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The use of factorial design in the analysis of air-gap membrane distillation data

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HIGHLIGHTS

- Data on air gap membrane distillation is analyzed using factorial designs.
- Two-level and three-level factorial designs are applied.
- Effects of porosity on permeate flux are greater than those of salt concentration.
- Effect of salt concentration on permeate flux: $MgCl_2 > NaCl > Na_2SO_4 > Na_2CO_3$
- Factorial design is able to predict the permeation rate quite satisfactorily

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ABSTRACT

A complete set of experimental data on air-gap membrane distillation (AGMD) is analyzed using the methods of factorial design (FD). A two-level and three-level FD were applied to investigate the influence of the main operating parameters on permeation flux of water. The data involves a study of the effects of salt concentration (at pre-set conditions of different input parameters such as feed temperature, coolant temperature, feed flow rate) on permeate flux for four inorganic salts ($MgCl_2$, NaCl, Na_2CO_3 and Na_2SO_4) using three commercial membranes in an air gap distillation unit. The objective is to gain an idea about the effects of the involved factors and their interactions. The factorial models have been obtained and validated by analysis of variance. Membrane pore diameter (membrane porosity) is found to be the most influential factor. Interaction terms are found to be insignificant. The predicted responses were compared with the experimental ones. In general, the predicted values were in reasonable agreement with the experimental data, thus confirming the prediction ability of the models. When salt type is treated as a third factor (factor C) besides salt concentration (A) and membrane porosity (B) some binary and ternary interactions were found significant for some salts.

1. Introduction

Several experiments in areas of engineering, medicine, and advanced industries are designed by involving the study of two or more factors on the response variable rather than the individual effect of a single factor. Full factorial design includes studying the effect of each factor (at some pre-set levels) on the response variable(s) in the experiment. Usually, two levels of each of k factors are considered in the experimental study, which results in what's called a 2^k factorial design. In the case of an experimental study where two levels are selected for each of two factors, the single replicate factorial design involves four combinations of treatments (runs).

Factorial designs have several advantages over the one-factor-at-a-time experimental approach [1]. They have higher efficiency compared to the one-factor-at-a-time-experiments, i.e., for the same level of accuracy, number of factorial experiments is less than that for one-factor-at-a-time runs. Factorial designs are also necessary when interactions between factors are significant to avoid misleading conclusions related to the main effects of the involved factors. In the case of experiments involving many (probable) input variables, factorial design is extremely valuable as a screening methodology for the important factors from those of less importance. This makes it an invaluable tool in the field of membrane desalination, where focused experiments can be designed following a general (screening) factorial design analysis. Finally, factorial designs result in conclusions that are valid over a wide range of experimental conditions.

Factorial experimental design is widely implemented in a variety of applied research areas [2–13]. As an example, a factorial experimental

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Nomenclature

AGMD	Air gap membrane distillation
ANOVA	Analysis of variance
C_j	Factor contrast
COD	Chemical oxygen demand
df	Degrees of freedom
E_j	Factor effect
f	Degrees of freedom
FD	Factorial design
MD	Membrane distillation
PEG	Polyethylene Glycol
SS	Sum of squares
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
x_i	Coded variable of factor i

Greek letters

β_i	Parameter related to factor i
β_{ij}	Parameter related to factors i and j
ε	Error
υ	Degrees of freedom

design with two factors and five levels for each was employed by Martin et al. [2] to study the effects of coagulant and flocculant dosages at a certain pH value in oily waste water on two response variables: chemical oxygen demand (COD) and soluble total organic carbon (TOC). Using the analysis of variance method (ANOVA), coagulant dosage was found to be the most influential factor on both responses for all pH conditions [3]. Moreover, response surface methodology contour plots were implemented for each response variable. For both factors at a certain pH level, the contour curves showed a considerable curvature for TOC, indicating a significant interaction between the two factors at that pH level. A factorial experiment was also designed in the filtration of oily water to study the removal of contaminants in batch and continuous systems [4]. Three levels (low, medium, and high) of two factors (packing density and flow rate) on two response variables (COD and turbidity) were employed in this study. Pareto charts were presented to describe the effect of each.

In membrane distillation processes, the requirement of optimization of the operating conditions is of extreme importance for improving membrane distillation processes. Factorial experimental design, therefore, finds growing interest in this evolving area of research. For example, Onsekizoglu et al. [14] used a two-level factorial design to study the effect of three major factor parameters, i.e., osmotic agent concentration of $CaCl_2$, flow rate, and temperature difference (ΔT) between osmotic agent and the feed, on two response variables: evaporative flux (J) and soluble solid content (SSC). Results using ANOVA showed significant effects of $CaCl_2$ concentration on evaporative flux and significant interaction between $CaCl_2$ concentration and ΔT. It was concluded that the most influential effect on both response variables was the main effect of $CaCl_2$ concentration. Polymeric membranes, which are considered as a potential substitute for some commercial microporous membranes [15,16], are currently in demand due to their special characteristics in MD processes. Factorial experimental design has been employed in the preparation processes of those membranes, where the main effects of the factors involved in the synthesis processes on certain response variables are investigated for their relative significance. Investigations of effects on pure water permeation flux, permeate flux, salt rejection coefficient were done by the analysis of variance (ANOVA) [15]. The factors studied include: copolymer and additive concentration, solvent evaporation time and coagulation bath temperature. From results of this study [15], the main effects of the three factors formed a direct proportionality with the salt rejection coefficient and an indirect proportionality with the permeate flux. Moreover, the main effect of Polyethylene Glycol (PEG) additive formed an indirect proportionality towards the three responses. The interaction between the factors in the regression model were omitted and not considered in the analysis.

In this work, a complete set of experimental data on air gap membrane distillation, that has been reported elsewhere [17] and also recently reproduced in [18], will be used in performing statistical analyses based on factorial design approach. That is, studying more than one factor for their main effects as well as for their interactions. Towards this objective: (a) permeate flux data for each salt, at two levels of salt concentrations (low (−) and high (+)) and two levels of membrane porosity (low (−) and high (+)) will be used in a 2^2 factorial design experiment, (b) permeate flux data for each salt, at three levels of salt

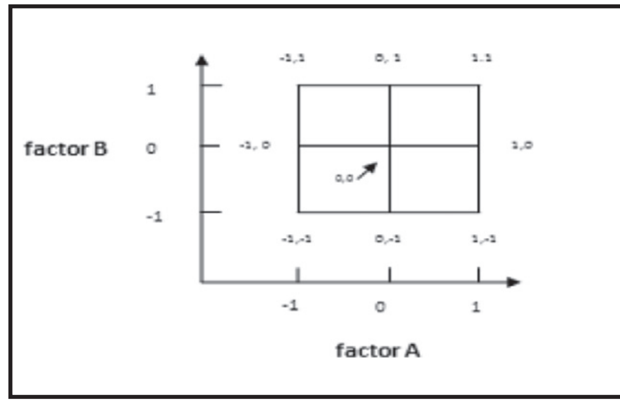

Fig. 2. Treatment combinations of the 3^2 factorial design.

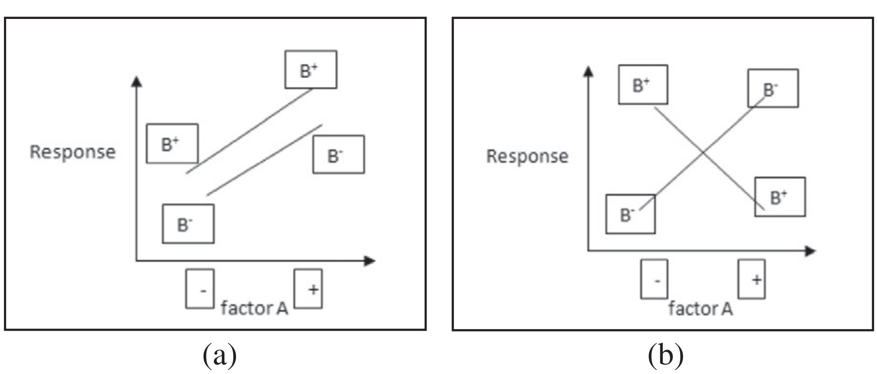

Fig. 1. Factorial design without (a) and with interaction (b) [1].