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Exergy efficiency enhancement of MSF desalination by heat recovery from hot distillate water stages

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ABSTRACT

This detailed exergy analysis of a 3800 m^3/h Multi-Stage Flash (MSF) desalination plant is based on the latest published thermodynamics properties of water and seawater. The parameters of the study were extracted from a validated model of MSF desalination using IPSEpro software. The results confirmed that the overall exergy efficiency of the unit is lower than would be desirable at only 5.8%. Exergy inputs were destroyed by 55%, 17%, 10%, 4.3%, and 14% respectively, in the heat recovery stages, brine heater, heat rejection stages, pumps and brine streams disposal. Moreover, the detail of the study showed that the lowest exergy destruction occurs in the first stage, increasing gradually in heat recovery stages and sharply in heat rejection stages. The study concludes that recovering the heat from the hot distillate water stages can improve unit exergy efficiency from its low 5.8% to a more economical 14%, with the hot water parameters suitable for powering other thermal systems such as absorption chiller and multi-effect desalination.

1. Introduction

The process of producing fresh water from seawater, namely desalination, has been in operation over 50 years. The impetus for the continuing development of this technology is clear as saltwater makes up 97.5% of the water resources on this planet, representing an effectively unlimited source of fresh water in the context of desalination [1]. Research and development in this field is focused on reducing either the energy source consumption or the operation and maintenance cost or both. Selection of desalination technology is influenced by many factors such as the energy source, life of the technologies, water parameters, capacity, etc. Statistically, Multi-Stage Flash (MSF) desalination is the preferred process; 74% of the world's total desalted water in 2003 was produced using the MSF process [2]. Fig. 1 illustrates the distribution of desalination technologies in the Economic and Social development Commission in Western Asia (ESCWA) countries.

Thermal systems are analyzed traditionally through *energy*. However, *exergy* analysis has increasing acceptance as a useful tool in thermal system design, evaluation, optimization and improvement. The efficiency of thermal systems such as desalination can be estimated by both the first and second laws of thermodynamics. While the first law focuses on the *quantity* of energy, second law analysis (exergy analysis) introduces *quality* as well as quantity [3–6]. Exergy analysis allocates the irreversibilities in the system and suggests economical modification and enhancement [7]. However, only a limited number of studies have analyzed seawater desalination exergy, due to the complexity of the determination of the seawater stream exergy.

Kempton et al. [8] analyzed exergy in three types of desalination: Reverse Osmosis (RO), Multi-Effect (MED) and MSF. They found typical exergy efficiencies were 30.10%, 14.27% and 7.73% for RO, MED and MSF, respectively. Kahraman and Cengel [9] analyzed the exergy of an MSF desalination plant in Saudia Arabia with the assumption that seawater was an ideal mixture of two components (NaCl and H_2O) which was suggested initially by Cerci [11]. They found that the exergy efficiency of the unit was only 4.20% and that the exergy input is destroyed by 77.80%, 5.30% and 8.30% in the MSF evaporator, pump motors and brine heater respectively. Sharqawy et al. [7] analyzed the exergy of the same plant. Their study covered both physical and chemical exergy of the seawater streams, and it concluded that the exergy efficiency or second law efficiency of the MSF plant was 7.65%. The majority of the input exergy was lost in the evaporator, brine heater and pump motors, 75.54%, 10.53% and 5.58% respectively.

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Nomenclature

E	Rate of exergy flow in stream (MW)
E_d	Rate of exergy destruction (MW)
E_{input}	Rate of input exergy (MW)
e	Specific exergy of stream (kJ/kg)
G	Gibbs energy (J)
g	Specific Gibbs energy (J/kg)
h	Enthalpy of the stream (J/kg)
P	Pressure of the stream (Pa)
s	Entropy of the stream (J/(kg K))
T	Temperature of the stream (°C)
v	Specific volume (m^3/kg)
w	Salinity of the stream (kg/kg)
W_{min}	Minimum work of separation (MW)

Greek symbols

η	Exergy efficiency (%)
μ	Chemical potential (J/kg)

Subscripts

0	Dead state
B	Brine disposal
BH	Brine heater
C	Cooling disposal
CH	Chemical
Co	Condensate disposal
HRC	Heat recovery
HRJ	Heat rejection
KE	Kinetic
P	Product disposal
PH	Physical
PO	Potential
PP	Pumps
s	Salt
sw	Seawater
T	Total in stream
Th	Throttling
w	Water

Superscripts

0	Dead state
*	Stream condition

Mistry et al. [12] studied different desalination technologies: MSF, MED, RO, Mechanical Vapor Compression (MVC), Direct Contact Membrane (DCM) and Humidification-Dehumidification (HD). They found the exergy efficiency of these technologies to be typically 2.9%, 5.9%, 31.9%, 8.5%, 1% and 2.4% respectively. In most of these previous studies the MSF desalination system was analyzed as a whole unit, without detailed exergy analysis of the internal components to specify the exact locations of exergy destruction. Nafey et al. [13] conducted a detailed exergy analysis of a 5000 m^3/day recycle MSF desalination plant and found that the exergy efficiency was 1.83%, which was considered too low. Most studies agree that, notwithstanding its wide acceptance, the exergy efficiency of MSF desalination plant is too low. However, Nafey et al. [13] covered exergy efficiency and destruction at each stage, indicating the potential for improvement and enhancement through reducing exergy destruction.

The present study, therefore, has two aims. Firstly, detailed exergy analysis of an existing operational 3800 m^3/h MSF desalination plant has been performed using the latest published thermodynamic properties of seawater to illustrate the ability to allocate the exergy destruction within the unit components. Secondly, it is suggested how such an analysis can be exploited to propose exergy efficiency enhancement, e.g., by the prospects for heat recovery from the hot distillate stages.

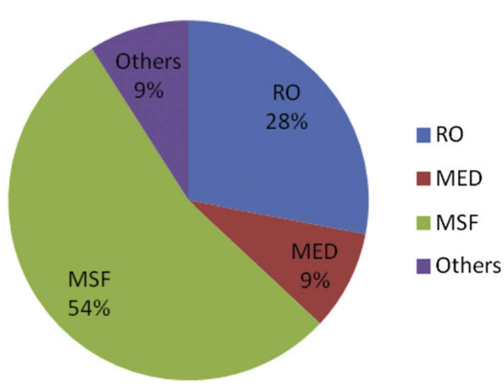

Fig. 1. Distribution of desalination technologies in ESCWA countries [2]. MSF = Multi-stage flash, RO = reverse osmosis, MED = Multi-Effect desalination.

2. Exergy analysis methodology

Exergy is defined as the maximum obtainable useful work when a system is moved to equilibrium from the initial state to the environmental state (Dead State) [5,6]. The total exergy (E_T) of any stream is defined as:

$$E_T = E_{PH} + E_{CH} + E_{PO} + E_{KE} \tag{1}$$

where E_{PH}, E_{CH}, E_{PO} and E_{KE}, are the total physical exergy, total chemical exergy, total potential exergy and total kinetic exergy, respectively. Specific exergy is total exergy divided by mass flow rate of the stream:

$$e_T = \frac{E_T}{\dot{m}} \tag{2}$$

Therefore, the specific exergy is a sum of the specific exergies of defined stream:

$$e_T = e_{PH} + e_{CH} + e_{PO} + e_{KE} \tag{3}$$

in which e_{PO} and e_{KE} are considered negligible since the stream is assumed to be at rest relative to the environment [3].

In the MSF process, the streams are pure water, seawater and heating steam. The physical and chemical exergy of the water and seawater streams is calculated by correlations suggested and validated (with maximum deviation of ±1.5%) by Sharqawy et al. [10]. Physical exergy (e_{PH}) of the fluid stream is:

$$e_{PH} = (h - h_0) - T_0(s - s_0) \tag{4}$$

where h_0, T_0, s_0, are the enthalpy (kJ/kg), temperature (K) and entropy in (kJ/(kg K)) of the stream at the dead state. For the water and seawater the enthalpy is given by (constants presented Table 7):