# MEMBRANE DISTILLATION

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**Keywords :** Membrane Distillation, Terminology, Biological Solutions, Transport Models, Wetting Processes

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**Summary**

Membrane distillation is a membrane separation process which may overcome some limitations of other membrane technologies. In particular, high solute concentrations can be reached, overcoming concentration polarization phenomena and ultrapure water can be produced as a permeate. The process uses microporous hydrophobic membranes, impermeable to the transport of liquid water, while water vapor can be transported across them, having as driving force a vapor pressure difference at the two solutions membrane interfaces. Various polymeric hydrophobic membranes have been prepared with an appropriate microporosity of the order e.g. of 0.2 mm, of interest for this process. The influence of the feed temperature, transmembrane temperature gradient, feed concentration, fluodynamic conditions, etc., have been studied theoretically and tested experimentally. Various membrane configurations and operation techniques have been also suggested for optimizing transmembrane fluxes and energy consumption. Membrane distillation has shown interesting potential in water desalination, fruit juice concentrations and in other various industrial productions. Furthermore, by using membrane distillation in integrated operations it is possible to achieve higher concentration values and better overall performance of the processes.

## 1. Introduction

Membrane distillation is a relatively new membrane separation process which might overcome some limitations of the more traditional membrane technologies. In particular high solute concentrations can be reached and ultrapure water can be produced in a single step. The possibility of an industrial development of this technology is related to the growing commercial availability of membranes of potential interest.

When a microporous hydrophobic membrane separates two aqueous solutions at different temperatures, selective mass transfer across the membrane occurs: this process takes place at atmospheric pressure and at temperatures which may be much lower than the boiling point of the solutions. The hydrophobicity of the membrane prevents the transport of the liquid phase across the pores of the partition while water vapor can be transported across them from the warm side, condensing at the cold surface. The driving force is the vapor pressure difference at the two solution membranes interfaces.

Because the process can take place at normal pressure and low temperature, membrane distillation could be used to solve various wastewater problems, to separate and recover chemicals, and also to concentrate to high osmotic pressures aqueous solutions of substances sensitive to high temperatures. The possibility of using solar, wave or geothermal energy, or existing low temperature gradients typically available in industrial processing plants is particularly attractive.

The fundamental simplicity of traditional distillation is compromised by various factors such as the need for complete removal of all noncondensable gases. The use of vacuum pumps, high pressure vessels, deaeration devices, etc. are required for removing the effects of the noncondensable gases, with a significant energy consumption. A number of distillation processes have been proposed with the aim of eliminating the need for creating a vacuum. A relatively large number of evaporators based on the circulation or convection of water-saturated air, from an evaporation surface to a condenser, have been designed. An interesting result was found in the study of this kind of systems: the production of pure water per unit area and per unit time was inversely proportional to the gap existing between the evaporation and condensation surfaces. Obviously, it is impossible to reduce this gap without causing contamination of the distillate by the feed water, but this fact suggested the use of membrane systems.

Hydrophobic microporous membranes allow easy passage of water vapor, but completely block the flow of liquid water. Surface tension of the water prevents its passage through the pores of the hydrophobic material. If feed water is in contact with one of the surfaces of the membrane, the gap distance between the evaporation and condensation surfaces could be reduced to the thickness of the membrane, thus preventing contamination by the feed water.

Early work was presented by Findley (1967) and Findley et al. (1969) where transport in vapor phase across porous partitions was studied. The membrane materials used in these works were paper hot cup, glass fibers, aluminum foil and similar. The efficiency of the process was related to the stability of membrane materials. In the 1980s new microporous hydrophobic membranes became commercially available and membrane desalination (MD) again attracted significant attention.

### 1.1. Principle of Membrane Distillation

Non-isothermal transport of fluids, especially water, through membranes has been studied since the beginning of the century . The first experiments in the field were based on dense membranes. The measured fluxes were small and the process of diffusive nature, was called "thermal osmosis" or "thermoosmosis". The description of the phenomenon was generally carried out within the framework of the Thermodynamics of Irreversible Process.

In the 1960s (Findley 1967; Findley et al. 1969) a much bigger non-isothermal water transport was found in porous hydrophobic partitions, and called "membrane distillation". The magnitude of fluxes were 1000 times greater than those found in dense membranes, at the same conditions.

Up to now membrane distillation has referred to the non-isothermal transport of water, via vapor phase, through the pores of a hydrophobic partition. The system consists of a porous hydrophobic membrane, separating two aqueous solutions of a non-volatile component maintained at different temperatures. Due to the liquid-rejecting properties of the membrane material, the liquid phase is prevented from penetrating the pores, as long as the pressure of liquid does not exceed the minimum entry pressure of the porous partition. Liquid-vapor interfaces are formed on both sides of the membrane pores and, due to the temperature difference, a vapor pressure difference is created between sides of each pore. Evaporation takes place at the warm interface and, after vapor is transported through the pores, condensation takes place at the cold interface. In this way a water flux occurs through the membrane in the direction from warm to cold. Obviously, for membrane distillation to proceed, it is essential that liquid water is excluded from the pores. In this sense, the role of the membranes is somewhat peculiar, since it acts as a physical support for the liquid-vapor interfaces. A schematic representation of the membrane distillation process is shown in Figure 1.

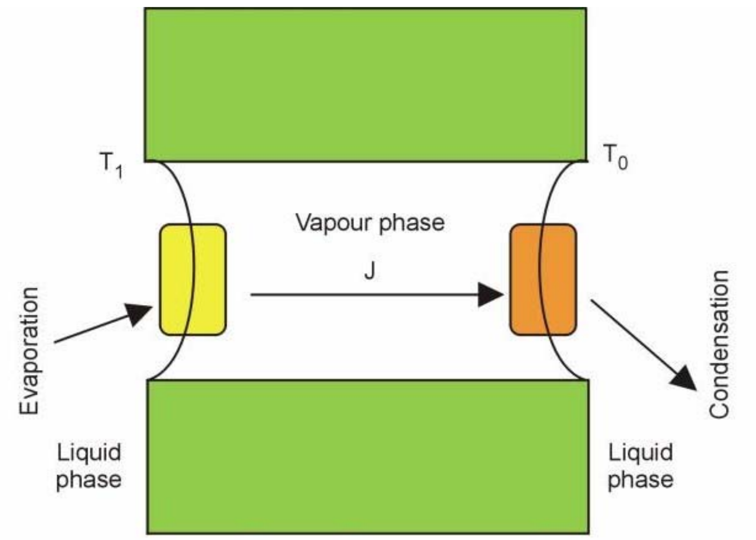


Figure 1. A schematic representation of the membrane distillation process: $T_1$, temperature at the hot side; $T_0$, temperature at the cold side; J, flux of the vapor phase.

The origin of water transport in this kind of process is a difference in water chemical potential created by a vapor pressure difference. This is produced by a temperature difference between the two solutions facing the membrane, but could also be produced by different concentrations between the two aqueous solutions (Mengual 1993; Sheng et al. 1991). The process is called "osmotic distillation" if the system is kept in isothermal conditions and the difference in concentration is produced by non-volatile solutes.

The systems described above are the so-called "direct contact membrane distillation" and "osmotic membrane distillation" methods where the distance between the evaporation and condensation surfaces is reduced to the membrane thickness. But, following the description of the membrane transport, it is possible to imagine other possible set ups, designed with the aim of increasing process efficiency. All these different configurations, for example "gas-gap membrane distillation" or "vacuum membrane distillation" will be considered in the next sections.

### 1.2. Future Development

Membrane distillation is an alternative to the traditional evaporative distillation systems used for desalination or water purification processes. On the other hand, membrane distillation can be compared with other membrane techniques, e.g. reverse osmosis.

Reverse osmosis is industrially used in desalination processes (nearly 30 per cent of desalinated water in the world is produced by this membrane technique), production of ultrapure water and food concentration (juices, sugars and milk, for example). RO is a pressure driven membrane process based on the solution-diffusion of the solvents, mainly water, across the membrane. Reverse osmosis efficiency is strongly affected by the osmotic pressure of the highly concentrate feed solutions (the osmotic pressure of seawater is about 25 bar) and by the concentration polarization phenomena that occurs on the pressurized membrane-solution interface. In addition, the membrane rejection is generally of the order of 98-99 per cent, and some salts can diffuse in the permeate.

In contrast, membrane distillation is a thermally driven membrane process where efficiency shows a slight decrease with increasing salt (or other inorganic solutes) concentration, because of a decrease in vapor pressure. In principle, MD can also produce ultrapure water from feeds at quite high concentrations where RO cannot practically operate.

In addition, the quality of the permeate (the separation efficiency) is virtually independent on the feed concentration. Mass transport in fact takes place in the vapor phase; non-volatile solutes are completely rejected by the membrane and only volatile solutes can be transported. This point has great relevance because it permits to design separation systems, with efficiencies near 100 per cent. But MD has some disadvantages. Compared to RO, the MD fluxes of permeate are usually lower and, being a thermally driven process there is necessarily a higher energy consumption. In addition, some membrane materials do not present a sufficiently high chemical resistance in the presence of salt, which implies a loss in the process efficiency, or they are still too expensive. These possible disadvantages could be overcome in different ways. In Table 1, a summary of the advantages and disadvantages of membrane distillation is shown.

| Advantages | Disadvantages<br>(⇒POSSIBILITIES TO OVERCOME) |
|---|---|
| The continuous vapor permeation increases the evaporation in the warm liquid solution.<br>Reduction of non-condensable species vapor phase.<br>High concentration at low pressures and temperatures.<br>Integration with other membrane operations.<br>Reduction of osmotic limits. | Energy consumption<br>Use of solar, wave or geothermal energy.<br>Use of existing temperature gradients available in industrial plants.<br>Use of MD in the treatment of solutions discharged at high temperature.<br>Fluxes are lower than in other membrane processes for industrial applications.<br>Integration with other membrane processes or traditional technologies.<br>Engineering improvement of the process. |

Table 1. Advantages and disadvantages of membrane distillation operation.

The applications of membrane distillation, described in Section 5, are not restricted to the desalination field. In fact, the applications are only determined by the wettability of the membrane, which implies that mainly aqueous solutions containing inorganic or dilute aqueous solutions of organic compounds could be treated.

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