium on Efficiency, Costs, Optimization, and Simulation of Energy Systems (ECOS'98), to be held in Nancy, France, July 8-10 1998.

International Symposium on Thermodynamic Analysis and Improvement of Energy Systems, Ruixian C and Moran M, Editors, TAIES'89, Beijing, China June 5-8 1989.

International Symposium on Thermodynamic Analysis and Improvement of Energy Systems, TAIES'97, Beijing, China June 10-13 1997.

Small Business Innovation Research, Program Solicitation, DOE/ER-0504, January 1992.

Small Business Innovation Research, Program Solicitation, NASA, SBIR 92-1, July 1992.

Techniques of Managing System Complexity

El-Sayed Y (1989) A Decomposition Strategy for Thermoeconomic Optimization, *Journal of Energy Resources Technology*, Vol. 111, September 1989, pp 111-120.

El-Sayed Y (1993) Advances in the methodologies of optimal thermal design. *Desalination*, 92, 1993, 79-101.

El-Sayed Y (1996) A Second Law-Based Optimization: Methodology Part 1and Application Part 2 *Journal of Engineering for Gas Turbines and Power, Transactions of the American Society of Mechanical Engineers*, Vol. 118, October 1996, pp 693-703.

Jackson P (1986) *Introduction to Expert Systems*, Addison-Welsey, Reading Mass.

Kowalski A (1987) Expert System Possibilites for Process Optimization Using Second Law Analysis, *Fourth International Symposium on Second Law Analysis of Thermal Systems*, Rome Italy, May 25-29 1987, pp 177-182.

Lazzaretto A and Tsatsaronis G (1997) On the Quest for Objective Equations in Exergy Costing *Proceedings of the Advanced Energy Systems Division of the American Society of Mechanical Engineers*, AES-Vol. 37, 197-210.

Linnhoff B (1983) New concepts in thermodynamics for better chemical process design. *Proceedings of the Royal Society of London* 386(790), 1-9.

Linnhoff B (1986) Pinch Technology for the Synthesis of Optimal Heat and Power Systems. *Journal of Energy Resources Technology*, Vol. 111, September 1989, pp 137-147.

Linnhoff B (1994) The Use of Pinch Analysis to Knock Down Capital Costs and Emissions. Chemical Engineering Progress, August 1994, pp 32-57.

Sama D (1996) Heat exchanger network optimization strategy based on reducing the number of heat echangers. *Proceedings of the Advanced Energy Systems Division of the American Society of Mechanical Engineers*, AES 36, 481-491.

Torres C, Serra L, Valero A and Lozano M (1996) The productive structure and thermoeconomic theories of system optimization. *Proceedings of the Advanced Energy Systems Division of the American Society of Mechanical Engineers*, AES 36, 429-444.

Tsatsaronis G (1993) Thermoeconomic analysis and optimization of energy systems. *Progress in Energy and Combustion Science* 19(3), Pergamon Press.

Valero A, Torres C and Lozano M (1989) On the unification of thermoeconomic theories. *Advanced Energy Systems Division* Vol. 9/HTD, American Society of Mechanical Engineers, pp. 63-74.

References Used for Performance/Cost Modeling

Cohen H, Rogers G and Saravenamuttoo H (1987) *Gas Turbine Theory*, Third Edition, John Wiley.

El-Sayed Y (1996) On the feasibility of large vapor compression distillation units. *Desalination* 107, 13-27.

El-Sayed Y (1997) On the development of large vapor compression distillation units. *International Desalination Association*, Desalination Seminar, Cairo Egypt, September 6-8, 1997.

El-Sayed Y and Gaggioli R (1988) The integration of synthesis and optimization for conceptual designs of energy systems. *Journal of Energy Resources Technology* 110, 109-113.

Hegetschweiler H and Bartlet R (1957) Predicting performance of large steam turbine-generator units. *Transactions of American Society of Mechanical Engineers*, July 1957, 1085-1114.

Hoyt H and Sarofim A (1967) *Radiative Transfer*, McGrawHill.

Rohsenow W, Hartnett J and Ganic E (1985) *Handbook of Heat Transfer Applications*, second edition, McGraw Hill Book Company.

Sabersky R, Acosta A and Hauptmann E (1989) *Fluid Flow, A First Course in Fluid Mechanics*, Third edition, Macmillan Publishing Company.

Sehra A, Bettner J and Cohen A (1992) Design of a high performance axial compressor for utility gas turbines. *Journal of Turbomachinery*, (2), 277-286.

Siegel R and Howell J (1981) *Thermal Radiation Heat Transfer*, Second Edition, Hemisphere Publishing Corporation.

References

A. Gambier, E. Badreddin, (2002), *Application of hybrid modeling and control techniques to desalination plants*, Desalination 152, Elsevier, pp. 175-184.

A. Ophir and F. Lokiec (2005), *Advanced MED process for most economical sea water*. Desalination, 182, Elsevier, pp. 187-198.

Abakr, Yousif A.; Ismail, Ahmad F.(2005) *Theoretical and experimental investigation of a novel multistage evacuated solar still*. Journal of Solar Energy Engineering, Transactions of the ASME. 127. 3. Pages: 381-385.

Abdullah I. Al-Khudhiri,(2006)Optimal Design of Hybrid MSF/RO Desalination Plant,Thesis submitted in partial fulfillmentof the requirements for the degree of Master of Science in Chemical Engineering,King Saud UniversityCollege of Engineering

Abdul-Wahab, S. A.(2007) Characterization of water discharges from two thermal power/desalination plants in Oman. Environmental Engineering Science. 24. 3. Pages: 321-337.

Ashrae Handbook (1997) *Fundamentals*. American Society of Heating, Refrigeration and Air-Conditioning Engineers.

Darwish, M.A., (1991), *Thermal analysis of multistage flash desalting system*, Desalination, 59-79.

E. Mathioulakis,V. Belessiotis and E.Delyannis(2007),*Desalination by using alternative energy: Review and state-of-the-art* ,Desalination Volume 203, Issues 1-3,

El-Dessouky, H. T., Ettouney, H. M. and Al-Juwayhel, F.,(2000) “Multiple effect evaporation-vapor compressiondesalination processes”, Trans IChemE, Vol. 78, Part A, pp: 662-676 .

Emad Ali, (2002), Understanding the operation of industrial MSF plants Part II: Optimization and dynamic analysis, Desalination 143, Elsevier pp. 73-91.

Emad Ali, (2002), Understanding the operation of industrial MSF plants Part I: Stability and steady-state analysis, Desalination 143, Elsevier pp. 53-72.

George Papadakis,The ADIRA HANDBOOK, “*A guide to autonomous desalination concepts*”

Hisham Ettouney, (2006), *Design of single-effect mechanical vapor compression*, Desalination 190, Elsevier, pp. pp. 1-15.

Hisham T. El-Dessouky,H.M. Ettouney, (1999), *Multiple-effect evaporation desalination systems: thermal analysis*, Desalination 125, pp. 259-276.

K.S. Spiegler, Y.M. El-Sayed, (2001), *The energetics of desalination processes*, Desalination 134, Elsevier, pp. 109-128.

Kays W M (1966) Convective Heat and Mass Transfer, McGraw-Hill.

M. Shafiur Rahman , Mushtaque Ahmed , X. Dong Chen (2007),Freezing melting process and desalination: review of present status and future prospects, International Journal of Nuclear Desalination Volume 2, Number 3

M.A. Darwish , Iain McGregor, (2005), *Five days’ Intensive Course on - Thermal Desalination Processes – Fundamentals and Practice*, MEDRC & Water Research Center Sultan Qaboos University, Oman

M.A. Darwish, Ammar Alsairafi, (2004), *Technical comparison between TVC/MED and MSF*, Desalination 170, Elsevier, pp. 223-239.

M.A. Darwish, M.M. El-Refaee, M. Abdel-Jawad ,(1995),*Developments in the multi-stage flash desalting system*, Desalination 100 ,35-64

M.A. Darwish, N. Al-Najem, N. Lior, (2006), *Towards Sustainable Energy in Seawater Desalting in the Gulf Area*, Tenth International Water Technology Conference, Alexandria, Egypt, pp. 655-684.

Mattheus F. A. Goosen, Shyam S. Sablani, Walid H. Shayya, Charles Paton, Hilal Al-Hinai,(2000),*Thermodynamic and economic considerations in solar desalination*, Desalination, Volume 129, Issue 1, 63-89

Michael Papapetrou (2009),Workshop on Renewable Energy and Water, IEA, Supporting renewable energy powered desalination: Experiences and lessons learnt

Moran M J (1982) Availability Analysis, A Guide to Efficient Energy Use, Prentice Hall.

Nafiz Kahraman, Yunus A. Cengel, Byard Wood, Yunus Cerci, (2004), *Exergy analysis of a combined RO, NF and EDR desalination plant*, Desalination 171, Elsevier, pp.217-232.

Naim H. Afgan, Mohammad Darwish, Maria G. Carvalho, (1999), *Sustainability assessment of desalination plants for water production*, Desalination 124, pp. 19-31

Prigogine I (1961) Thermodynamics of Irreversible Processes, John Wiley.

Radwan Al-Weshah, (2002), *The role of UNESCO in sustainable water resources management in the Arab World*, Desalination 152, Elsevier, pp. 1-13.

Roberton Borsani, Silvio Rebagliati (2005), Fundamentals and costing of MSF desalination plants and comparison with other technologies, Desalination 182, Elsevier, pp. 29-37.

V. Belessiotis, E. Delyannis, (2001), *Water shortage and renewable energies (RE) desalination* – possible technologies applications, Desalination 139, pp. 133-138.

Van Wylen (1976) Fundamentals of Classical Thermodynamics, John Wiley.

W.E. Alnaser, B. Eliagoubi, A. Al-Kalak, H. Trabelsi, M. Al-Maalej, H.M. El-Sayed, M. Alloush, (2004), First solar radiation atlas for the Arab World, Renewable Energy 29, Elsevier, pp. 1085-1107.

Y.M. El-Sayed, (2001), *Designing desalination systems for higher productivity*, Desalination 134, Elsevier, pp. 129-158.