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Design and economic analysis of membrane-assisted crystallization processes

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ABSTRACT

Reverse-osmosis (RO) and porous hydrophobic membranes have attracted attention as an alternative to conventional evaporation for crystallization processes, the latter being recommended especially if low-grade waste heat is available to provide the enthalpy of vaporization. In this work, these two types of membrane-assisted processes are designed and costs are compared with those of conventional single or multiple-effect vacuum evaporation processes. When waste heat is not available, RO processes are shown to be the least expensive because the pumping costs, while significant, are more than offset by the fact that it is not necessary to provide the enthalpy of vaporization of the solvent. When waste heat is available, a conventional evaporation process is favorable because it can also be powered by the waste heat and does not require the capital cost for the membranes.

1. Introduction

Crystallization is a solid–liquid separation and purification process that is ubiquitous in the chemical and related industries. Although usually less energy intensive than distillation, crystallization processes can still consume a significant amount of energy if the solvent is removed by evaporation. Additional drawbacks of evaporative crystallization include difficulty in controlling particle size distribution and crystallizing material forming crust on the vessel wall which can reduce heat flux [1]. Recently, as membrane technology has improved and prices have decreased, membrane-based processes have been proposed as a compliment to or a replacement for conventional evaporation for crystallization processes [2–8].

Two major types of membranes have been proposed for this purpose. Reverse osmosis (RO) membranes have the smallest pore size of all membrane types and are widely used for example in the production of fresh drinking water from seawater. A substantial pressure gradient is generally required to overcome the osmotic pressure of the solution, but it is not necessary to supply the enthalpy of vaporization of the water since the water remains in the liquid phase on both sides of the membrane. RO membranes are limited by the maximum pressure gradient that they can be designed to withstand and therefore are not suitable by themselves for crystallization where the osmotic pressure of a saturated solution of solute exceeds this limitation.

More recently, porous hydrophobic membranes have been proposed for water removal in crystallization processes. While several different configurations are possible [9–21], including direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), air-gap membrane distillation (AGMD), and sweeping gas membrane distillation (SGMD), the general feature of these membranes is that the water evaporates as it passes through the membrane. Therefore these membranes are not limited by the osmotic pressure of the solution, but the enthalpy of vaporization must still be provided. Therefore when a RO membrane process is not feasible, porous hydrophobic membranes may provide some of the same benefits such as reduced equipment size and more stable operation compared to evaporation from a boiling solution [22–25].

It has also been suggested that since porous hydrophobic membranes permit evaporation at a lower temperature (at atmospheric pressure) than a conventional boiling evaporative process, low-grade waste heat could be used to provide the enthalpy of evaporation resulting in a substantial cost savings [14,17,26–28]. However, previous reports recommending the use of porous hydrophobic membranes when low-grade waste heat is available have not considered the fact that a conventional evaporation process could also make use of such waste heat if it was operated under vacuum. In order to make a valid comparison with a conventional evaporation process, a membrane-based process powered by waste heat should be compared to a conventional process powered by waste heat. Therefore in this work, conceptual designs and preliminary cost analysis are completed for two membrane-based

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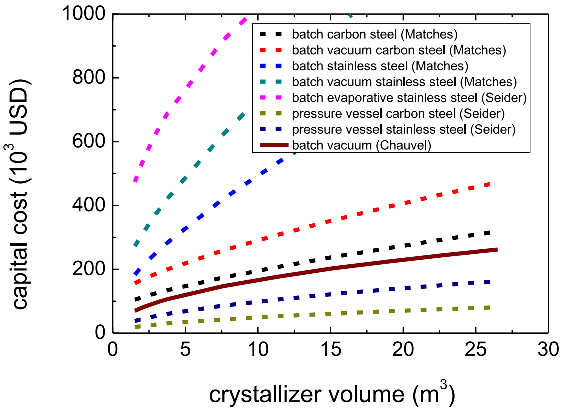

Fig. 1. Capital cost of batch crystallizers with respect to crystallizer volume from different references. The solid line is chosen in this work.

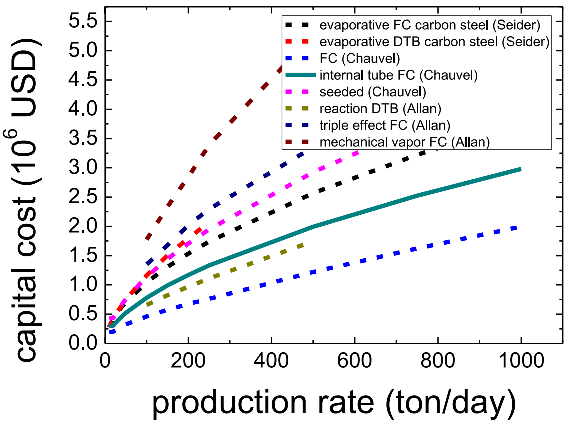

Fig. 2. Capital cost of continuous crystallizers with respect to production rate from different references. The solid line is chosen is this work.

processes and a conventional multi-effect evaporation process under eight different scenarios: for two different products (adipic acid and potassium chloride), with two different production rates (representing a small-scale batch process and a large continuous process) and under two conditions: with or without a source of free or low-cost waste heat. The costs of these 24 (3 × 2 × 2 × 2) processes are compared to determine under what conditions, if any, porous hydrophobic membranes may offer an economic advantage compared to other alternatives for crystallization processes.

The remainder of this article is organized as follows. In Section 2, models for the two case studies are presented. In Section 3, results are drawn for both case studies and finally in Section 4 conclusions are presented.

2. Model development

2.1. Cost equations for economic analysis

This section presents the methods and equations used to estimate the capital and operating costs of all equipment used in the processes, including crystallizers and vessels, high pressure pumps, vacuum systems, heat exchangers, and membranes.

For crystallizer and vessel cost, the capital cost of a batch crystallizer or a vessel is based on the volume of the tank, while the cost of a continuous crystallizer is based on the production rate of solid crystals [29]. Information about capital cost of crystallizers and vessels was collected from several references and is shown in Figs. 1 and 2 [29–32]. The equation of Chauvel et al. is used for batch and continuous crystallizers, and the equation of Seider et al. is used for other vessels. The correlations for capital cost of batch crystallizers, continuous crystallizers and vessels, CC_{bc}, CC_{cc}, and CC_{vessel}, are

$$CC_{bc} = \left(\frac{CE}{500}\right)\left(9.5527{V_b}^3 - 586.33{V_b}^2 + 16923V_b + 48359\right) \quad (1)$$

$$CC_{cc} = \left(\frac{CE}{500}\right)\Big(2.4442 \times 10^{-3}PR^{3.} - 5.3146PR^2 + 5621.3PR + 237830\Big) \quad (2)$$

$$CC_{vessel} = \left(\frac{CE}{500}\right)265{V_{vessel}}^{0.51}F_{BMvessel} \quad (3)$$

where V_b is volume of batch crystallizer in m^3 (1.5–26.5), PR is crystal production rate of continuous crystallizer in t/day (10–1000), V_{vessel} is volume of vessel in gal (10^4–10^7), CE is cost index factor, and $F_{BMvessel}$ is bare-module factor for vessel, which is 3.05.

For a high pressure pump, two stage radial centrifugal pump constructed of stainless steel is selected. The size factor S is [29]

$$S = Q_p(H)^{0.5} \quad (4)$$

where Q_p is volumetric flow rate through the pump in gal/min (50–1100) and H is pump head of fluid flowing in ft (300–1100).

The capital cost of a high pressure pump includes the pump purchase cost and the motor purchase cost. The pump purchase cost CC_{pp} is

$$CC_{pp} = F_{Tp}F_M\left(\frac{CE}{500}\right) \times \exp\left\{9.7171 - 0.6019[\ln(S)] + 0.0519[\ln(S)]^2\right\} \quad (5)$$

where F_{Tp} is the pump-type factor, which is 2.7 for two stage radial centrifugal pump, F_M is the material factor, which is 2 for stainless steel, and CE is cost index factor.

Besides the pump purchase cost, the motor purchase cost CC_{mp} should also be considered, which can be calculated by calculating pump efficiency η_P, pump brake horsepower P_B, motor efficiency η_M, and power consumption of motor P_C as following equations [28]:

$$\eta_P = -0.316 + 0.24015(\ln Q_p) - 0.01199(\ln Q_p)^2 \quad (6)$$

$$P_B = \frac{Q_pH\rho}{33000\eta_P} \quad (7)$$

$$\eta_M = 0.8 + 0.0319(\ln P_B) - 0.00182(\ln P_B)^2 \quad (8)$$

$$P_C = \frac{P_B}{\eta_M} \quad (9)$$

$$CC_{mp} = F_{Tm}\exp\begin{bmatrix}5.8259 + 0.13141(\ln P_C) + 0.053255(\ln P_C)^2\\ +0.028628(\ln P_C)^3 - 0.0035546(\ln P_C)^4\end{bmatrix} \quad (10)$$

where ρ is the liquid density in pounds per gallon, F_{Tm} is the motor-cost factor, which is 1.8 for a motor operating at 3600 rpm with an explosion-proof enclosure. Therefore, the capital cost of high pressure pump CC_{hp} is the summation of pump purchase cost and motor purchase cost,

$$CC_{hp} = CC_{pp} + CC_{mp}. \quad (11)$$

The crystallization process can be operated under rough vacuum (760–1 Torr) [29]. Two types of vacuum systems are considered, a two-stage steam jet ejector and a single-stage liquid-ring pump. The former has a lower capital cost, but the annual operating cost to supply the steam is more expensive, while the latter has a higher capital cost but a lower operating cost for electricity.

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