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Holistic Optimisation of Solar-assisted Multiple Effect Evaporators (MEE)

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Abstract. The effects of heat transfer performance of systems can be studied in combination with thermodynamic performance. The design solution of maximizing heat transfer always leads to increased entropy generation else if minimizing entropy was aimed then heat transfer got minimized. Hence there is need for holistic optimization. This paper attempts to merge the two competing criteria's - (i) heat transfer and (ii) the thermodynamic performance of a solar assisted multiple effect evaporator system and optimize study parameters for its energy efficient operation. Solar assisted multiple effect evaporators use steam as source of energy to evaporate wastewater.

The idea of amalgamating these two factors is to observe how much reduction in the performance of one factor will improve the performance of the other. This study couples the two criteria, which has been dealt with separately, to arrive at the parameters of interest which must be fine-tuned for ensuring system performance.

Mass flow rate of steam and wastewater appeared to chiefly influence heat transfer and entropy generation of the system, negligible influence was observed on changing the concentration of the waste water or optical efficiency of the solar concentrator in single legged analysis. However through this holistic optimization study, it was found that variations in Prandtl number, i.e., the concentration of the waste water and optical efficiency of solar concentrator drastically shift the optimization balance of entropy generation and heat transfer rate.

Keywords: Multiple effect evaporators, Holistic optimisation, Solar, Exergy, Entropy, Wastewater

1. Introduction

Multiple effect evaporation process is a thin film evaporation process, in which the vapor formed in one chamber, or effect, condenses in the next one, providing a heat source for further evaporation. (See Figure 1. Multiple effect evaporator-Concept (MC Georgiou et al)) [1] Advantage of the process is steam economy. It is estimated that for a single effect evaporators nearly 0.8 kg of water can be evaporated with 1 kg steam. [2] To treat the reverse osmosis rejects multiple effect evaporators were found the best option. This device is indispensable in wastewater treatment systems because to do any end-of the life functions with concentrated salt rejects – separation of salt and water is necessary. Vaporisation and separation is the best possible technique to achieve this. [3] Hence it is agreed upon by researchers that further advancements must be made in multiple effect evaporators. Unlike traditional boilers where heat is supplied to vaporize products, in single-effect evaporator systems steam provides energy for vaporization instead of direct heat and the vapor product is condensed and removed from the system, while in double-effect evaporator, the vapor product off the first effect is used to provide energy for a second vaporization unit. [4] This cascading of effects continues for many stages. Vapor from Effect I will be used to heat Effect II, which consequently will operate at lower pressure. These continue through the train: pressure drops through the sequence so that the hot vapor will travel from one effect to the next. Effects are numbered beginning with the one heated by steam which will have the highest pressure.

Normally, all effects in an evaporator will be physically the same in terms of size, construction, and heat transfer area. [5] Unless thermal losses are significant, they will all have the same capacity as well.
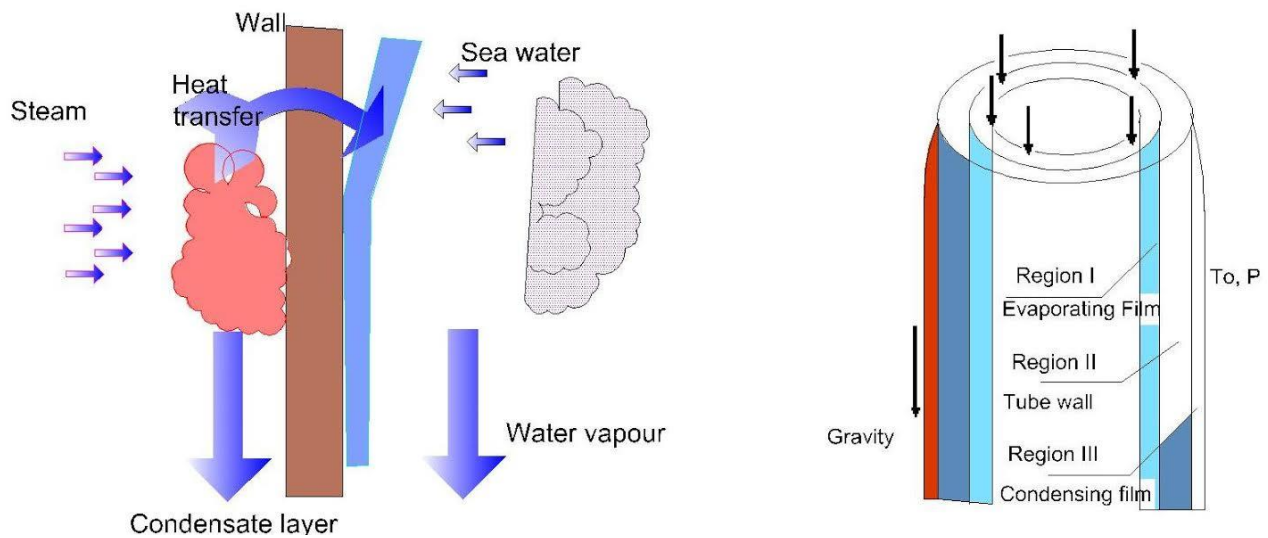

Figure 1. Multiple effect evaporator-Concept (MC Georgiou et al)

2. Multiple effect evaporators: System description

Theoretically evaporators may be built with any arbitrary number of stages, however the stages are limited in practical cases by constraints such as space, cost, etc. Several configuration models have been developed in the past depending on the configuration of feed flow. [6]

Equation 1 gives the heat transfer up-to 'n' effects/chambers/evaporators-

$$Q_n = m_s \lambda_s = U_{Dn} A_n (T_{sn} - T_{Bn}) = U_{Dn} A_n \Delta T_n \tag{1}$$

Specific entropy of the steam was calculated using simplified equation given by Affandi et al (2012) depending on the temperature of the steam [7],

$$\ln S_g = a + b \left(0.35 * \ln(\frac{1}{T_s})\right) + \frac{c}{T_s^2} + \frac{d}{T_s^4} + \frac{e}{T_s^5} \tag{2}$$

where a = 1.47735, b=0.53242, c=-0.01923, d=0.02974, e=-0.00802

And exergy using the entropy calculated above,
$$X = h - h_0 - T(S - S_0) \tag{3}$$

3. Parameters influencing the performance

A general formula for heat transfer coefficient during evaporation processes in the first effect of the multiple effect evaporator attached with a solar concentrator can be put in the form:

$$Nu = a(Re)^b (Pr)^c (\eta_0)^d \left(\frac{A_a}{A_r}\right)^e) \tag{4}$$
where a, b, c, d and e are constants.

Similarly the function for entropy was obtained as

$$S_{gen} = f(Re)^g \, (Pr)^h \, (\eta_0)^i \left(\frac{A_a}{A_r}\right)^j) \tag{5}$$

In the model equation (5), the below parameters were altered and the associated dimensionless number were recorded (see. **Table 1.** Constraints Range Sampled). Based on the below described constraints which were obtained from industry, equation (4) and (5) were solved for correlation.

Table 1. Constraints Range Sampled

S. No.	Constraint	Range
1.	Optical efficiency of the solar collector	40-80%
2.	Concentration Ratio	2 - 600
3.	Mass flow rate	20 – 335 kg/h
4.	Concentration	1-52 g/kg
5.	Temperature of the steam in 1st effect	150 – 300 ^{0}C
6.	Number of effects	3 – 15
7.	Overall heat transfer coefficient of the material in the 1st effect of the evaporator	2,270 – 6,000 W/m-K

The below correlation was obtained through the multiple regression analysis,

$Nu = a \, Re^b \, Pr^c \, \eta_0{}^d$ concentration ratio^e
$r^2 = 0.97$ $\tag{6}$
where a = 0.183, b = 1.692, c = 0.513, d = 0.283, e = 0.18

The correlation had a good parity with the model data with standard deviation error of 0.1-8% and R-square of 0.97. Similarly correlation was obtained associating entropy of the steam generated with Reynolds number, Prandlt number, optical efficiency and concentration ratio for evaluating the performance of the system by second law of Thermodynamics.
$S_{gen} = 0.015 \, Re^{0.604} \, Pr^{0.345} \, \eta_0{}^{0.015}$ concentration ratio$^{0.117}$
$r^2 = 0.98$ $\tag{7}$

4. Holistic Optimisation

The effects of heat transfer performance of systems is to be studied in combination with thermodynamic performance. The design solution of maximizing heat transfer always leads to increased entropy generation else if minimizing entropy was aimed then heat transfer got minimized. Hence need for holistic optimization was recognized. The idea of amalgamating these two factors is to observe how much reduction in the performance of one factor will improve the performance of the other [8]. As far as the heat transfer of a system is concerned the performance parameter of choice is the heat dissipated per unit mass of the system and with regard to irreversibility, the entropy generation rate is taken as the parameter for comparison [9].

To obtain the heat transfer in the first effect of the MEE, the Nusselt number [10] is used to obtain heat content of the steam as,

$$h = 0.183 k Re^{1.692} Pr^{0.513} \eta_{\circ}^{0.283} CR^{0.18} \tag{8}$$

It is to be noted that this heat content of the steam is basically the heat transferred to the wastewater for steam generation neglecting the sensible heat requirements as per the model hence instead of the conventional ΔT method to obtain heat transfer, the indirect heat content measurement has been used here, to obtain the heat transfer neglecting sensible heat requirements of the phase change. Similarly analysis was extended to estimate the entropy generated.

For the range of parameters discussed in Table 1, the corresponding energy and entropy generation were computed. This was followed by obtaining the ratio of heat transfer to maximum possible heat transfer (q/qmax) and ratio of the minimum possible entropy generation to the minimum entropy generated (Smin/S). The ratios presented the penalty percentage, if 50% is the penalty range considered, i.e the system needs to operate for say 50% of best heat transfer rate possible, with 50% of minimized entropy generation rates for the given parameter range then the corresponding was obtained by plotting graphs of q/qmax, Smin/S against the parameter sampled. This can give a preliminary idea on the solution range, however this would be insufficient. For holistic optimization penalty ranges must be varied and weightages considered for the ratios must be altered as in Rakshit et al. [11],

$$\Phi = \alpha \left(\frac{q}{q_{max}}\right)^a + (1-\alpha)\left(\frac{S_{min}}{S}\right)^b \qquad (9)$$

where, $0 \le \alpha \le 1$

In order to obtain a holistic optimum, Φ needs to be minimized, a and b are constants and can have the same or different values. For the present case, a = b = 1 is considered which signifies equal weightage for heat transfer per unit mass maximization and entropy generation minimization. To determine the optimized parameters the value of α needs to be identified such that Φ is minimum and this determines the minimum total penalty.

5. Results and Discussion

5.1. Single-legged analysis

Exergy efficiency of the device depends on the amount of solar insolation. Also the exergy efficiency and heat transfer of the system is chiefly related to Reynolds number or waste water flow in the system. Change in Prandtl number did not significantly affect the energy need of the system as change in the properties of the fluid only marginally shifted the boiling temperature of the fluid by about 50°C which did not alter the energy needs as change in mass stream velocity in Reynolds number. This was also verified by parametric study where for a range of Prandtl and Reynolds number the Nusselt number showed significant concave linear variation for change in Reynolds number rather than Prandtl number which signifies change in concentration of the waste water flow would not affect significantly the Nusselt number.

Similarly the entropy had a convex linear variation with change in Reynolds number. Upto a value of Reynolds number 400, change in optical efficiency does not alter the Nusselt number, however post 400 there are variations in the order of 1/10000 for different optical efficiency for the same Reynolds number. (See. **Figure 2.** Variation of Nusselt number with Reynolds number and Optical efficiency). Similar range of variation was observed when the concentration of the property of waste water was kept constant with varying optical efficiency. No variation in Entropy however was observed with varying optical efficiency and constant Reynolds number and Prandtl number respectively. Also from the study one can understand that the variation in concentration ratio of solar collector or optical efficiency of the solar thermal collector system did not significantly influence the Nusselt or exergy efficiency of the system which clarifies hourly variations in solar radiations does not significantly affect the performance of the solar assisted MEE system as a whole.
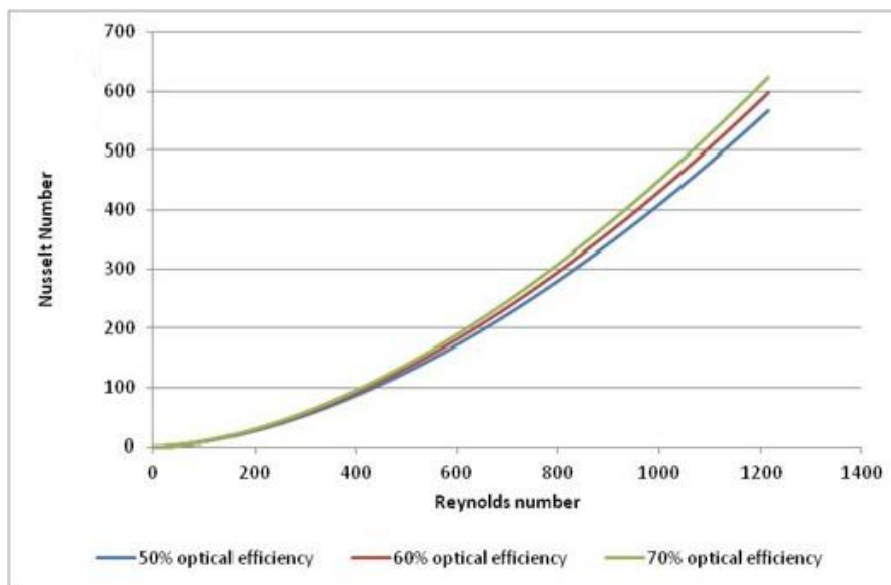
Figure 2. Variation of Nusselt number with Reynolds number and Optical efficiency

5.2. Holistic Optimisation
In the present case where equal weightage was given for both heat transfer per unit mass maximization and entropy generation minimization, the minimum total penalty in heat transfer (approx.) was 20% and reduction in entropy generation (approx.) was 80%. The least value of **Φ** was obtained in the case of Reynolds number (see. **Table 2.** Parameter range and values of **Φ**). This signifies that the parameter holds in the case of arriving at the holistic optimization.

Table 2. Parameter range and values of **Φ** (a=1, b=1, **α**=0.2)

Parameter	Range	Φ
Reynolds number	3,270-16,370	0.03
Concentration ratio	2-10	0.5
Prandtl number	6.8-7	0.9
Optical efficiency	60-65%	0.9

6. Conclusion

The above results thus signifies that changes in Prandtl number, i.e the concentration of the waste water and optical efficiency of solar concentrator can drastically shift the optimization balance of entropy generation and heat transfer rate. While when these parameters were studied separately it appeared their changes had negligible influence on change in heat transfer or entropy generation. Also it was observed that no significant changes appeared on altering weightages, which implies keeping the mass flow rate low or making sure the heat transfer rates are bare minimum is the best way to destroy entropy generation.

7. Nomenclature

m   flow rate in kg/s
H   enthalpy in kJ/kg-^{0}C
λ latent heat in kJ/kg
U_D heat transfer coefficient of the evaporator in kJ/ sq.m-^{0}C-s
T   temperature in ^{0}C
Q   heat transfer in each effect in kJ

A	heat transfer area in the evaporator in sq.m
CR	Concentration Ratio
S_g	Entropy in kJ/kg
X	Exergy in kJ/kg
μ	dynamic viscosity in N/m
l	length in m
C_p	Specific heat in kJ/kg-°C
k	Thermal conductivity in kJ/kg-°C-s
η_c	Efficiency of the solar collector
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number

Subscript

f	feed flow rate
s	steam
B	brine flow rate
1,2,..n	effect/chamber/evaporator number.

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