Grand Challenges in Emerging Separation Technologies

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In recent years, chemists have been working on the efficient separation and purification of compounds (Aaron and Tsouris, 2005; Cheng and Sabatini, 2007). This process, such as traditional distillation, accounts for about 10–15% of global energy consumption (Humphrey, 1997; Angelini et al., 2005). If the method with higher separation efficiency is applied to industries such as petrochemicals and printing, it will reduce 100 million tons of carbon emissions and 4 billion US dollars in processing costs each year (Brueske et al., 2015). The tremendous interests drive people to search for the low-energy-consumption separation technologies which are independent on phase changes of fluids (Sholl and Lively, 2016; Lively and Sholl, 2017). For example, advanced separation membranes technology enables such a green process that can greatly reduce the energy consumption and the carbon and space intensity of conventional distillation processes for separation and purification of compounds (Jimenez-Solomon et al., 2016; Liu et al., 2016; Wang et al., 2018, 2019; Zhang et al., 2019). Significantly, the energy consumption of per liter in the emerging membrane separation process is about 1/25 times as much as in the conventional distillation process (Rundquist et al., 2012; Yang et al., 2020).

However, up to date, emerging energetic-efficient separation technologies replacing distillation are under developed and expensive to large-scale production (Cuperus and Smolders, 1991; Wang et al., 2006, 2012; Striemer et al., 2007; Feng et al., 2016). Therefore, industrial production and academia need to develop better and economical processes to separate and refine compounds. Here we point out crucial chemical separation processes. If these processes can be improved, it will greatly increase global benefits and save resources. It is worth noting that these separation processes we proposed are not all but important and urgently needed improvement.

SEPARATION OF ALKANES FROM ALKANES

The manufacture of plastics (for example, polyethylene and polypropylene) requires olefin-hydrocarbons (for example, ethylene and propylene, known as olefins) (Angyal et al., 2010). Ethylene and propylene are produced about 200 million tons (equivalent to 30 kg per person) per year worldwide (Lu et al., 2006). Ethylene and ethane are usually separated by high-pressure cryogenic distillation, with temperatures down to −160°C. The energy consumption for the separation and purification of ethylene and propylene is around 0.3% of global energy consumption, which is roughly equal to energy annual consumption of Singapore.

The development of a new membrane separation technology which can reduce the energy intensity of ethylene and propylene separation and purification to the original 1/10 has laid the foundation for solving this problem (Koros and Lively, 2012). For example, porous carbon membrane was developed to achieve the separation of gaseous olefins and alkanes under mild conditions (room temperature and low pressure) (Xu et al., 2012). However, this carbon membrane cannot achieve 99.9% ethylene separation, so it cannot meet the purity of
ethane required in the chemical production process. However, the emergence of ZIF membranes, especially ZIF-8 MMMs (Li et al., 2020; Oh et al., 2020), solved this problem well, but the common problems of ZIF membranes are the dispersion and compatibility of nanoparticles, which makes it difficult for ZIF membranes to achieve large-scale production. In general, the industry might need up to 1 million square meters of membrane.

**REMOVAL OF CONTAMINANTS IN WATER**

Desalination, such as distillation, is an energy-intensive water treatment technology, which is not suitable in many arid regions. Obviously, distillation is not a viable method due to the fact that the energy required is 50 times more than the minimum energy which is required to produce drinking water from seawater according to thermodynamic definition (Zhang et al., 2020).

The energy consumption of reverse osmosis process, a technique that applies the relatively high pressures on the asymmetric membrane to brine for producing drinkable water, is only ~25% of the thermodynamic minimum energy (Koros and Lively, 2012; Zhang et al., 2020). However, the permeance of the reverse osmosis membrane is very low under applied pressures, >2 L m$^{-2}$ h$^{-1}$ bar$^{-1}$, which leads to inefficient water treatment (Lee et al., 2011). To increase permeance, large-scale and expensive reverse osmosis membranes are introduced into plants, which caused an increase in water treatment costs. Reverse osmosis seawater desalination technology is commercialized in the Middle East and Australia. However, when dealing with heavily polluted water, reverse osmosis technology encounters a series of difficulties (including scaling, corrosion, biofilm formation, and particle deposition) in practical applications, which require expensive pretreatment systems.

In summary, it is important to reduce operating costs that the development of high-permeance, inexpensive, and pollution-resistant reverse osmosis membranes, which is conducive to the technology's commercial feasibility even in the treatment of highly polluted water bodies.

**GREENHOUSE GAS CAPTURE AND UTILIZATION**

Anthropogenic carbon dioxide and other hydrocarbons (like methane from refineries/oil wells) are key factors in global warming (Khaliilpour et al., 2015). Among them, carbon dioxide accounts for the main component (Khaliilpour et al., 2015). Traditional capture technologies require high temperatures, such as carbon dioxide capture using monoethanolamine that react easily with carbon dioxide, which is not economically feasible for power generation. If traditional capture technologies are applied to every power station in the United States, carbon dioxide capture may occupy 30% of GDP (Sheet, 2013). Therefore, it is necessary to develop low-cost carbon dioxide capture technology.

Emerging membrane separation technology can effectively reduce costs because no heating is required during processing (Ze and Sx, 2014). For example, hollow fiber membrane gas capture technology has been widely used in industrial sectors and laboratories (Ze and Sx, 2014). Due to technical and economic issues, membrane gas capture technology is difficult to achieve large-scale industrial applications. For large-scale applications, the challenges of membrane gas capture technology mainly focus on the following aspects.

First, the design of the membrane structure and the choice of materials are key factors. It is necessary to develop high temperature, corrosion and pollution resistant gas permeable membranes. Secondly, the permeability and selectivity, mechanical properties, stability, and process compatibility need to be carefully considered. However, the existing research mainly focuses on the permeability of the gas membrane, and lacks consideration of other important factors. Secondly, the impact of trace gas components (for example, O$_2$, SO$_2$, NO$_x$, and NH$_3$) on membrane capture technology has been ignored in existing articles and researches that focus on the separation of binary mixtures of N$_2$ and CO$_2$ (Adewole et al., 2013). In addition, it may not be feasible to use single stage membrane gas capture technology because of the low carbon dioxide content in the flue gas, even if the membrane demonstrates high permeselectivities. Therefore, multi-stage membrane gas capture technology may be feasible and at the same time improve the separation efficiency of carbon dioxide and product purity, which leads to an increase in processing costs and an improvement of processing technology. In short, in the application of membrane contactors for gas absorption, the limitation of the trade-off between cost and performance is ultimately to be resolved.

Furthermore, how to deal with purified products is an important issue. Carbon dioxide can be used in crude oil production and in agricultural, chemical and biological refining feedstocks. However, humans emit large amounts of gas that is stored in underground reservoirs for a long time, which causes many other problems.

**BENZENE DERIVATIVE SEPARATION**

The synthesis of many polymers, fibers, solvents, plastics and fuel additives requires benzene, cyclic hydrocarbons and their derivatives, such as ethylbenzene, toluene and xylene isomers which are mainly produced by distillation from distillation columns. Around 50 GW of energy is consumed in this production process worldwide, which is enough to power 40 million home users.

Xylene isomers are analogous molecules with differences in subtle structures from each other, which results in differences in properties between the isomers. Among them, para-xylene, the most required isomer, is the key substance for synthetic polymers, such as typical polyesters. In the United States, paraxylene production is ~8 kg per person per year. Various xylene isomers have similar boiling points, which makes it difficult to achieve separation by conventional methods such as distillation.

In recent years, advanced membrane separation technology that can effectively reduce energy consumption has been increasingly concerned by researchers to achieve the separation of benzene derivatives. From benzoylchitosan (Inui et al., 1998)
to MFI zeolite to MIL-160 (Wu et al., 2018), membrane separation technology is gradually applied to the separation of simple benzene derivatives at the laboratory level, which is very far from industrial applications. In addition, the introduction of adsorbents can also effectively reduce the energy consumption of the separation process. As for other alternative technologies, their feasibility needs to be further proved.

**CRUDE OIL DERIVED HYDROCARBONS**

Hydrocarbons are the main materials for the preparation of diverse plastics and fossil fuels. The worldwide refineries a \( \sim 90 \) million barrels of crude oil per day, which is equivalent to 2 L of crude oil per person per day. Crude oil is mainly processed by atmospheric distillation. This method consumes \( \sim 230 \) GW globally, which is equivalent to the total UK energy consumption in 2014 (Brueske et al., 2015). In a typical refinery, 200,000 barrels of crude oil need to be heated in a 50-meter-high tower every day, and thousands of compounds are released based on differences in boiling points. Light gases appear on top of the lower temperatures (at around 20°C). Gradually heavier liquids are discharged lower and hotter (up to 400°C) locations.

It is difficult to find alternatives to distillation, because crude oil contains many complex molecules, some of them have high viscosity and many pollutants. Based on the theoretical basis, the separation of hydrocarbons can be achieved based on their molecular properties, like chemical affinity and molecular sizes. Therefore, the emerging membrane separation technology that consumes less energy and is more energy efficient, compared to using thermally driven distillation methods may be promising alternative technology. However, few studies have focused on the application of membranes materials in crude oil.

For now, researchers are eager to develop materials that can simultaneously separate many molecular families. The material must be able to withstand high temperatures and the material will not be blocked by contaminants as crude oil flows.

**NEXT STEPS**

At this stage, traditional separation methods, such as distillation and adsorption, remain the main processing technologies. However, traditional separation technologies need to be improved or replaced because of problems such as high energy consumption and adsorbent life. Emerging membrane separation technology can solve these problems but the widespread application of the technology is limited because of membrane factors and environmental factors. The factors of the membrane itself mainly include the heat resistance, corrosion resistance, pollution resistance, long-term stability, trade-off between permeance and selectivity, large-scale production and cost, etc. Environmental factors include the composition of the applied chemical mixture, the compatibility of the membrane with the process, and the environmental conditions (including temperature and pH) where the membrane is located. These factors need to be addressed at the process development stage in order to realize the widespread application of membrane separation technology. Based on this, researchers on separations need to focus on the following issues.

First, the improvement of traditional methods can gain time for the widespread application of membrane separation technology. Researchers need to improve the distillation process in order to minimize energy consumption. In addition, the development of high-performance adsorbents is necessary. The adsorbent needs to have high specific surface area, superior stability and adsorption, and most importantly, long lifetime and low cost.

Second, researchers and engineers need to consider chemical mixtures separated in practical applications, rather than simple mixtures in the laboratory, which is conducive to promoting the application of membrane separation technology in actual production processes. However, most studies are limited to the separation of simple chemical mixtures, and the behavior of mixtures is inferred from this information, which leads to the neglect of the separation behavior of some chemical mixtures (the effects of trace substances, etc.) and is detrimental to practical applications. Researchers and leaders should establish reasonable standardized alternative mixtures for common separations, including major chemical components and typical contaminants.

Third, both economics and sustainability of emerging separation technology in practical applications must be carefully evaluated throughout the process. Performance indicators need to be used, such as cost per kilogram of product and energy consumption per kilogram. In addition, it is necessary to consider the lifetime, heat resistance, pollution resistance and cost of the membrane module.

Fourth, the scale of practical applications must be considered in the early stages of technology development. From laboratory applications to pilot scale, new physical and chemical infrastructure will be required, for example, experimental benches for academic and industrial operations, which can reduce the risks in the entire process. It is necessary to manage these that collaboration between academia, government agencies, and industry partners.

Fifth, for now, the training in separation applications usually focuses on traditional distillation for chemical engineers and chemists, which is not conducive to the application of other separation technologies, especially emerging separation technologies such as membrane separation technology. Therefore, it is very important to build an all-round team capable of realizing various separation technologies in the future, especially emerging separation technologies, which is conducive to promoting the application of separation technologies, thereby saving resources and achieving energetic-efficient sustainable development.

**AUTHOR CONTRIBUTIONS**

The author confirms being the sole contributor of this work and has approved it for publication.
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Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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