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A Comparative Study on Steam Economy of Forward-Feed and Backward-Feed Multiple Effect Evaporators

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Abstract

Evaporation is one of the separation processes with high energy consumption in industrial applications, and the selection of flow configuration in multiple-effect evaporators plays a decisive role in overall system performance. In this study, the energy performances of forward-feed and backward-feed configurations in a four-effect multiple-effect evaporator are comparatively investigated. Within the scope of the case study, the concentration of a solution with an initial NaCl mass fraction of 10% is considered under operating conditions of 220 kPa inlet steam pressure and 10 kPa outlet pressure. The overall heat transfer coefficients are assumed constant and set to 2300, 1600, 1300, and 900 W/m²K from the first to the fourth effect, respectively. Using mass and energy balance models developed in the MATLAB environment, the steam requirement and steam economy of the systems are calculated for various feed temperatures, feed flow rates, and product solution solid concentrations. The results indicate that an increase in product solid concentration leads to an increase in total steam consumption in both feed configurations due to boiling point elevation. However, in the backward-feed evaporator, nearly %15 lower steam consumption and higher steam economy are achieved at the same product solid concentration, as the highly concentrated solution is evaporated in the effect operating at the highest temperature. An increase in feed flow rate results in higher steam demand in both systems; nevertheless, the backward-feed configuration exhibits a more stable steam economy over a wide range of flow rates. Increasing the feed temperature significantly reduces steam consumption from 6448kg/h to 4385 kg/h and improves steam economy from 2.33 to 3.42 in the forward-feed evaporator, whereas this effect is found to be limited in the backward-feed system. The findings demonstrate that forward-feed evaporators are more suitable from an energy efficiency perspective at high feed temperatures, while backward-feed evaporators are more advantageous for processes requiring high concentration increases and operating under variable flow rates. This study quantitatively highlights the critical importance of selecting the appropriate flow configuration based on process conditions in the design of multiple-effect evaporators.

1. Introduction

Energy plays a crucial role in sustaining technological development and ensuring sustainability. As a result of technological advancements, global energy demand has been increasing steadily. This growing demand has made it imperative to use existing energy resources more efficiently and to develop energy-saving technologies. Reducing energy consumption in the industrial sector is of great importance not only for lowering economic costs but also for mitigating environmental impacts. For this reason, the efficiency of evaporation processes, which are among the most energy-intensive operations, must be carefully evaluated in industrial applications[1].

Evaporation is a separation process commonly employed in binary systems to concentrate on a non-volatile component or to recover a volatile component. Water is most frequently used as the solvent; however, in the pharmaceutical, chemical, and food industries, alternative solvents such as benzene, carbon disulfide, or carbon tetrachloride may also be preferred[2–4]. During the process, the solute does not evaporate, whereas the solvent vaporizes and is removed from the system[5]. Thus, a mass transfer and separation operation is carried out for

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production or purification purposes. The resulting concentrated solution is generally treated as a valuable product, while the vapor phase is either discharged or condensed and reused[6].

In industrial applications, evaporation systems are generally classified into two main categories: single-effect and multiple-effect systems[7]. In single-effect systems, the process occurs in a single evaporator, whereas in multiple-effect systems, several evaporators are arranged in series to enhance energy efficiency[8]. Multiple-effect evaporation is based on the principle that the vapor generated in one evaporator is used as the heating steam in the subsequent evaporator[9]. This method can be implemented through appropriate interconnections between evaporators without requiring additional structural modifications. Various flow configurations are available, including forward feed, backward feed, parallel, and mixed flow arrangements[10]. The selection of an appropriate configuration depends on the physical properties of the solution, operating conditions, and energy requirements. Due to their ability to achieve high steam economy, multiple-effect systems are particularly preferred in large-capacity industrial facilities[11,12].

Cong Liu and others, in their study, compared two different optimization methods using forward-feed and parallel-feed multiple-effect evaporators. In this comparison, a four-effect evaporator was selected, and preheating was applied before each effect[5]. Mayank Kaysariya and others, in their study, investigated the integration of geothermal energy into a desalination application and addressed a desalination system based on a forward-feed multiple-effect evaporator[13]. Smitarani Pati and others, in their study, addressed the optimization of a multiple-effect evaporator in different ways. To achieve this, an optimization tool was used and an optimization problem was formulated. In addition, tanks were added to the system for heat recovery, and both solar energy systems and a wind energy system were integrated into the multiple-effect evaporatör, thereby improving steam economy. In the literature review conducted, the optimization of multiple-effect evaporators has generally been examined, and steam economy has been improved using different approaches and various tools[14].

In this study, unlike the existing literature, the focus is not placed on system optimization; instead, the aim is to enable the selection of the most appropriate evaporator system for practical applications. For this reason, forward-feed and backward-feed configurations in multiple-effect evaporators are comparatively investigated. The effects of different feed arrangements on energy efficiency are analyzed, and the advantages and disadvantages of each configuration are evaluated. In addition, the performances of both feed configurations are quantitatively compared through a representative case study. The findings obtained are expected to facilitate the selection of the most efficient evaporator system for different applications and to contribute to the more efficient and sustainable design of evaporator systems.

2. Materials and Methods

2.1. Forward-Feed Multi Effect Evaporator

In systems operating with the forward-feed configuration, the solution fed to the first evaporator is sufficiently concentrated and then transferred to the second evaporator[15]. This process continues depending on the number of evaporators in the system. The solvent vapor generated in the first evaporator is used as the heating steam for the second evaporator. Therefore, the operating temperatures of the evaporators decrease progressively from the first effect onward. This type of evaporation is particularly suitable for solutions with increasing concentration. In the final evaporator, which operates at the lowest temperature, the solution reaches its highest concentration, whereas in the first evaporator, which operates at the highest temperature, the concentration is the lowest. A schematic diagram of a system operating under forward-feed configuration is shown in Figure 1.

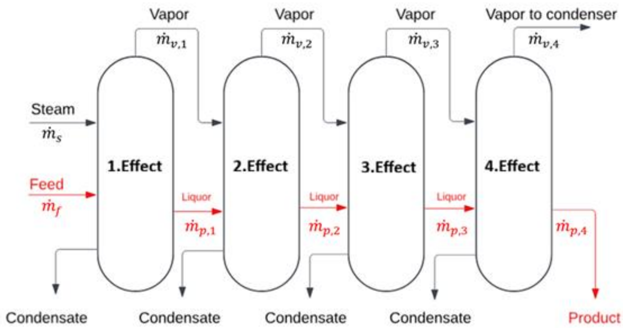

Figure 1. Schematic representation of a four-effect forward-feed evaporator.

If the effect number is denoted by i, the mass balance can be expressed as shown in Eq. (1). Here, $\dot{m}_{vi}$ represents the mass of liquid evaporated within the ith effect. This vapor is used to heat the subsequent effect. In the same equation, $\dot{m}_{pi}$ denotes the mass of the solution leaving the effect, while $\dot{m}_{p(i-1)}$ represents the mass flow rate entering the effect, which can also be referred to as the feed.

Eq. (2) expresses the mass fraction of the solution. In this equation, x_{fi} and $\dot{m}_{pi}$ represent the mass fraction within the effect and the mass of the solution leaving the effect, respectively. The term $\dot{m}_f$ denotes the total mass flow rate entering the first effect, and x_f represents the mass fraction of the solution fed to the first effect[5,6,9,10].

$$\dot{m}_{pi} = \dot{m}_{p(i-1)} - \dot{m}_{vi} \quad (1)$$
$$x_{fi} = \dot{m}_f x_f / \dot{m}_{pi} \quad (2)$$

Eq. (3) represents the total temperature difference in the system, where T_s denotes the temperature of the steam used to heat the first effect, and T_n represents the temperature of the solution in the last effect. Eq. (4) presents the total boiling point elevation, while Eq. (5) defines the net temperature difference[6,9,10,16].

$$\Delta T_{total} = T_s - T_n \quad (3)$$
$$\sum BP = BP_1 + BP_2 + BP_3 + BP_n \quad (4)$$
$$\Delta T_{net} = \Delta T_{total} - \sum BP \quad (5)$$

The expression defining the temperature differences is given in Eq. (6). Here, T_{fi} denotes the temperature of the solution in the *i*th effect, and ΔT_{fi} represents the temperature difference between the solution in the effect and the steam used to heat that effect. $T_{v(i-1)}$ is the temperature of the steam used for heating the effect; for the first effect, the heating steam temperature is denoted as T_{v0}, which represents the externally supplied steam. Eq. (7) presents the saturation temperature of the steam[6,9,10,16].

$$T_{fi} = T_{v(i-1)} - \Delta T_{fi} \quad (6)$$
$$T_{vi} = T_{fi} - BP_i \quad (7)$$

The energy balance equations are given in Eq. (8). Here, q_i represents the energy supplied to the "i"th effect, h_{fi} denotes the enthalpy of the heating steam in its liquid phase, and $h_{v(i-1)}$ represents the enthalpy of the heating steam. In addition, $\dot{m}_{v(i-1)}$ denotes the mass flow rate of the steam used to heat the system. Considering Eq. (9), the heat transfer area required to heat the system is calculated. Here, A_i denotes the heat transfer area of the "i"th effect, U_i represents the overall heat transfer coefficient of the effect, and ΔT_{fi} is the temperature difference between the liquid in the effect and the heating steam[5,6,9,10].

$$q_i = (h_{v(i-1)} - h_{fi})\dot{m}_{v(i-1)} \quad (8)$$
$$A_i = (U_i - \Delta T_{fi})/q_i \quad (9)$$

The expression describing the enthalpy balance is given in Eq. (10). Here, $\dot{m}_{v(i-1)}$ and $\lambda_{v(i-1)}$ denote the mass flow rate and the latent heat of vaporization of the heating fluid, respectively; $\dot{m}_{p(i-1)}$ and $h_{p(i-1)}$ represent the mass flow rate and enthalpy of the solution entering the effect; $\dot{m}_{pi}$ and $\dot{m}_{vi}$ correspond to the mass flow rates of the solution and vapor leaving the effect; and finally, h_{pi} and h_{vi} denote the enthalpy of the solution leaving the effect and the enthalpy of the vapor leaving the effect, respectively[6,9,10].

$$\dot{m}_{v(i-1)}\lambda_{v(i-1)} + \dot{m}_{p(i-1)}h_{p(i-1)} = \dot{m}_{pi}h_{pi} + \dot{m}_{vi}h_{vi} \quad (10)$$

Eq. (11) presents the steam economy, which is used to evaluate the efficiency of the system. Here, $\dot{m}_{v,total}$ represents the total mass of vapor produced, and $\dot{m}_s$ denotes the mass of steam supplied to the first effect[6,9,10].

$$\dot{m}_{v,total}/\dot{m}_s \quad (11)$$

2.2. Backward-Feed Multi-Effect Evaporator

In systems operating under a backward-feed configuration, the dilute solution flows in the direction opposite to that of the solvent vapor. In other words, the dilute solution is fed to the last evaporator and, after being sufficiently concentrated there, is transferred to the preceding evaporator[15]. This process continues to the first evaporator, from which the concentrated solution is withdrawn. This method is particularly suitable for dilute solutions that are prone to thermal degradation at low boiling temperatures. For example, achieving critical concentration helps prevent the decomposition of compounds such as acetaldehyde or certain esters at elevated temperatures.

In this configuration, the evaporator with the highest concentration is also the one operating at the highest temperature. A schematic diagram illustrating the principle of a backward-feed system is shown in Figure 2.

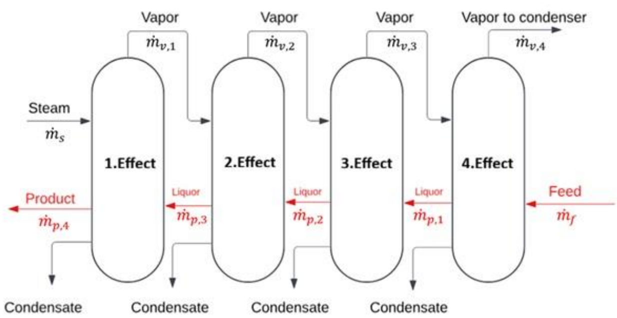

Figure 2. Four-effect backward-feed evaporator.

If the effect number is denoted by i and the total number of effects by n, the mass balance can be expressed as shown in Eq. (12). Here, $\dot{m}_{vi}$ represents the mass of liquid evaporated within the ith effect. This vapor is used to heat the subsequent effect. In the same equation, $\dot{m}_{pn}$ denotes the mass of the solution leaving the effect. The term $\dot{m}_{p(n-i)}$ represents the mass flow rate entering the effect. Eq. (13) expresses the mass fraction of the solution. In this equation, x_{fi} and $\dot{m}_{p(n-i+1)}$ represent the mass fraction within the effect and the mass of the solution leaving the effect, respectively. The term $\dot{m}_f$ denotes the total mass flow rate entering the nth effect, and x_f represents the mass fraction of the solution fed to the nth effect[5,6,9,10].

$$\dot{m}_{pn} = \dot{m}_{p(n-i)} - \dot{m}_{vi} \quad (12)$$
$$x_{fi} = \dot{m}_f x_f / \dot{m}_{p(n-i+1)} \quad (13)$$

Eq. (14) represents the total temperature difference in the system, where T_s denotes the steam used to heat the first effect, and T_n represents the temperature of the solution in the last effect. Eq. (15) presents the total boiling point elevation, while Eq. (16) defines the net temperature difference[6,9,10,16].

$$\Delta T_{total} = T_s - T_n \quad (14)$$
$$\sum BP = BP_1 + BP_2 + BP_3 + BP_n \quad (15)$$
$$\Delta T_{net} = \Delta T_{total} - \sum BP \quad (16)$$

The expression describing the temperature differences is given in Eq. (17). Here, T_{fi} denotes the temperature of the solution in the "i"th effect, and ΔT_{fi} represents the temperature difference between the solution in the effect and the steam used to heat that effect. $T_{v(i-1)}$ is the temperature of the steam used to heat the effect. Eq. (18) presents the saturation temperature of the steam[6,9,10,16].

$$T_{fi} = T_{v(i-1)} - \Delta T_{fi} \quad (17)$$
$$T_{vi} = T_{fi} - BP_i \quad (18)$$

The energy balance equations are given in Eq. (19). Here, q_i represents the energy supplied to the "i"th effect, h_{fi} denotes the enthalpy of the heating steam in its liquid phase, and $h_{v(i-1)}$ represents the enthalpy of the heating steam. In addition, $\dot{m}_{v(i-1)}$ denotes the mass flow rate of the steam used to heat the system. Considering Eq. (20), the heat transfer area required to heat the system is calculated. Here, A_i denotes the heat transfer area of the "i"th effect, U_i represents the overall heat transfer coefficient of the effect, and ΔT_{fi} is the temperature difference between the liquid in the effect and the heating steam[5,6,9,10].

$$q_i = (h_{v(i-1)} - h_{fi})\dot{m}_{v(i-1)} \quad (19)$$
$$A_i = (U_i - \Delta T_{fi})/q_i \quad (20)$$

The expression describing the enthalpy balance is given in Eq. (21). Here, $\dot{m}_{v(i-1)}$ and $\lambda_{v(i-1)}$ denote the mass flow rate and the latent heat of vaporization of the heating fluid, respectively; $\dot{m}_{p(n-i)}$ and $h_{p(n-i)}$ represent the mass flow rate and enthalpy of the solution entering the effect; $\dot{m}_{p(n-i+1)}$ and $\dot{m}_{vi}$ correspond to the mass flow rates of the solution and vapor leaving the effect; and finally, $h_{p(n-i+1)}$ and h_{vi} denote the enthalpy of the solution leaving the effect and the enthalpy of the vapor leaving the effect, respectively[6,9,10].

$$\dot{m}_{v(i-1)}\lambda_{v(i-1)} + \dot{m}_{p(n-i)}h_{p(n-i)} = \dot{m}_{p(n-i+1)}h_{p(n-i+1)} + \dot{m}_{vi}h_{vi} \quad (21)$$

Eq. (22) presents the steam economy, which is used to evaluate the efficiency of the system. Here, $\dot{m}_{v,total}$ represents the total mass of vapor produced, and $\dot{m}_s$ denotes the mass of steam supplied to the first effect[6,9,10].

$$\dot{m}_{v,total}/\dot{m}_s \quad (22)$$

2.3. Case Study

In this study, forward-feed and backward-feed multiple-effect evaporators with four effects were analyzed under different feed temperatures, outlet solution solid concentrations, and feed flow rates. The analyses were performed using models developed in MATLAB, and the results were obtained through numerical solutions. MATLAB commands were developed using For and While loops. For these codes, the equations given in Section 2 were employed. The reason for using a MATLAB program is that the equations are interrelated, and some of the relations were solved with the aid of thermodynamic tables. In addition, the thermodynamic tables were embedded into MATLAB and utilized in calculations. For example, the corresponding temperature for a given known enthalpy value was determined in this manner. In the solutions of these equations, some parameters were assumed to be constant. The parameters kept constant are presented in Table 1. Here, the specific heat capacity of the solution was assumed to be equal to that of water, and this assumption was applied to each effect. The reason for this approach is that the difference between the solution concentrations is very small during the comparison; therefore, the effect of solution concentration on the specific heat capacity was neglected.

As a result of the analysis performed, the inlet temperature of the NaCl solution, the solid concentration of the solution obtained at the end of the process, and the NaCl feed flow rates were considered as variable parameters, and the steam requirement and steam economy of the evaporator were calculated. These parameters are critical indicators of the evaporator's performance and efficiency.

Table 1. Constant parameters used in the case study.

Constant parameters	
Heat transfer coefficient (W/m^2K) 1. Effect	2300
Heat transfer coefficient (W/m^2K) 2. Effect	1600
Heat transfer coefficient (W/m^2K) 3. Effect	1300
Heat transfer coefficient (W/m^2K) 4. Effect	900
NaCl feed concentration	0.10
Inlet steam pressure (kPa)	220
Outlet steam pressure (kPa)	10
Specifi heat for water C_p $(kJ/kg.K)$	4.184

3. Results and Discussion

In the case study considered, separate MATLAB codes were developed to evaluate the forward-feed and backward-feed configurations. While writing these codes, the equations presented in the Materials and Methods section were employed, and the steam requirement and steam economy of the system were examined for different product concentrations, feed flow rates, and feed temperatures. All other parameters were kept constant.

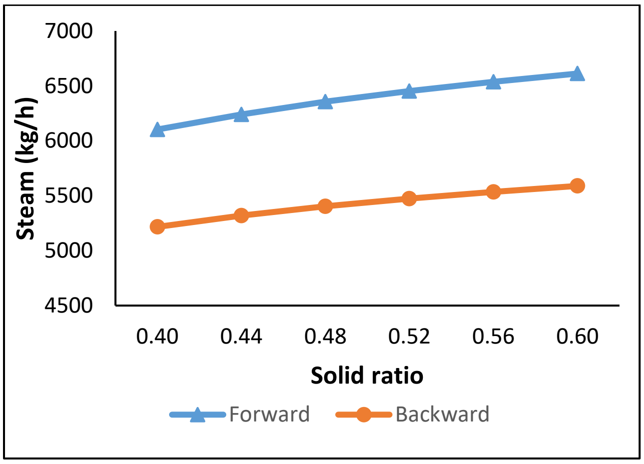

Figure 3. Effect of steam consumption on the solid concentration of the product solution.

Figure 3 shows that, as the solid concentration in the product solution increases, the steam requirement of the system increases for both feed configurations. An increase in solid concentration leads to an elevation of the boiling point of the solution (boiling point elevation, BPE), which reduces the effective temperature difference between the effects and thereby limits heat transfer. Díaz-Ovalle C.O. and Jafari S.M., in their study, comprehensively addressed the use of multiple-effect evaporators in the food industry and stated that an increase in the solid content of the feed directly increases the required energy consumption[17]. As a result, a greater amount of external steam is required to achieve the same evaporation capacity.

In the forward-feed system, the presence of the highly concentrated solution in the final effects operating at lower temperatures causes the BPE effect to become more pronounced. Consequently, the increase in steam demand with rising solid concentration is more significant. In contrast, in the backward-feed system, placing the most concentrated solution in the hottest effect partially compensates for the temperature losses associated with BPE and results in lower steam consumption for the same product solid concentration. This outcome indicates that the backward-feed arrangement can provide an energy advantage in processes requiring high levels of concentration.

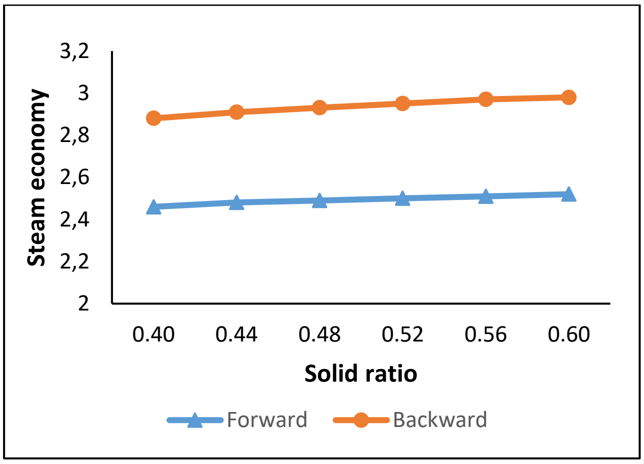

Figure 4. Variation of steam economy with respect to the solid percentage of the product.

Figure 4 shows that the steam economy increases with increasing product solid concentration in both systems. The main reason for this trend is that achieving higher solid concentrations requires the evaporation of a larger amount of water, which increases the total amount of vapor produced per unit of external steam supplied.

However, it is observed that the backward-feed evaporator provides a higher steam economy than the forward-feed system across the entire range of solid concentrations. This behavior arises from the evaporation of highly concentrated solutions at higher temperatures, which enhances inter-effect heat recovery. The findings indicate that under conditions where boiling point elevation is significant, the backward-feed configuration enables more efficient steam utilization.

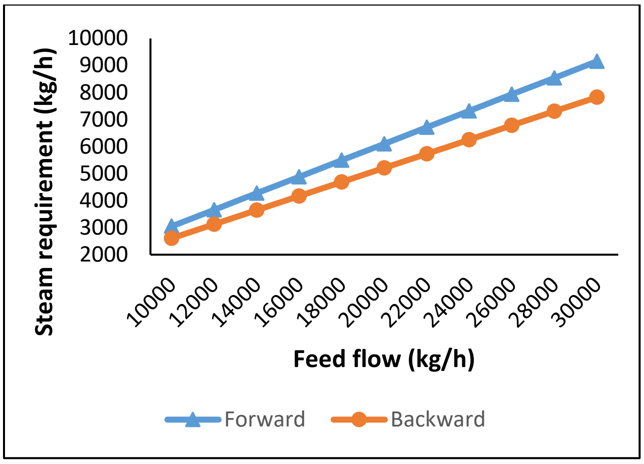

Figure 5. Effect of feed flow rate variation on the required steam consumption.

Figure 5 shows that the total steam requirement increases in both systems as the feed flow rate increases. An increase in feed flow rate raises the total amount of solvent that must be removed from the system, which is directly reflected in the evaporation load. S. Chantasiriwan, in a study conducted in 2020 on both forward-feed and backward-feed multiple-effect evaporators, demonstrated that an increase in the feed flow rate leads to an increase in steam requirement[18]. In addition, R. Simpson and others, in their 2008 study, observed that in multiple-effect evaporators with different numbers of effects, an increase in the feed flow rate results in an increase in both the steam pressure and the required amount of steam[19].

In the forward-feed system, heat transfer becomes more limited at high flow rates, particularly in the final effects, due to the low temperature differences. In contrast, in the backward-feed system, the progression of the dilute solution from lower-temperature effects toward progressively hotter effects allows a more balanced distribution of the heat load among the effects. As a result, the increase in steam demand is observed to be more controlled in the backward-feed system.

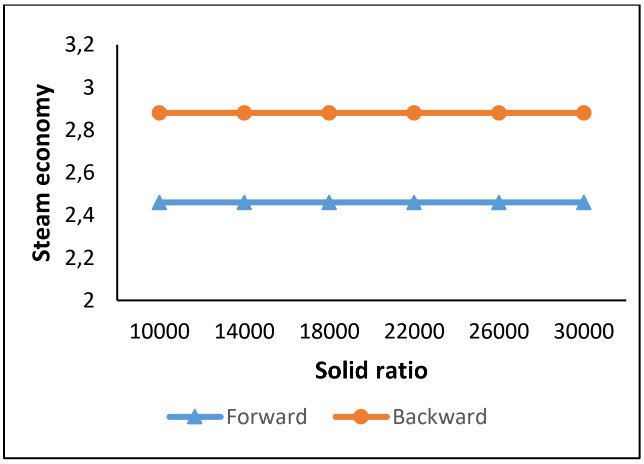

Figure 6. Effect of feed flow rate variation on steam economy.

Figure 6 indicates that, as the feed flow rate increases, the steam economy exhibits limited variation in both systems, while the backward-feed system demonstrates a more stable performance. In the forward-feed system, high flow rates can adversely affect steam utilization efficiency due to the reduction in temperature differences between the effects.

In the backward-feed configuration, the relatively stable steam economy under varying flow conditions indicates that this system offers greater robustness against changing operating conditions. This finding enhances the suitability of backward-feed evaporators for industrial applications where feed flow rate fluctuations are frequent.

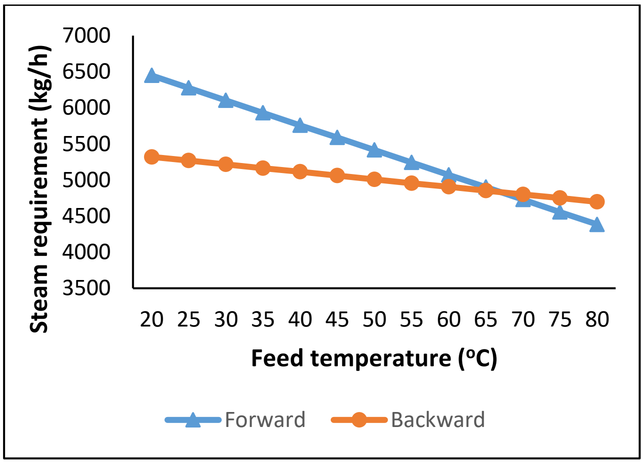

Figure 7. Effect of feed temperature on the steam requirement of the system.

Figure 7 shows that increasing the feed temperature significantly reduces the steam requirement in the forward-feed system. Supplying high-temperature feed directly to the first effect allows a portion of the heat load in the first effect to be met by the feed itself, thereby reducing the demand for external steam. Ramanathan S. and others, in their study, stated that preheating can provide steam savings of up to 24%[4]. In addition, Akın M.B., in his study, emphasizes that increasing the feed temperature in multiple-effect evaporators reduces the steam requirement and improves the steam economy[20]. Ali E. and others, in their study, stated that heating seawater before treatment reduces energy consumption[21].

In the backward-feed system, since the feed is introduced into the effect operating at the lowest temperature, the impact of increasing feed temperature on the overall steam requirement of the system remains limited. This result demonstrates that the influence of feed temperature on evaporator performance is strongly dependent on the flow configuration.

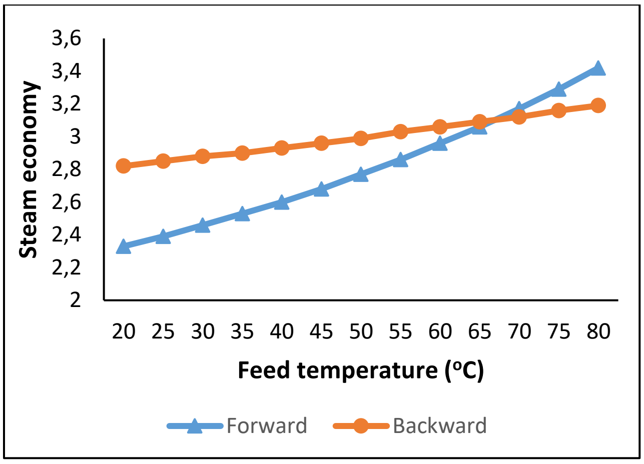

Figure 8. Effect of feed temperature on steam economy.

Figure 8 shows that, in the forward-feed system, the steam economy increases significantly as the feed temperature rises. This increase is attributed to more effective heat recovery throughout the evaporatör system, which results from the larger temperature difference in the first effect.

In contrast, the steam economy in the backward-feed system is less sensitive to increases in feed temperature. The main reason for this behavior is that the feed heat is introduced into the system at the effect operating at the lowest temperature, limiting the extent to which this energy can be distributed across the effects.

4. Conclusions

In this study, four-effect forward-feed and backward-feed evaporator systems were comparatively investigated under different feed temperatures, feed flow rates, and product solid concentrations. The steam requirement and steam economy performances of the systems were evaluated through mass and energy balance analyses conducted in the MATLAB environment.

The results obtained indicate that:

• Increasing the feeding temperature significantly reduces the steam requirement and improves the steam economy in forward-feed systems. In contrast, the effect of feed temperature remains more limited in backward-feed systems. This finding demonstrates that the temperature level of the effect at which the feed is introduced plays a decisive role in the overall energy performance of the system.

• An increase in feed flow rate leads to higher steam consumption in both systems; however, the backward-feed evaporator exhibits a more stable steam economy under varying flow conditions. This characteristic indicates that the backward-feed configuration offers greater operational flexibility under fluctuating operating conditions.

• As the solid concentration of the product solution increases, boiling point elevation becomes more pronounced, resulting in higher steam demand. Nevertheless, in the backward-feed system, locating the highly concentrated solution in the hottest effect mitigates the adverse effects of boiling point elevation and provides lower energy consumption compared to the forward-feed system.

The findings of this study show that forward-feed evaporators are more suitable for processes operating at high feed temperatures, whereas backward-feed evaporators are more advantageous for processes requiring high concentration increases and operating over wide ranges of feed flow rates. In addition, particularly for forward-feed evaporators, the implementation of feed preheating can reduce the required steam consumption and enhance steam economy. Overall, selecting the appropriate flow configuration based on process conditions is of critical importance for improving energy efficiency in the design of multiple-effect evaporators.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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