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# Integration of Multiple Effect Evaporators with Solar Thermal Systems

Prashant Sharan, Santanu Bandyopadhyay*

Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India.
santanub@iitb.ac.in

Multiple effect evaporators (MEE) are energy intensive equipments and generally thermal energy is supplied to it through combustion of fossil fuels which are polluting as well as non-renewable. This paper deals with integration of solar thermal energy with MEE. A methodology for calculating optimal operating temperature for the solar system is developed in this paper to minimize the total initial cost of the overall system for a given solar radiation. A parametric study is carried to find the effects of various important parameters on the overall system performance. The proposed methodology is illustrated with the help of a case study with evacuated tube solar collectors.

## 1. Introduction

Multiple effect evaporators (MEE) are used for concentrating solute in the solution phase and find their application in various industries such as sugar, pulp and paper, fruit juice, pharmaceutical, desalting, etc. External thermal energy is provided to the first stage of a MEE for caring out the evaporation. Generally the heat produced in conventional boiler acts as a heat source for MEE. Fossil fuels used in a conventional boiler are environmentally harmful. Solar thermal energy, which is renewable as well as non-polluting can be used as energy source for MEE. Kalogirou (1997) and El–Nashar (2000) reported economic analysis for solar desalination system. Kalogirou (1997) observed that solar desalination is beneficial for large installation while El-Nashar (2000) concluded that with rising crude oil prices solar desalination may become economically beneficial. Eames et al. (2007) did experimental analysis for calculating solar collector area to produce a minimum of 30 L of fresh water daily. Li et al. (2013) carried out a review on solar assisted sea water desalination.

Integration of solar thermal energy for low temperature process applications were also reported in literature. Souza et al. (2007) studied the effect of collector inclination angle on falling film evaporator. Chen et al. (2012) studied the efficiency of flat plate collector at different flow and observed that efficiency increases with increase in flow rate through solar collector. Walmsley et al. (2014) integrated solar thermal heat for low pinch temperature process application. Desai et al. (2014) developed an analytical method to calculate optimal design radiation for concentrating solar thermal power plant. Objective of this paper is to develop a methodology to determine the optimal operating temperature of solar integrated MEE systems for the minimum capital cost of the entire system.

## 2. System description and system Grand Composite Curve

Figure 1 shows a solar collector integrated with MEE. Solar system typically consists of a solar collector, pump, and recirculating heat transfer fluid. Heat transfer fluid picks up the heat from the collector array and passes to the MEE system. The feed liquor is pre-heated in heat exchanger before it enters the first stage of MEE. Liquor gets partially vaporized in the first stage. The vapour generated in the first stage acts as a heat source for the second stage. The heated fluid from the solar collector loses its heat and is sent back to the solar collector at temperature $T_{in}$. The hot oil temperature entering the collector is controlled by MEE first effect temperature.

Both MEE and the solar system can be represented on a Grand Composite Curve (GCC), proposed by

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Linnhoff et al. (1982), for better Heat Integration. MEE can be represented as a set of process streams for generation of its GCC.

Evaporation: Every stage requires energy for vaporization of water. Since the energy is required, it is represented as a cold stream.

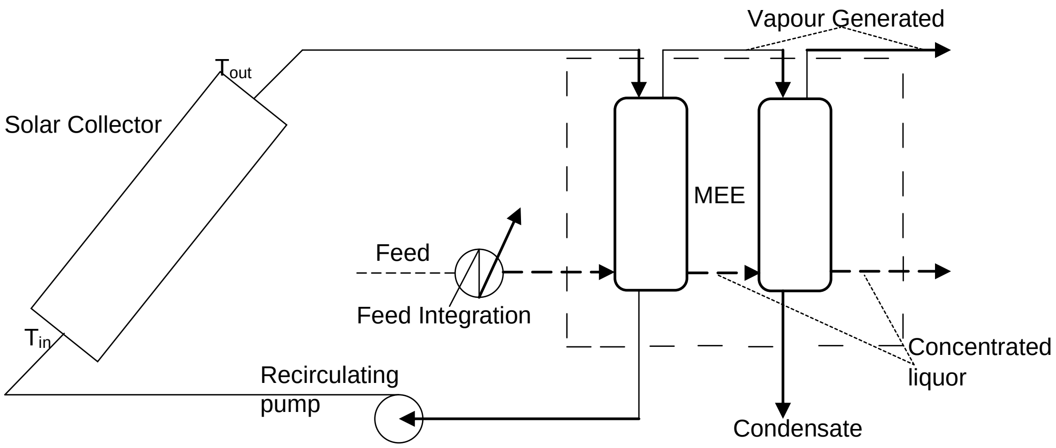


*Figure 1: Schematic of a solar integrated MEE system*

Vapour Desuperheating: The vapour is generated in every effect because of vaporization of water. This vapour acts as a source of heat for the stages which are operating at lower temperature and pressure. Vapour coming out from any stage gets superheated because of rise in boiling point.

Condensation: Once the vapour gets desuperheated, it condenses by losing its latent heat of vaporization. Since the stream is getting cooled it is a hot stream.

Condensate cooling: Condensate coming out from every stage has to be cooled down to a particular temperature before it is discharged to environment. Since it is also getting cooled, so it is also a hot stream.

Liquor integration: Feed going into the evaporator is at a different temperature in comparison to effect temperature. So they can be integrated with the other stream. Based on the initial temperature of the feed, it is either hot or a cold stream. Similarly the product coming out from MEE is also considered as a stream.

After identifying various process streams, GCC of the MEE may be generated (Bandyopadhyay and Sahu, 2010) to target the energy requirement. Subsequently, the solar thermal system can be designed. Figure 2 shows a typical GCC for MEE (solid line in Figure 2) and solar thermal system (dashed line in Figure 2). From the GCC shown in Figure 2, 1-2 represents liquor pre-heating ($Q_{HE}$) and 2-3 represents energy required for evaporation in first effect ($Q_{effect\ 1}$).

## 3. System model

Efficiency of any solar collector (η) is a function of optical efficiency ($\eta_o$), heat loss coefficient ($U_l$), outlet ($T_{out}$) and inlet ($T_{in}$) temperatures of the working fluid, solar isolation on solar collector ($I_t$), as well as ambient temperature (Ta).

$$\eta = \eta_o - \frac{U_l}{I_t}\left(\frac{T_{out} + T_{in}}{2} - Ta\right) \quad (1)$$

Collector area required to provide sufficient energy to the first effect of the MEE ($Q_{MEE}$) is given as:

$$A_{solar} = \frac{Q_{MEE}}{q} = \frac{Q_{MEE}}{\eta_o I_t - U_l\left(\frac{T_{out} + T_{in}}{2} - Ta\right)} \quad (2)$$

Eq(3) may be expanded based on the integration between MEE and solar thermal collector (Figure 2):

$$A_{solar} = \frac{2Q_{MEE}}{2\eta_o I_t - U_l(T_{out}(1-f) + (Y_1 + \Delta T_{MEE/Solar})(1+f) - 2Ta)} \quad (3)$$

Where $Y_1$ is effect 1 temperature, $\Delta T_{MEE/Solar}$ is minimum temperature driving force between MEE and solar system and *f* is ratio of heat required by heat exchanger to heat required by effect 1.
Evaporator area required for evaporation is given as:

$$A_{MEE} = \frac{Q_{Effect\,1}}{U_{Effect\,1} LMTD} = \frac{Q_{Effect\,1} \ln\left(\frac{T_{out} - Y_1}{\Delta T_{MEE/Solar}}\right)}{U_{Effect\,1}(T_{out} - Y_1 - \Delta T_{MEE/Solar})} \tag{4}$$

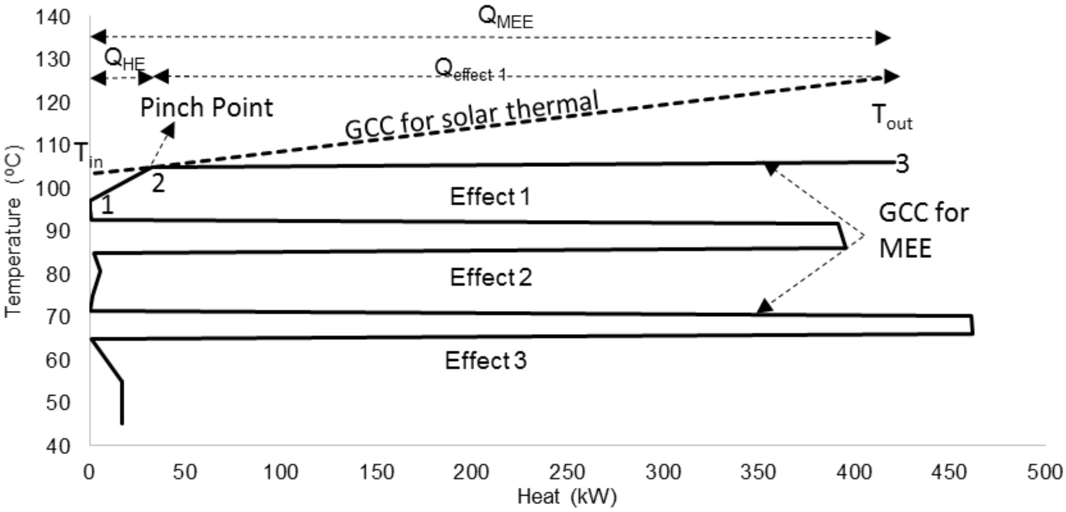


*Figure 2: GCC for MEE and solar thermal system*

Where $U_{effect\,1}$ is the heat transfer coefficient for effect 1, LMTD is logarithmic mean temperature difference between heat transfer fluid and effect1. It must be noted that only heat transfer area for first effect is considered, as area requirement for other effects are independent of the external heat source. Similarly, heat exchanger area required for pre-heating the feed is given as:

$$A_{HE} = \frac{Q_{HE} \ln\left(\frac{(Y_1 + \Delta T_{MEE/Solar})(1+f) - f * T_{out} - T_1}{\Delta T_{MEE/Solar}}\right)}{U_{HE}(((Y_1 + \Delta T_{MEE/Solar})(1+f) - f * T_{out} - T_1) - \Delta T_{MEE/Solar})} \tag{5}$$

Where $T_1$ is the temperature at which feed is supplied and $U_{HE}$ is heat transfer coefficient for heat exchanger. Heat exchanger area for internal integration of MEE is not included. Let the cost per unit area for solar collector, MEE and heat exchanger be $C_{solar}$, $C_{MEE}$ and $C_{HE}$. Neglecting the pumping cost the total cost is given by Eq(6).

$$C = C_{solar} A_{solar} + C_{MEE} A_{MEE} + C_{HE} A_{HE} \tag{6}$$

Let, the ratio of product of $\eta_o$ and $I_t$ to collector loss coefficient be characteristic temperature $T_{solar}$, ratio of solar collector cost to evaporator cost per unit area be $C_1^*$, ratio of heat exchanger cost to evaporator cost per unit area be $C_2^*$, ratio heat loss coefficient for collector to heat transfer coefficient for effect 1 be $U_1^*$ and ratio heat loss coefficient for collector to heat transfer coefficient for heat exchanger be $U_2^*$.In order to find the optimal operating temperature $T_{out/optimal}$, the total cost of the system must be minimized for a given solar isolation, $I_d$. So Eq(6) is differentiated with respect to $T_{out}$ and equated to zero for minimization of the overall cost.

$$T_{out/optimal} = function(C_1^*, C_2^*, U_1^*, U_2^*, f, T_{Solar}, Ta, Y_1, \Delta T_{MEE/Solar}) \tag{7}$$

$T_{out}$ calculated will give minimum cost of the system for given solar isolation $I_d$. It may be noted that the actual algebraic expression of Eq(7) is not provided for brevity. Once the outlet temperature is calculated the mass flow rate of oil can be calculated as:

$$MCp\left(T_{out/optimal} - T_{in}\right) = Q_{MEE} \tag{8}$$

Small numerical difference between the optimal temperature, calculated using Eq(7), and the inlet temperature leads to very high mass flow rate of the working fluid through solar collector. Solar system may not be designed to handle such large flow rate. In such a case, the outlet temperature should be calculated by using the maximum permissible mass flow rate.

## 4. Illustrative Example

A case study from Hukkerikar (2006) for manufacturing of corn glucose is considered. Input data for the evaporator design and solar thermal system are listed in Table 1. Cost parameters for MEE are taken from Westphalen and Maciel (2000) and are updated using Chemical Engineering Plant Cost Index (CEPCI). Solar system, based on the evacuated tube collector, is selected for this example and relevant data are taken from Thawonngamyingsakul and Kiatsiriroat (2012).

*Table 1: Input parameter*

| | | | |
|---|---|---|---|
| Feed rate (kg/s) | 1.17 | Effect 1 Temperature ($^oC$) | 100 |
| Feed concentration (%) | 40.75 | Effect 2 Temperature ($^oC$) | 80 |
| Feed temperature ($^oC$) | 92 | Effect 3 Temperature ($^oC$) | 60 |
| Final desired concentration (%) | 82 | $C_{MEE}$ ($/m$^2$) | 1,440.5 |
| Product temperature ($^oC$) | 75.77 | $C_{HE}$ ($/m$^2$) | 284.5 |
| Number of effects | 3 | $C_{Solar}$ ($/m$^2$) | 183.33 |
| Liquid flow pattern | Forward feed | $\eta_o$ | 0.81 |
| $\Delta T_{min\ MEE}$ ($^oC$) | 10 | $U_l$ (W/m$^2$k) | 2.531 |
| $\Delta T_{MEE/Solar}$ ($^oC$) | 20 | $I_d$ (W/m$^2$) | 600 |

For input parameters listed in Table 1, the mass flow rate of the liquor coming out from different stages are calculated and process stream data is generated. There are five streams for the first and the last effects and four streams for the second effect (as inter-stage liquor integration is not considered). Based on these stream data, the minimum energy requirement may be targeted (Bandyopadhyay and Sahu, 2010). GCC of the MEE is shown in Figure 2 and the minimum hot utility requirement targeted to be 421.2 kW.
The temperature of hot oil entering the solar collector and the optimaloutlet temperature are calculated to be 118.5 $^oC$ and 137.5 $^oC$. First effect area requirement is 76.8 m$^2$ and heat exchanger area requirement for pre-heating is 14m$^2$. Second and third effect areas are 20.45 m$^2$ and 37.48 m$^2$. Heat exchanger area required for internal integration is 14 m$^2$. Net collector area required is 1,785.2 m$^2$ and the total capital cost of the system is 529,345 $.Though evacuated tube collector is selected, but the methodology is applicable for any collector.

## 5. Parametric Study

It can be observed from Eq(7) that outlet temperature is function of many parameters, some of these parameters are studied and their effects on stage1 area, solar area, cost and outlet temperature are analysed. The effect of area, cost and temperature are represented in the form of their ratio to the respective design condition, calculated in example before.

### 5.1. Design solar radiation

Operating temperature is directly proportional to solar radiation. Higher the radiation, higher is the net heat gain by heat transfer fluid in solar collector. As the net heat gain by collector increases its net area requirement decreases. Similarly the area requirement for MEE also decreases with increase in design radiation as the LMTD increases. Since both areas are decreasing with increase in design radiation, the net cost also decreases. Variations of different parameters with respect to design solar radiation are plotted in Figure 3a. The system cannot be designed for radiation less than 531 W/m$^2$ as the mass flow rate exceeds the maximum permissible mass flow rate of 20 kg/s. It must be noted that the total design cost decreases with increase in design radiation but at the same time, the auxiliary heating requirement will increase for higher design radiation. So there is a tradeoff which has to be optimized.

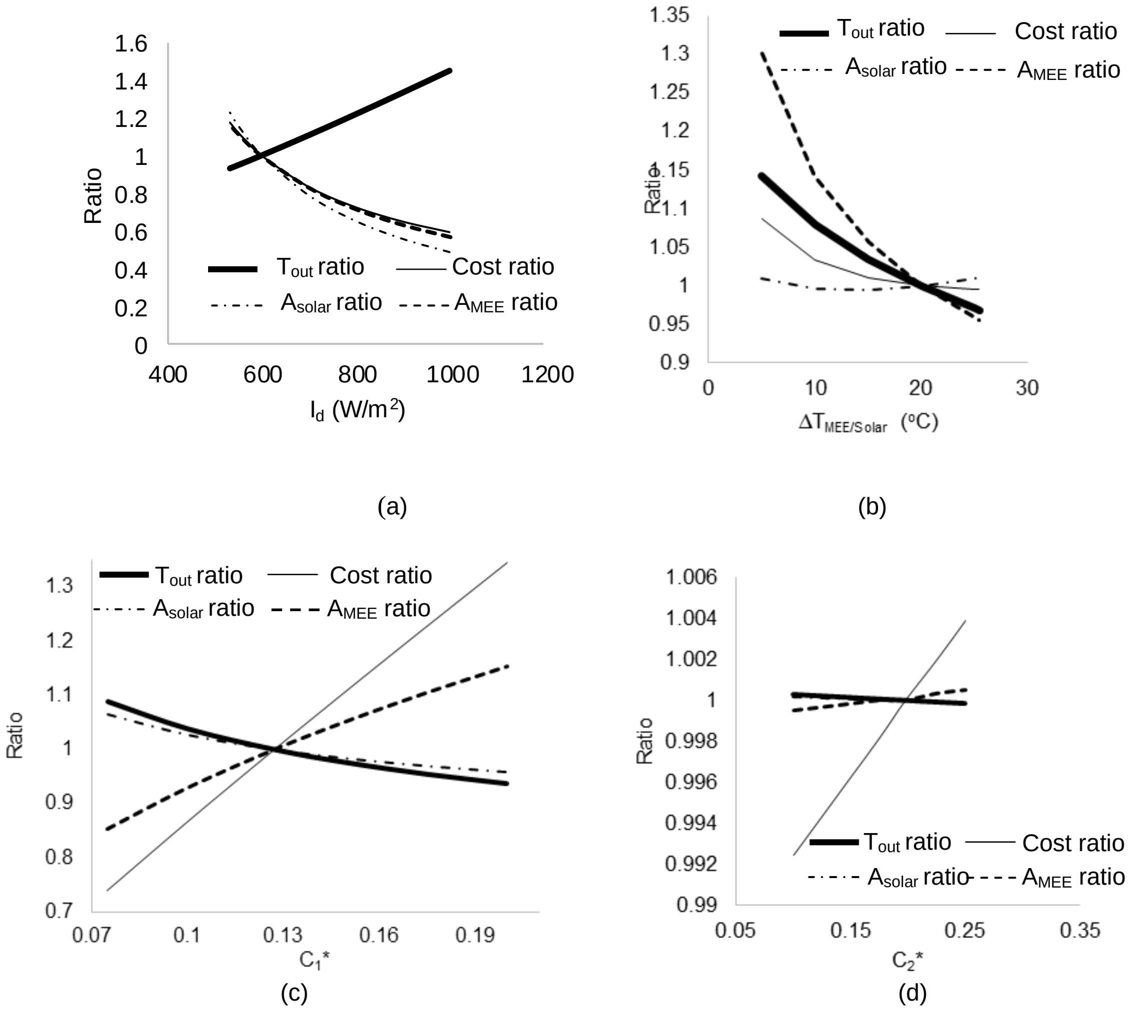


*Figure 3: Variations of optimal outlet temperature, capital cost, solar collector area, and heat transfer area of first effect as function of (a) design solar radiation, (b) minimum temperature driving force, (c) solar collector cost to cost of MEE, and (d) heat exchanger cost to MEE cost.*

**5.2. Minimum driving force between solar thermal and MEE ($\Delta T_{MEE/Solar}$)**

For lower value of $\Delta T_{MEE/Solar}$ the temperature driving force at outlet of MEE side is low, so in order to compensate this, the outlet temperature increases. However, the LMTD value remains low and the evaporator area requirement increases. It may be noted that the mean temperature of the heat transfer fluid almost remains constant, so solar area does not varies much. Net effect is rise in cost of the system. Exactly opposite happens for higher the value of $\Delta T_{MEE/Solar}$. So with increase in driving force, the capital cost of the overall system decreases. Variations of different parameters with respect to the driving force are plotted in Figure 3b. The maximum driving force, calculated corresponding to the maximum mass flow rate, is 25.45 °C.

**5.3. Variation in $C_1$***

$C_1$* is the ratio of cost of solar collector per unit area to the evaporator cost per unit area. For lower value of $C_1$*, capital cost of MEE dominates the overall cost of the system. Therefore, the outlet temperature of heat transfer fluid increases to have higher value of LMTD and lower evaporator area. However, increase in outlet temperature reduces the collector efficiency and consequently solar collector area increases. As the unit cost of solar collector is low, the net effect is decrease in capital cost of the overall system. Variations of different parameters with respect to this cost parameter are plotted in Figure 3c.

### 5.4. Variation in $C_2$*

$C_2$* is the ratio of cost of heat exchanger per unit area to the evaporator cost per unit area. Figure 3d shows the variation of cost ratio, outlet temperature ratio, $A_{mee}$ ration and $A_{solar}$. It can be observed that there is hardly any change in parameter values, as the value of *f* is very low.

### 5.5. Number of effects

With change in number of effects, the process stream data for MEE are changed and as a result the utility requirement for MEE changes. As the number of effect is changed, the area required for evaporation also changes. For the example considered in this paper, if the number of effect is increased from 3 to 4, total utility requirement decreases by 25.9 %.Therefore, this leads to reduction in the solar collector area by 23 %.It should be noted that the net MEE area requirement goes up by 9.2 %. Total capital cost of the entire system is reduced by 10.3 % as the number of effect is increased from 3 to 4. Variations of other parameters are not shown for brevity.

## 6. Conclusion

Present study deals with integration of solar thermal system with MEE without storage. GCCs for MEE and solar thermal are generated and matched to improve understanding for integration between these two systems. An expression for calculating the optimal operating temperature of the solar thermal system is developed in this paper to minimize the total capital cost of the system. A case study for integrating MEE with evacuated tube collector system is discussed. However the expression for calculating the operating temperature of the solar thermal system is applicable for any type of solar collector. Effects of various cost coefficients, minimum driving force, and design solar radiation on various design parameters of the system are studied and reported in the paper. It is important to note that cost of heat exchanger, used for preheating the feed, plays insignificant role in determining the overall capital cost of the system.

In the particular example, considered in this paper, capital cost of the system reduces by 10.3 % as the number of effects increased from 3 to 4. Therefore, it is important to determine the optimum number of effects that minimizes the overall capital cost of the system. Design solar radiation plays a significant role in determining capital cost of the system as well as the auxiliary energy requirement (and hence operating cost of the system) due to daily and seasonal variation of solar radiation. Future research is directed towards determining the optimal design radiation as well as optimization of the overall system considering variation of solar radiation.

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