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# Statistical analysis of air-gap membrane desalination experimental data: Hypothesis testing

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## HIGHLIGHTS

- Data on membrane distillation are analyzed using methods of statistical hypothesis.
- Multiple comparison tests like F-test, Fisher's LSD, and Tukey's test are applied.
- Variance of data has dramatic effect on membrane selection process.
- Replication in membrane experimentation is of paramount importance.

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## ABSTRACT

Membrane distillation (MD) is a process in which the driving force for mass transfer is temperature gradient rather than conventional ones based on density, static pressure, chemical nature, affinity, and freezing point gradients. Using a porous hydrophobic membrane, MD comes into four configurations; direct contact, air gap, sweeping gas, and vacuum MD. The current technical literature shows a growing interest in experimental investigation of MD processes. In this work, a complete set of experimental data on air gap membrane distillation is analyzed using statistical methods. The experimental data involves a study of the effects of salt concentration on permeate flux for $MgCl_2$, $Na_2SO_4$, and NaCl using three commercial membranes in AGMD unit. Hypothesis testing regarding the mean permeation flux under different salt concentrations is implemented. The objective is to gain an idea about the statistical significance of performance differences among these membranes. Several statistical techniques, i.e., F-test, Fisher's LSD test, Bonferroni and Tukey's test for multiple comparisons are applied. The F-test predicts that all three membranes handle the three salts at their low salt concentration levels in a comparable manner with no significant differences in permeate fluxes but handle the same salts differently at the higher level of salt concentrations.



## 1. Introduction

### 1.1. Membrane distillation configurations

Membrane distillation (MD) is a process in which the driving force of mass transfer is temperature gradient that results in a vapor pressure difference across a micro-porous hydrophobic membrane. In conventional separation processes, the driving forces could be: density, static pressure, chemical nature, affinity, electric field or freezing point gradients or a combination therefrom [1]. The membrane selectivity in MD results from its hydrophobic nature which causes retention of liquid molecules that have strong dipole effects and allows only the passage of vapor molecules through the pores. As a result, the non-polar membrane is not wetted by the liquid due to water's high surface tension [2,3].

Both membrane distillation and conventional distillation depend on vapor–liquid equilibrium as a starting point for separation. Additionally, phase change in both separation processes is achieved by acquiring the latent heat of vaporization [4]. MD benefits compared to other conventional separation processes arise from (1) operation at temperatures below the boiling point, (2) operation at low pressure compared to pressure-driven separation processes, resulting in reduced costs for the process and membrane, (3) minimization of corrosion troubles that could occur due to interactions between process solutions and membranes, (4) probability of combining membrane processes with other separation process (hybrid system), (5) utilizing solar energy as an alternative energy source [4,5], (6) ability to produce ultrapure water from saline feed, (7) transporting only volatile solutes through the membrane while

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**Nomenclature**

| | |
|---|---|
| a | number of treatments |
| AGMD | air gap membrane distillation |
| ANOVA | analysis of variance |
| APAM | anionic polyacrylamide |
| COD | chemical oxygen demand |
| df | degrees of freedom |
| DCMD | direct contact membrane distillation |
| f | degrees of freedom |
| FAME | fatty acid methyl esters |
| $H_0$ | null hypothesis |
| J | flux ($g/m^2$ s) |
| LEP | liquid entry pressure |
| LSD | least significant difference |
| MD | membrane distillation |
| MS | mean square |
| n | number of observations |
| N | total number of observations |
| PP | polypropylene |
| PTFE | polytetrafluoroethylene |
| PVDEF | polyvinylidene fluoride |
| $R^2$ | coefficient of correlation |
| RSM | response surface methodology |
| SGMD | sweeping gas membrane distillation |
| SS | sum of squares |
| $T_\alpha$ | Tukey critical parameter at a certain level of confidence |
| TF-200 | Teflon membrane with mean pore size of 0.20 μm |
| TF-450 | Teflon membrane with mean pore size of 0.45 μm |
| TF-1000 | Teflon membrane with mean pore size of 1.00 μm |
| TMP | trans-membrane pressure |
| TOC | total soluble organic carbon |
| VMD | vacuum membrane distillation |
| $\bar{y}_{i.}$ | average experimental response value |
| $y_{i.} = \sum_{j=1}^{j=b} y_{ij}$ | sum over j for all observations in treatment i |
| $y_{..} = \sum_{i=1}^{i=a} \sum_{j=1}^{j=b} y_{ij}$ | sum of all observations over i and j |

*Greek letters*

| | |
|---|---|
| σ | standard deviation |
| α | level of significance |
| μ | treatment mean value |

completely rejecting non-volatile solutes [6], and (8) easy scale-up with no requirements of additives [1]. On the other hand, MD has some drawbacks such as (1) large heat loss by conduction, (2) small permeate flux due to many factors including polarization, (3) mass transfer resistance due to trapped air in the membrane, which reduces permeate flux [7,8], (4) low membrane lifetime, (5) membrane fouling [1], and (6) high energy consumption.

As shown in Fig. 1, there are four different configurations for MD: Direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD).

In DCMD hot solution and cold permeate feed solutions are charged to evaporator and permeate sides, respectively. Each solution is in direct contact with the micro-porous hydrophobic membrane. At the hot side of feed-membrane surface, evaporation takes place where vapor molecules pass through the membrane to the cold permeate side where condensation takes place inside the membrane module [4,5,8]. DCMD is the simplest configuration and can be easily set up in a laboratory. However, the heat loss by conduction due to poor conductivity of the membrane is the main drawback of this configuration.

AGMD employs an air gap between the membrane and condensation surface, where the vapor molecules must pass through membrane pores then through the air gap, and lastly condensation takes place on a cold surface inside the membrane module. The advantage of this configuration is the reduction in heat loss because of the air gap between the membrane and the condensation surface. However, that will cause further mass transfer resistance and less permeate flux. An additional advantage of AGMD over DCMD is the ability to separate volatile substances from dilute solutions due to the barrier between the membrane and liquid permeate [3].

In SGMD configuration, a cold inert gas is introduced at the permeate side to sweep the vapor molecules so that condensation takes place outside the membrane module. Because the gas barrier is not stationary, the permeate flux is higher compared to both DCMD and AGMD mainly due to less mass transfer resistance. However, the main disadvantage of SGMD configuration is the requirement of an external condensation system [7]. SGMD configuration is effective in ammonia removal (up to 97%) from wastewater containing low levels (up to 100 mg/L). Increasing the sweep gas flow rate, results in decreasing the mass transfer boundary layer resistance and ammonia removal becomes more efficient [10].

In the VMD configuration a pump is used to create vacuum in the membrane permeate side and the pressure applied is lower than the equilibrium vapor pressure of the molecules to be separated from the feed. Similar to the SGMD, condensation takes place outside the membrane cell and heat loss by conduction is insignificant [8]. VMD is used to separate volatile compounds from water and is effective in desalination of sea water [9].

### 1.2. Operating parameters in membrane distillation

There are five important operating factors that affect the performance of membrane distillation, i.e., feed temperature, coolant temperature, feed concentration, feed circulation rate, and air gap width (in AGMD). The temperature of hot feed solution has a sound impact on the permeate flux [8]; The permeate flux increases as feed temperature increases. The increase in feed temperature causes an exponential increase in feed vapor pressure according to Antoine's equation; hence, the vapor pressure driving force becomes larger and the permeate flux increases (other MD parameters are held constant). Regarding coolant temperature, generally, as permeate temperature increases, permeate flux decreases because the vapor-pressure difference becomes less. In AGMD, permeate flux is almost independent of permeate temperature because the overall heat transfer coefficient depends mainly on the air gap in the membrane module. However, in DCMD, permeate flux is increased by lowering permeate temperature [3].

For feed saline solution containing non-volatile solutes, the vapor pressure decreases as salt concentration increases since boiling point increases, thus the driving force becomes less, generating low permeate flux. On the other hand, in solutions containing volatile components, increasing feed concentration increases the partial pressure of volatile components in the feed, thus permeate flux increases [3].

Increasing feed circulation rate enhances the permeate flux because heat transfer coefficient increases in the feed side of the membrane. Moreover, reduction in concentration and temperature polarization causes an increase in permeate flux. Three membrane configurations (DCMD, AGMD, VMD) exhibit direct relationship between feed circulation rate and permeate flux, but SGMD has negligible feed circulation effect on permeate flux [3,8].

Decreasing the air gap width in AGMD configuration causes an increase in temperature gradient across the sides of the gap and thus vapor pressure driving force increases resulting in an increase in the permeate flux [8,10].