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Fuzzy Logic-Based Model for Prediction of Separation Percent of NaCl Solution Using Electrodialysis

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Fuzzy system is known to predict model in the electrodialysis process. This paper aimed to predict separation per cent of NaCl solution as a function of concentration, temperature, flow rate and voltage. A Sugeno type FL inference system was to model NaCl solution using electrodialysis. Besides, in the Matlab, ANFIS (adaptive neuro-fuzzy inference system) based on Sugeno fuzzy model, its structure was similar to neural network and could generate fuzzy rules automatically, using the error back propagation algorithm and least square method to adjust the parameters of fuzzy inference system. We obtained fitted values of separation percent by ANFIS. Separation per cent from experiments compared with the fitted values of separation per cent. The result is shown that the correlation coefficient is 0.988. Therefore, it is verified as a good performance in the electrodialysis process.

Key Words: Electrodialysis, Fuzzy system, Adaptive neuro-fuzzy inference system.

INTRODUCTION

Electrodialysis (ED) is a process that compares with reverse osmosis for desalination and the removal of inorganic contaminants. Electrodialysis is one such separation process in which ions are transported through membranes by the application of an electrical potential difference and as a consequence of a direct electric current. The technological importance of electrodialysis separation process has led to a number of studies concerning the application of cation-exchange membranes (CEM)as an attractive alternative to conventional unit operations for transport, separation and concentration of ions[1,2]. Electrodialysis is used mainly for the desalination of saline solutions producing concentrated brines and salt depleted water such as the production of potable water mainly from brackish water[3,4], seawater[5] and industrial water[6] sources. But in the electrodialysis process, separation per cent is hard to predict, for there is a non-linear relationship between a variety of influencing factors and separation per cent. In this paper, we use a Sugeno type FL inference system to deal with experimental data.

In recent years, fuzzy mathematics has greatly developed and permeated in many fields, such as, social sciences and natural sciences, even remarkable achievements on theory and practical application. Fuzzy logic was developed by Zadeh in 1965. Moreover, fuzzy logic is a multivalued logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, *etc*. Notions like rather tall or very fast can be formulated mathematically and processed by computers, in order to apply a more human-like way of thinking in the programming of computers.

Using fuzzy set theory allows the user to include unavoidable deviation of the data. Fuzzy inference is the actual process of mapping from a given set of input data to an output based on a set of fuzzy rules. There are four fundamental units in the application of any fuzzy modeling. These are, namely, the fuzzification unit, the knowledge base(which is composed of the database and the rule base), the inference engine unit and the defuzzification unit[7].

In the fuzzification unit, the input variables and output ones are fuzzified by thinking out convenient linguistic subsets such as hot, warm, big, small, heavy, light, *etc*. Moreover, separation of variables into groups is a difficult task. Various methods have been developed in the literature, such as the neural network-based method[8], the inductive learning[9], the genetic algorithm[10], the fuzzy clustering[11] and uses of statistics[12].

In the knowledge base unit, "if-then" fuzzy rules are built up based on the expert knowledge and/or available data. The rules make input and output fuzzy sets transform. Premise part input fuzzy membership functions (MFs) are combined interchangeably with a logical "and" or "or" a conjunction whereas the rules are combined with the logical "or" the conjunction.

In the inference engine unit, the implication part of a fuzzy system is defined as the forming of the consequent membership functions based on the membership degrees of the premise part.

In the defuzzification unit, the result shows as a fuzzy set is defuzzified to figure out a crisp value, which is asked for engineering applications[7].

Fuzzy inference system is built by fuzzy set theory, "if-then" fuzzy rules and fuzzy reasoning. Its membership functions are adjusted by reversed propagation algorithm and least square method and approach nonlinear functions with any arbitrary accuracy. Fuzzy inference system has many advantages, such as, fast convergence, minor error, fewer training samples. Therefore, it provides with important application values in the field of nonlinear system modeling and data processing.

To a certain extent, fuzzy sets allow some elements to belong to a certain set and this extent is depicted or described by a value which is called membership in the range of 0 to 1. Membership functions map from a specific element to an appropriate membership. Membership functions can form any shape of curves and which shape we choose depends on whether we use it simple, convenient, fast and effective or not and the unique constraint is the range of membership functions, namely, from 0 to 1[13]. This data processing used Gaussian membership function.

Takagi and Sugeno[14] proposed a T-S fuzzy model and later scholars called Sugeno fuzzy model, which was a nonlinear model and suitable to express dynamic characteristics of complex systems. It was the most useful fuzzy reasoning model. The typical fuzzy inference rule is:

$$\text{If } x \text{ is } A \text{ and } y \text{ is } B \text{ then } z = f(x,y)$$

where: A and B use as fuzzy numbers, $z = f(x, y)$ is the exact number. Usually, $f(x, y)$ is a polynomial which contains x and y. When $f(x, y)$ is a first-order polynomial, the model is called the first-order Sugeno fuzzy model (Fig. 1).

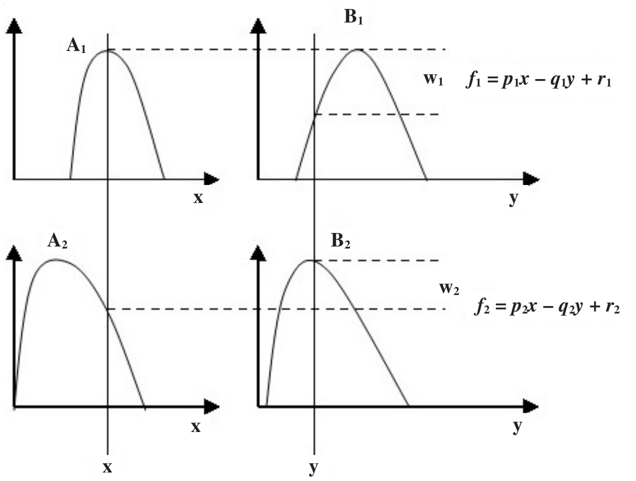


Fig. 1. First-order Sugeno fuzzy model

Rule 1: If x is A_1 and y is B_1, then $f_1 = p_1x + q_1y + r_1$

Rule 2: If x is A_2 and y is B_2, then $f_2 = p_2x + q_2y + r_2$

Fig. 1 is shown that inputs vectors [x,y], weights (w_1, w_2) are obtained by membership function μ values product and the output f is weighted average output of every rule[15].

EXPERIMENTAL

An analytical grade salt (99.5 % NaCl)and deionized water were used in all experiments to prepare solutions with wastewater qualities. This purpose of the experiments was to study the effects of temperature, voltage, flow rate and feed concentration on the electrodialysis cell performance.

Cell and membranes: Electrodialysis cell consisted of plexiglass (PMMA). Cell was made of three inseparable parts, a pair of cation and anion exchange membranes (CEM and AEM) and a pair of platinum electrodes(cathode and anode). The length, height and width of electrodialysis cell were, respectively 191, 181 and 21 mm. The effective areas of membrane and electrodes were both 90 mm × 110 mm. Room volumes of concentrate and dilute channel were respectively 120 mm × 100 mm × 6 mm and 120 mm × 100 mm × 1 mm.

Principle: Electrodialysis technology is one of membrane separation technologies. Now electrodialysis has been widely used in different fields for its high efficiency and low energy consumption. Under the direct electric field, electrodialysis technology utilizes the permeability of ion-exchange membrane to separate the electrolyte from the solution, with the potential difference, in order to realize the purposes of dilution, concentration or purification of the solution. Desalination process is mainly ions migration between solution and ion exchange membranes. Fig. 2 shows electrodialysis process of NaCl solution in an ideal ion-exchange membranes cell.

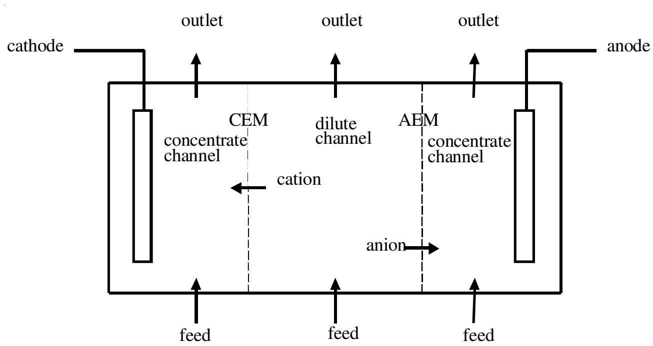


Fig. 2. Electrodialysis process principle

Design: This experiment used self-designed electrodialysis cell which was made of PMMA. Electrodialysis cell composed of two clamping devices (A,B) and a partition. The side of device A had two inlets and two outlets and the side of device B had an inlet and an outlet. Feed which was NaCl solution entered electrodialysis cell from three inlets which were under two clamping devices and discharged from three outlets which were the upper end of clamping devices. Feed was divided into two parts through the electrodialysis cell treatment: one part was dilute water and needed to measure flow rates and electrical conductivities of its outlet; the other was brine which recycled at outlet and needed to supply solution which was the same concentration as feed, then added to feed for reuse. The main process was shown in Fig. 3.

Experiments were carried out under limiting current density. It is believed that they have the greatest effect on electrodialysis: feed concentration, flow rate, feed temperature and voltage. Based on the full factorial design four factors were

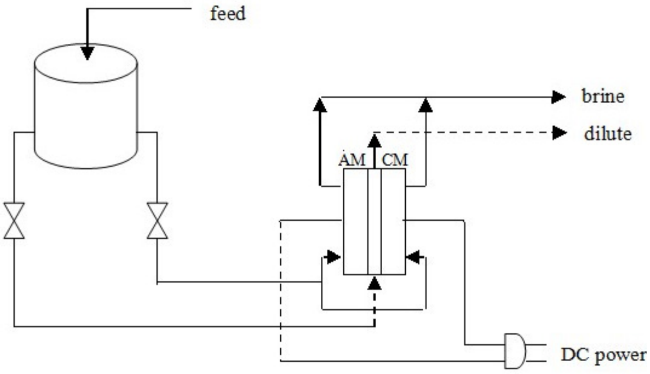


Fig. 3. Electrodialysis cell

studied: feed concentration (500, 1000 and 1500 ppm), flow rate (0.05×10^{-6}, 0.5×10^{-6} and 1.0×10^{-6} m^3/s), temperature (15, 35 and 50 º), voltage (2, 5 and 8 V).

Each experiment was lasted for 15 min to reach steady state condition. Samples were taken every 5 min and the average values were calculated.

RESULTS AND DISCUSSION

The main factors on separation percent were initial concentration C, voltage V, flow rate Q and temperature T. These factors regarded as inputs and separation percent SP was output, finally selected randomly 69 sets of data which considered as training samples and the remaining 12 sets were testing data.

In order to predict the results with high precision, maximum values made inputs defining new dimensionless subsets(for instance, voltage 2/8, 5/8, 8/8), then original data were between 0 and 1. Then, ANFIS algorithm trained and tested these data. Each input corresponded to two linear functions of Gaussian membership. ANFIS generated model structure (Fig. 4).

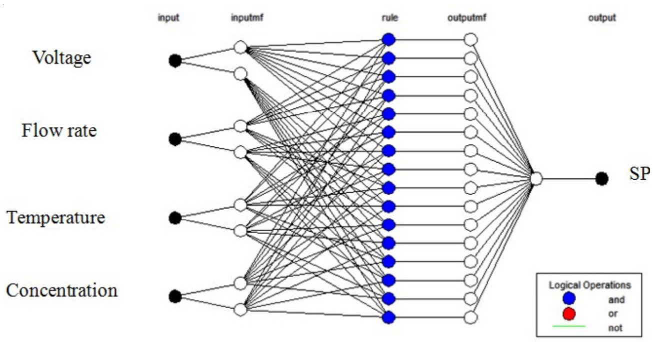


Fig. 4. ANFIS node structure

Testing groups of training data and test data was to solve the mean squared error (MSE), then set up an appropriate model. Mean squared error is calculated as follows:

$$\text{Mean squared error (MSE)} = \frac{\sum_{i=1}^{N}(SP_{cal,i} - SP_{exp,i})^2}{N} \quad (1)$$

Subscript "cal" and "exp" represent calculated and experimental values of SP. N is the quantities of test and training data. In statistics, R stands for the positive or negative direction of two variables linear correlation.

$$R = \frac{N\sum_{i=1}^{N}(SP_{cal,i} \times SP_{exp,i}) - \sum_{i=1}^{N}SP_{cal,i}\sum_{i=1}^{N}SP_{exp,i}}{\sqrt{N\sum_{i=1}^{N}(SP_{cal,i})^2 - \left(\sum_{i=1}^{N}SP_{cal,i}\right)^2}\sqrt{N\sum_{i=1}^{N}(SP_{exp,i})^2 - \left(\sum_{i=1}^{N}SP_{exp,i}\right)^2}} \quad (2)$$

R^2 can be positive values, ranging from $R^2 = +1.0$ for a perfect correlation (positive or negative) down to $R^2 = 0.0$ for a complete absence of correlation. The advantage of R^2 is that it can indicate the method of coefficient strength, namely, the closest to the line of best fit.

Another appropriate method is MSRE, the formula is as follows:

$$MSRE = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{SP_{cal,i} - SP_{exp,i}}{SP_{exp,i}}\right)^2 \quad (3)$$

According to the formula (1), (2) and (3) :

$MSE = 0.875$, $R = 0.977$, $R^2 = 0.988$, $MSRE = 0.00488$

During investigation of voltage, temperature, concentration and flow rate, we drew two curves, one curve was the correlation of voltage and SP in different flow rates and the other was the correlation of temperature and SP in the condition of different concentrations (Fig. 5). We could obtain nice fitting in the range of permissible errors.

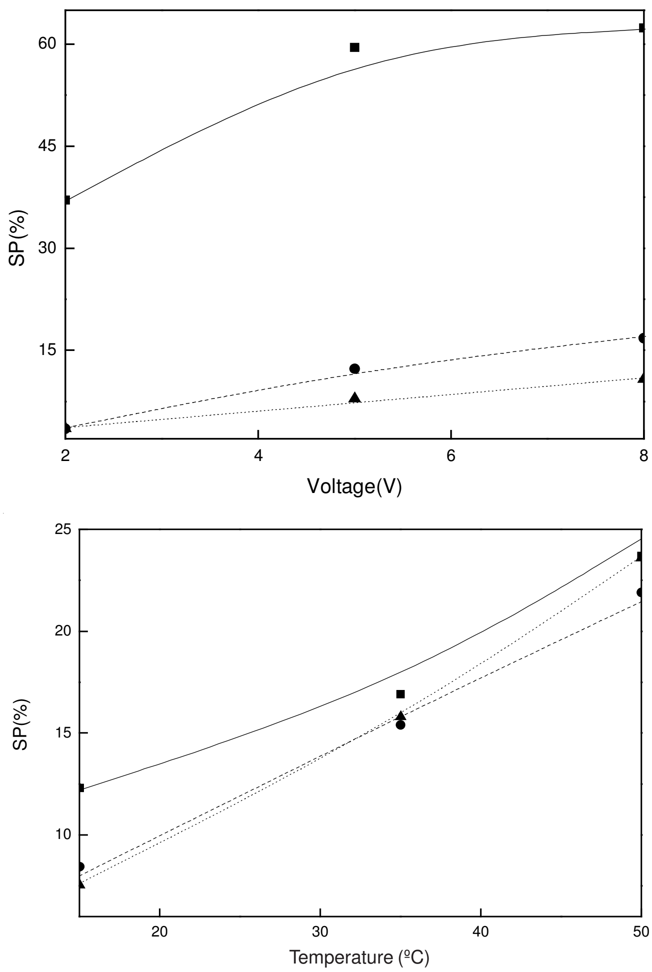


Fig. 5. Fitting effect of experimental and calculated values; –: Q = 0.05 mL/s, exp; ---: Q = 0.5 mL/s, exp; ···: Q = 1.0 mL/s, exp; ■: Q = 0.05 mL/s, cal; ●: Q=0.5 mL/s, cal; ▲: Q = 1.0 mL/s, cal

According to the results of experimental and calculated values, we plotted the correlation curves. Between experimental values and calculated values the closer diagonal, the better correlation we obtained. From Fig. 6 we could gain the neural network fit well.

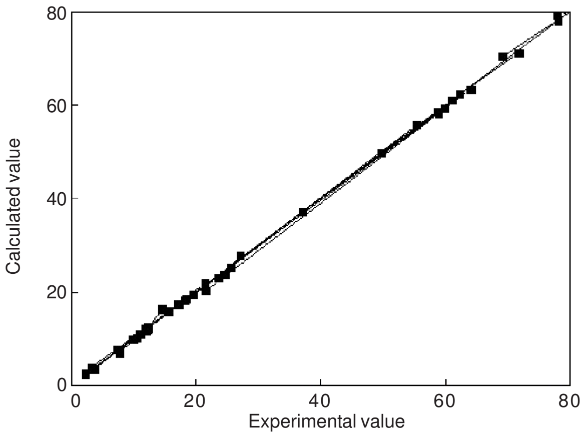
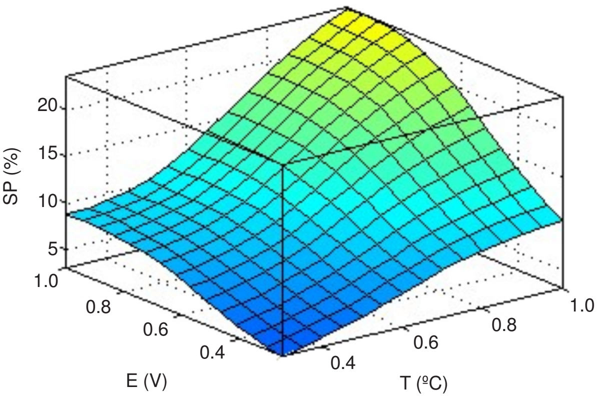


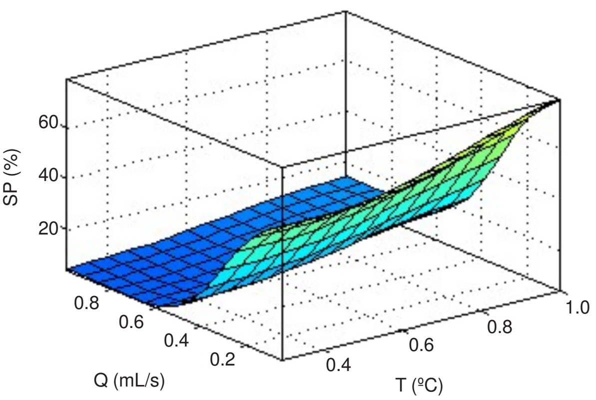
Fig. 6. Correlation of experimental and calculated values

Neural network predicted test data of multiple inputs. In 3D figure, the correlation of SP and different inputs is shown (Fig. 7).

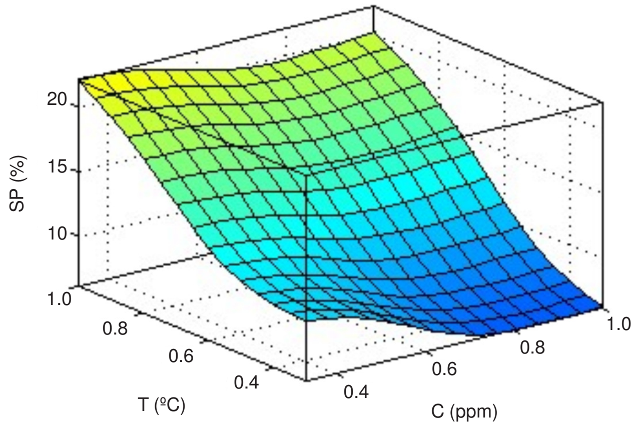
From Fig. 7(a-c), in the condition of increasing temperature, when flow rate and concentration decreased and voltage increased, SP would be added. In addition, from Fig. 7(b), (e) and (f), in the condition of decreasing flow rate, when temperature and voltage increased and concentration decreased, SP would rise.



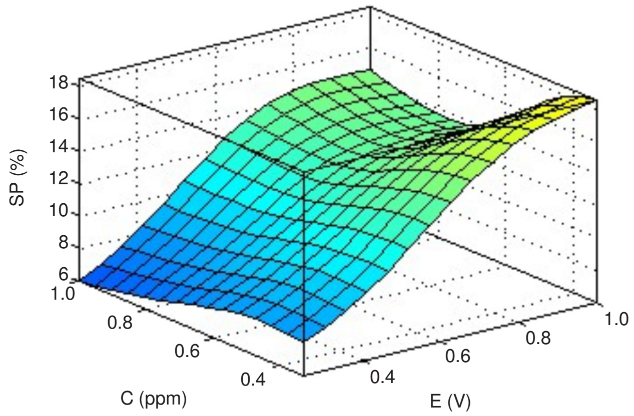
(a)



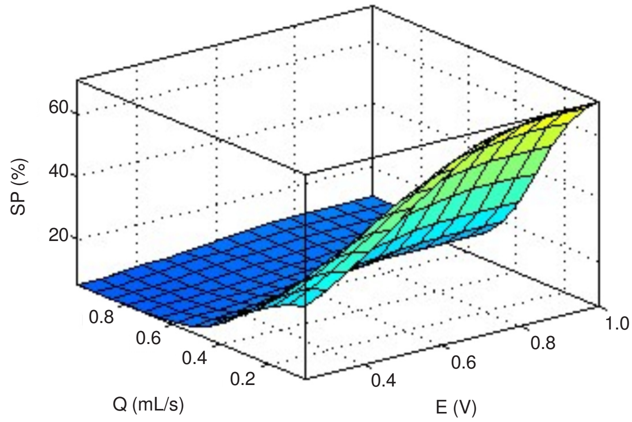
(b)



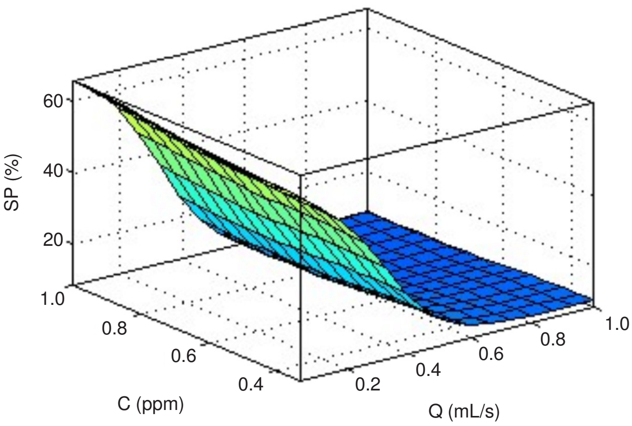
(c)



(d)



(e)



(f)

Fig. 7. Correlation of SP and different inputs

We found that voltage and temperature had the proportional correlation of SP, but concentration and flow rate had the opposite correlation of SP, this is because increasing temperature and decreasing concentration, resistance of solution decreases; adding to voltage is to enhance driving force of the technology. However, elevation of flow rate makes residence time shortened and ions which are between two membranes have not enough time to go through the ion exchange membrane, so the values of SP fall.

Conclusion

The experiment studied four factors (initial concentration C, voltage V, flow rate Q and temperature T) on the influence of electrodialysis cell. Along with the increase of voltage and temperature, SP value added. And as concentration and flow rate decreased, SP value still increased. Neural network was employed for prediction of electrodialysis. And a multilayer network was applied to predict SP of Na^+ ions in the dilute compartment of a laboratory scale electrodialysis cell. Neural network successfully tracked the nonlinear behaviour of SP versus voltage, temperature, concentration and flow rate with MSE, R, R^2, MSRE of 0.875, 0.977, 0.988 and 0.00488, respectively. Neural network modeling technique was found out to have plenty of favourable features such as efficiency, generalization and simplicity, which make it an attractive choice for modeling of complex systems, such as water treatment processes.

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