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Application of adaptive neuro-fuzzy inference system as a reliable approach for prediction of oily wastewater microfiltration permeate volume

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ABSTRACT

In this paper, ANFIS (adaptive neuro-fuzzy inference system) as a powerful tool for modeling complex and nonlinear systems, was used to predict permeate volume of oil/water membrane separation process. The data used for modeling the flux behavior consisted of three inputs (TMP, oil concentration, filtration time) and experimental permeation values as the output. First type gaussian membership function was used for fuzzification of input variables and hybrid algorithm was chosen for the learning method of input–output data. Very well agreements were observed between experimental and simulation results. From the results, the ANFIS can be used as a reliable tool for prediction of microfiltration systems' behavior. The coefficient of determination (R^2) between the experimental and predicted values was greater than 0.99 and the mean percentage error was less than 2%, showing the great efficiency and reliability of the developed model.

1. Introduction

Water consumption in industrial processes has resulted in production of potentially harmful wastewater for the environment. The discharge of oily wastewater creates a major ecological problem throughout the world. This unfavorable side-product is considered to be hazardous because it contains toxic substances that are repressive toward plant and animal growth and mutagenic and carcinogenic to human being, thus treatment of oily wastewater is of great importance [1–3]. Industrial wastewaters are mostly generated in oil refining and distribution processes, chemical and petrochemical plants, metal working plants and food production facilities [4–7].

Conventional oily wastewater treatment methods such as gravity separation [8], dissolved air floatation [9], adsorption [10] and biological treatment [11] have several disadvantages like low efficiency, high operation costs [12]. Moreover, these methods are not effectual in small oil droplets and emulsions removal. These disadvantages caused the development of new processes for oil/water separation [4].

Membrane technology is vastly applied in many industries and has successfully been utilized in oil in water treatment over the past years. Membrane separation processes have been growing rapidly and gained significant progress due to higher water quality requirements. Membranes are direct water–oil separator, need no additive and cause no phase change. In spite of low operation costs and energy consumption, they are more effective in dealing with emulsified and smaller oil droplets and have higher oil removal rate in comparison with other conventional methods [4,6,13–15].

Modeling of systems and experimental processes are of fundamental importance in all fields because models enable us to understand, analyze, simulate and even predict the behavior of a particular system [16]. Due to the complex nature of membrane separation systems, the development of analytical models is a challenging and time consuming process and also lacks accuracy in simulation [17].

An adaptive neuro-fuzzy inference system (ANFIS) is a multilayer feed-forward network, which is a hybrid of two powerful (ANN & FIS) intelligent systems. This methodology does not need the explicit expressions of the physical meaning of the system or process understanding. An important property of an Artificial Neural Network (ANN) is generalization. It is very efficient and adaptive; however, it has the negative attribute of "black box". A Fuzzy Inference System (FIS) performs a nonlinear mapping from its input to output space. It is not effective in learning but grants the advantage of approximate reasoning. ANFIS combines the computational power of ANN with the

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Table 1
Statistics summery of the experimental data sets.

Statistical parameter	Variable			
	Oil concentration (ppm)	TMP (bar)	Filtration time (s)	Permeate volume (m^3/m^2)
Min	1000	0.5	0	0
Max	20,000	2	4200	0.20254
Mean	9000	1.25	975	0.02345
Stdev	7106	0.55902	1109	0.02796
Number of data	750	750	750	750
Number of missing data	0	0	0	0

remarkable reasoning capability of FIS. It has the advantages of both systems and none of their disadvantages because ANFIS is adaptive and unlike black box systems modifications can be made according to user's preferences, which makes it the finest function approximator among various neuro-fuzzy models [16,18–21]. In comparison with other models, ANFIS has the maximal training speed and the most efficient learning algorithm to deal with nonlinear and complex systems such as the membrane separation process [5,22–24].

In recent years, ANFIS has successfully been utilized for modeling and simulation of various kinds of membrane process. Sargolzaei et al. [22] used intelligent systems including ANFIS to predict the starch removal performance of a food processing company's wastewater using polyethersulfone membrane. ANFIS represented more accurate prediction of permeate flux and rejection factor of the membrane among other techniques. Salahi et al. [5] utilized ANFIS as a model to predict the permeation flux in ultrafiltration of oily wastewater. Filtration time, TMP and cross-flow velocity (CFV) were considered as input, whereas permeate flux was set as the output and the second type of gaussian membership function was used for fuzzification of input variables. The simulation was carried out, which resulted in good agreement of the model and experimental data. Vural et al. [23] used ANFIS model for performance prediction of a proton exchange membrane fuel cell. The purpose of their study was to predict the fuel cell voltage on different operating condition. Mean absolute percent error was measured during training as an indication of the model performance, which confirmed ANFIS capability to simulate complex membrane process. Due to high costs associated with hydrogen measuring equipment, Becker et al. [25] utilized ANFIS as a predictive model for proton exchange membrane to simulate hydrogen flow rate. The accuracy of the model was appraised using statistical techniques such as root mean square error. ANFIS model was found to be reliable predictive tools with excellent accuracy of 3% compared with experimental data. Rahmanian et al. [26] proposed ANN and ANFIS for permeate and rejection prediction of micellar-enhanced ultrafiltration of lead ions from aqueous solution. Coefficient of determination values proved that both models were highly efficient in simulation; however, ANFIS responded more accurately and rapidly.

In this study, the application of ANFIS, as an exquisite learning tool for modeling complex systems was explored in order to achieve the lowest prediction error, fastest computation time and develop the most efficient model to cope with the given data. Experimental investigation of microfiltration of oily wastewater as several sets of input–output data was fed to ANFIS in order to learn the mechanism of the separation system and generate a flawless simulation to predict the outcome of separation. TMP, oil concentration and filtration time was measured during the experiment as the input and permeation volume of water was tracked as the output of the system. Highly efficient model was developed by adjusting the ANFIS properties (type and number of membership functions) appropriately, so the best fit to the experimental data is reached.

2. Experimental data

The experimental data of Fouladitajar et al. [27] has been used for training and validation of the developed ANFIS model. The microfiltration membrane used in the study was a porous hydrophilic polyvinylidene fluoride (PVDF) flat sheet (Millipore Co., 0.45 μm nominal pore size, 125 μm thickness, porosity 70%, and effective membrane area 50 cm^2). The filtration process was carried out under four different transmembrane pressures (TMPs) (0.5, 1.0, 1.5 and 2.0 bar) and four different oil concentrations (1000, 5000, 10,000 and 20,000 ppm). Permeate volume values for a wide range of filtration time (from 1 to 70 min) was obtained during the examination. The statistical parameters if inputs and output variables are presented in Table 1.

2.1. Theory

Fuzzy logic (FL) [28] is a well-known computational technique that replaces numbers with linguistic variables [29] for better computing and reasoning. Fuzzy systems are built from a number of if-then rules and membership functions (MF) that determine the relation between the input–output variables. These rules and membership functions are defined by using either human insight or data derived from the system [30]. Considering the lack of expertise in the field and nonlinear and complex nature of the membrane separation process, designing a fuzzy system based on human experience is costly and lacks accuracy. Therefore, experimental data was used to adjust the system parameters [24].

ANFIS is a Sugeno-type [31] multilayer feed forward network that maps connections between the input–output data via a learning algorithm to adjust the parameters of the fuzzy inference system [19]. ANFIS approach is fundamentally a fuzzy logic system where its parameters are optimized through neural network training. This adaptive technique benefits from the learning ability of ANN in order to determine the rules and membership functions of the FL system [24].

The goal here is to construct a network for accomplishing desired nonlinear mapping that is arranged by a set of data that includes several input–output pairs of the target system. This data

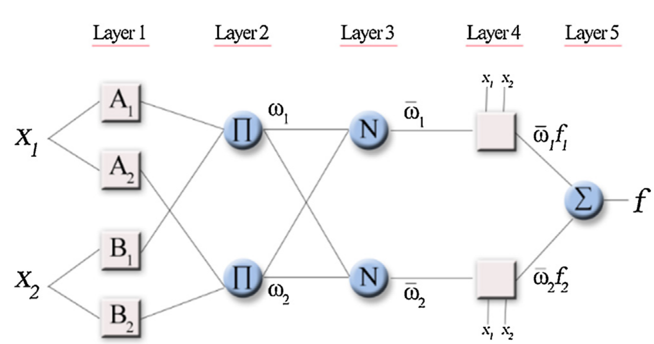

Fig. 1. ANFIS architecture with two inputs, two rules and one output.