ECP 2024 Conference
The 3rd International Electronic Conference on Processes
29–31 May 2024 | Online

Recent Trends in Azeotropic Mixture Separation

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INTRODUCTION & AIM

Separating azeotropic mixtures poses challenges in many industries. Due to similar composition in the vapor and liquid phases, conventional distillation methods were rendered ineffective in separating the components because the boiling point of the component is essentially constant.

Innovative approaches to traditional methods like azeotropic distillation and membrane-based techniques were seen as alternatives to overcome this limitation.

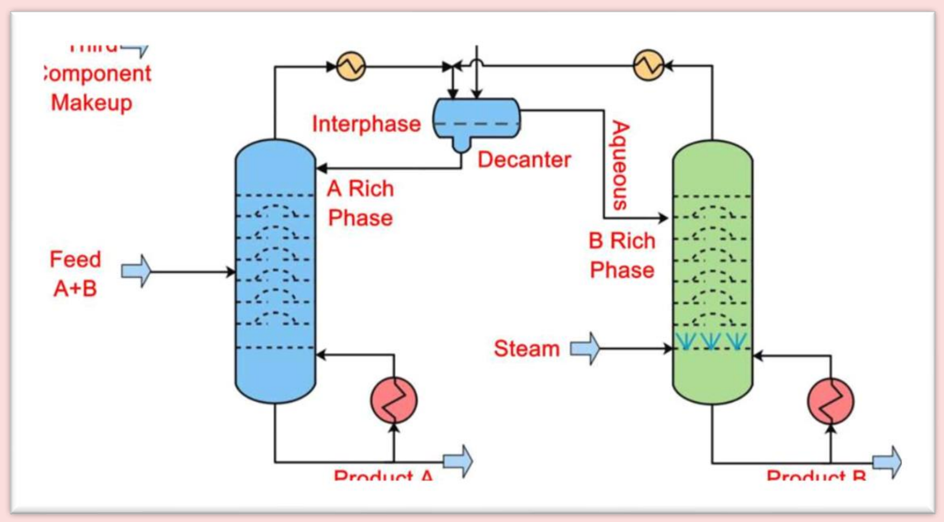
AZEOTROPIC DISTILLATION

Azeotropic distillation uses an entrainer, which functions as a solvent or mass separating agent, to effectively separate non-ideal binary mixtures into pure components, which is commonly used in equilibrium reactions such as water removal to shift reaction equilibrium.

Key considerations in azeotropic distillation include selecting the appropriate entrainer based on vapor-liquid equilibrium and thermodynamic analysis, as well as development of methods for entrainer recovery from products [1].

To achieve optimal efficiency in azeotropic distillation, it is essential to maintain a significant concentration of entrainer throughout the distillation column and carefully consider its placement to influence concentration gradients. Overall, azeotropic distillation plays an important role in solvent purification processes, particularly in industries like chemical processing, which enhances purity levels, and improves distillation outcomes on top of providing benefits in energy efficiency and consumption reduction.

Azeotropic Distillation



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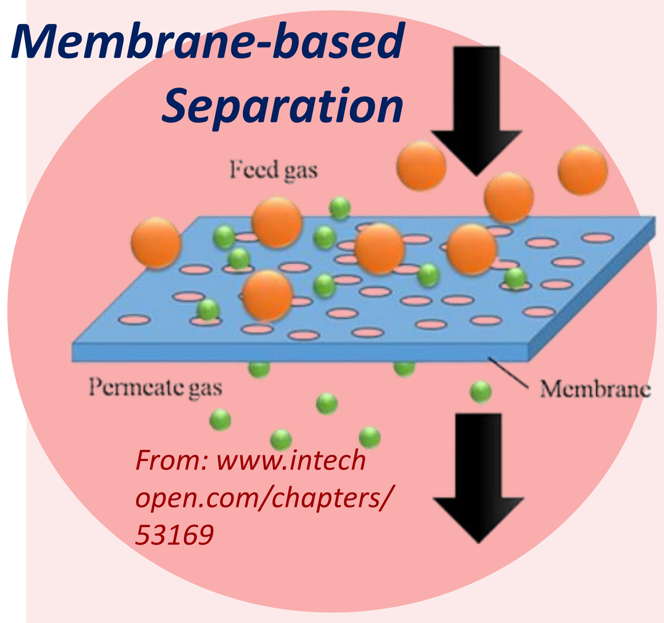
MEMBRANE-BASED SEPARATION TECHNIQUES

Membrane-based separation techniques, which uses semi-permeable materials to separate components based on physical properties, are preferred alongside azeotropic distillation for separating azeotropic mixtures, with membrane types including organic, polymeric, and inorganic varieties suited for the applications [2].

In terms of sustainability, membrane-based methods are preferred over azeotropic distillation. Techniques like membrane distillation and pervaporation, along with hybrid processes combining membranes with distillation, hold potential in reducing energy usage and setting new industry standards for azeotropic mixture separation.

a. Membrane Distillation

Membrane-based Separation



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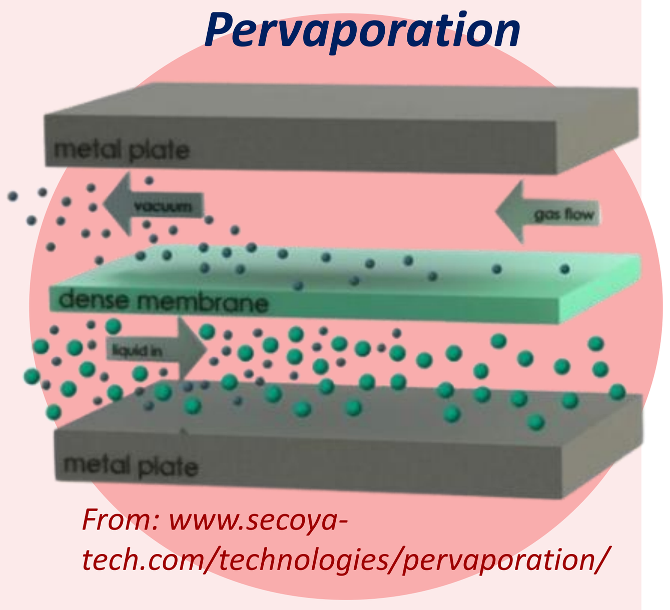
Membrane distillation (MD) separates substances based on volatility differences and uses temperature gradient across a hydrophobic membrane and low-grade thermal energy from renewable sources. However, issues in MD like membrane selectivity and scalability issues are still present, although advancements in module design may overcome scalability concerns by enhancing membrane materials to handle larger volumes [3].

b. Pervaporation

Pervaporation (PV) technology separates components based on solubility and diffusivity differences using a nonporous membrane operating under mild conditions without the need for additional chemicals to ensure stream purity. However, PV systems may suffer from membrane damage and swelling, impacting long-term efficiency [2]. Few studies show that covalent organic frameworks (COFs) can potentially improve stability, yet their application for organic azeotropic mixtures requires further research for practical use.

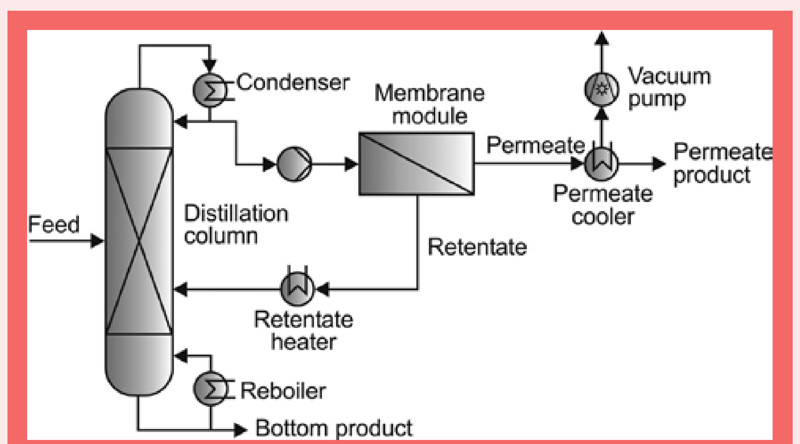
Pervaporation



From: www.secoya-tech.com/technologies/pervaporation/

c. Hybrid Separation

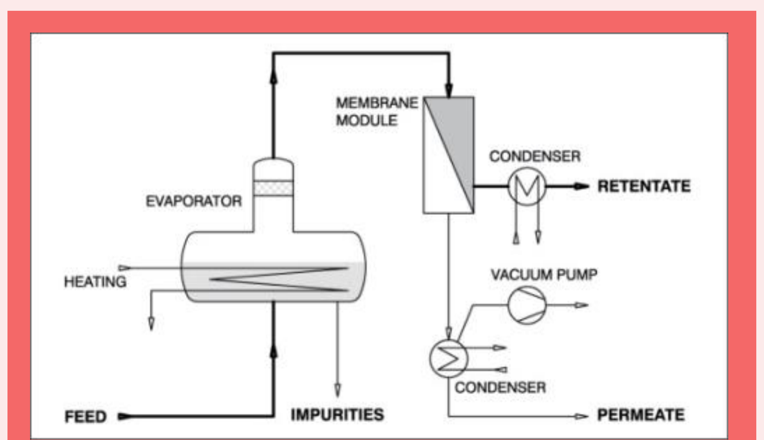
A subset of membrane-based methods, this combines two or more separation methods to maximize their individual capacities and address common issues encountered in single-method separation procedures of azeotropes. The integration of distillation with membrane separation aims to capitalize on the high selectivity of membranes to enhance overall process efficiency which could enable higher purity products at lower energy conditions [4].



Distillation with Pervaporation

From: www.researchgate.net/figure/Hybrid-process-combining-distillation-with-pervaporation-for-a-binary-system-with-a_fig21_321916735

It is a hybrid membrane separation technique particularly beneficial in bioethanol production. It concentrates azeotropes upstream of distillation, reducing energy demands and costs. Furthermore, this approach also has the potential to reduce solvent costs and enhance solvent recovery efficiency but may require extensive research [5].



Pervaporation with Vapor Permeation

From: www.filtsep.com/content/features/chemicals-pervaporation-and-vapour-permeation-processes-meet-specialist-needs/

This process removes water from azeotropic mixtures, reducing the load on subsequent vapor permeation steps for higher purification levels. It allows for specialized separation, potentially reducing operational costs and energy consumption compared to conventional or other hybrid methods. Pervaporation with vapor permeation systems is especially useful for processing temperature-sensitive mixtures or components requiring precise compositional control [6].

LIMITATIONS

1. **Entrainer Selection and Process Optimization:** Selecting an appropriate entrainer with optimal properties can be particularly difficult as the efficiency of the process may vary based on the characteristics of the mixture.
2. **Energy Consumption:** Some techniques used for separation require an additional input of energy to facilitate the separation process, which is why some studies suggest that the key process parameters be further optimized.
3. **Membrane Fouling:** Since the components present in azeotropic mixtures have the tendency to induce fouling which diminishes the process efficiency over time, the accumulation of impurities on the membrane surface may require frequent cleaning, or worse, replacement.
4. **Scale-up Challenges:** Scalability issues of azeotropic distillation for industrial applications are also among the issues commonly encountered, particularly affecting the heat and mass transfer, column design, process stability maintenance, and proper flow of the mixture.

FUTURE RESEARCH

Current separation techniques for azeotropic mixtures face sustainability challenges due to high energy requirements, hence the need for research into alternative methods that reduce energy consumption and enhance efficiency.

Extensive research and development efforts may also be needed to optimize energy-intensive processes for azeotropic mixtures by using principles in material science to understand thermodynamic properties, fluid dynamics, and phase equilibria, which may help in predicting and controlling dynamic behavior.

While membrane technologies have received significant attention, innovative non-membrane techniques like reactive-extractive distillation (RED) may also potentially be used for azeotropic mixture separation. RED systems require less energy input and may benefit from sustainability assessments and process evaluations through process intensification to establish industry-wide applicability while maintaining efficiency [7].

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