

Comprehensive Study of the Energy Consumption of Membranes and Distillation

Jose Adrian Chavez Velasco, Major Professors: Rakesh Agrawal, Mohit Tawarmalani.

Molecular separations are essential in the production of many chemicals and purified products. Of all the available separation technologies, distillation, which is a thermally driven process, has been and continues to be one of the most utilized separation methods in chemical and petrochemical plants. Although distillation and other commercial technologies fulfilled most of the current separation needs, the energy-intensive nature of many molecular separations and the growing concern of reducing CO₂ emissions has led to intense research to seek for more energy-efficient separation processes.

Among the emerging separation technologies alternative to distillation, there is special attention on non-thermally driven methods, such as membranes. The growing interest in non-thermal methods, and particularly in the use of membranes, has been influenced significantly from the widespread perception that they have a potential to be markedly less energy-intensive than thermal methods such as distillation. Even though many publications claim that membranes are more energy-efficient than distillation, a thorough analysis comparing the energy consumption of these processes is absent from the literature. One of the objectives of this work focuses on introducing a framework for comparative analysis of the energy intensity of membranes and distillation.

A complication generally encountered when comparing the energy consumption of membranes against an alternative process is that often the purity and recovery that can be achieved through a single membrane stage is limited. While using a multi-stage membrane process is a plausible solution to achieve both high purity and recovery, even for a binary separation, finding the most suitable multistage membrane process is a difficult task. This is because, for a given separation, there exists multiple cascades that fulfill the separation requirements but consume different amounts of energy. Moreover, the energy requirement of each cascade depends on the operating conditions. The first part of this work is dedicated to the development of a Mixed Integer Non-linear Program (MINLP) which allows for a given gaseous or liquid separation, finding the most energy-efficient membrane cascade. The permeator model, which is derived from a combination of the cross-flow model and the solution diffusion theory, and is originally expressed as a differential-algebraic equation (DAE) system, was integrated analytically before being incorporated in the optimization framework. This is in contrast to the common practice in the literature, where the DAE system is solved using various discretization techniques. Since many of the constraints have a non-convex nature, local solvers could get trapped in higher energy suboptimal solutions. While an option to overcome this limitation is to use a global solver such as BARON (Tawarmalani & Sahinidis, 2005), it fails to solve the MINLP to the desired optimality in a reasonable amount of time for most of the cases. For this reason, we derive additional cuts to the problem by exploiting the mathematical properties of the governing equations and from physical insights. Through numerical examples, we demonstrate that the additional cuts aid BARON in expediting the convergence of branch-and-bound and solve the MINLP within 5%-optimality in all the cases tested in this work.

The proposed optimization model allows identifying membrane cascades with enhanced energy efficiency that could be potentially used for existing or new separations. In addition, it allows to compare the optimum energy consumption of a multistage membrane process against alternative separations methods and aid in the decision of whether or not to use a membrane system. Nevertheless, it should be noted that when a membrane process or any other non-thermal separation process is compared with a thermal process such as distillation, an additional complication often arises because these processes usually use different types of energies. Non-thermal processes, such as membranes, consume electrical energy as work, whereas thermal processes, such as distillations, usually consume heat, which is available in a wide range of temperatures. Furthermore, the amount of fuel consumed by a separation process strongly depends on how its supplied energy is produced, and how it is energy integrated with the rest of the plant. Unfortunately, common approaches employed to compare the energy required by thermal and non-thermal methods often lead to incorrect conclusion and have driven to the flawed perception that thermal methods are inherently more energy-intensive than non-thermal counterparts. In the second part of this work, we develop a consistent framework that enables a proper comparison of the energy consumption between processes that are driven by thermal and non-thermal energy (electrical energy). Using this framework, we refute the general perception that thermal separation processes are necessarily the most energy-intensive and conclusively show that in several industrially important separations, distillation processes consume remarkably lower fuel than non-thermal membrane alternatives, which have often been touted as more energy efficient.

In order to gain more understanding of the conditions where membranes or distillation are more energy-efficient, we carried out a comprehensive analysis of the energy consumed by these two processes under different operating conditions. The introduced energy comparison analysis was applied to two important separation examples; the separation of p-xylene/o-xylene, and propylene/propane. Our results showed that distillation is more energy favored than membranes when the target purity and recovery of the most volatile (resp. most permeable) component in the distillate (resp. permeate) are high, and particularly when the feed is not too concentrated in the most volatile (resp. most permeable) component. On the other hand, when both the recovery and purity of the most volatile (resp. most permeable) component are required at moderate levels, and particularly when the feed is highly enriched in the most volatile (resp. most permeable) component, membranes show potential to save energy as compared to distillation.

References

Tawarmalani, M., & Sahinidis, N. (2005). A polyhedral branch-and-cut approach to global optimization. *Mathematical programming*, 103, 225–249.