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Modeling and optimization of cross-flow ultrafiltration using hybrid neural network-genetic algorithm approach

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ABSTRACT

Precise modeling flux decline under various operating parameters in cross-flow ultrafiltration (UF) of oily wastewaters and afterward, employing an appropriate optimization algorithm in order to optimize operating parameters involved in the process model result in attaining desired permeate flux, is of fundamental great interest from an economical and technical point of view. Accordingly, this current research proposed a hybrid process modeling and optimization based on computational intelligence paradigms where the combination of artificial neural network (ANN) and genetic algorithm (GA) meets the challenge of specified-objective based on two steps: first the development of bio-inspired approach based on ANN, trained, validated and tested successfully with experimental data collected during the polyacrylonitrile (PAN) UF process to treat the oily wastewater of Tehran refinery in a laboratory scale in which the model received feed temperature (*T*), feed pH, trans-membrane pressure (TMP), cross-flow velocity (CFV), and filtration time as inputs; and gave permeate flux as an output. Subsequently, the 5-dimensional input space of the ANN model portraying process input variables was optimized by applying GA, with a view to realizing maximum or minimum process output variable. The results obtained validate the estimates of the ANN–GA technique with a good accuracy. Finally, the relative importance of the controllable operation factors on flux decline is determined by applying the various correlation statistic techniques. According to the result of the sensitivity analysis based on the correlation coefficient, the filtration time was the most significant one, followed by *T*, CFV, feed pH and TMP.

1. Introduction

The yearly increasing amount of the produced wastewaters by various industries, especially oil refineries, could cause grave ecological problems throughout the world. This environmental concern makes wastewater treatment a very crucial issue in the oil refineries. Among the existing treatment techniques, membrane processes have become important approaches and used dramatically in recent years [1] because their efficiency has been proven from a technical and economical, as well as an ecological, point of view [2]. Investigation of the membrane separation processes for oily wastewaters treatment has been emerged since 1973 [3]. Membrane-based separation processes, particularly microfiltration (MF) and ultrafiltration (UF) processes are proving to be promising alternatives for conventional industrial separation methods, due to enjoy numerous advantages such as high selectivity, easy separation, mild operation, continuous and automatic operation, no extraneous chemicals are needed, economic and fast operation, as well as relatively low capital and running investment [4–7].

Nonetheless, the major drawback associated with cross-flow UF membrane-based separation process that precludes the widespread use of this process is the decline in permeate flux during operation, especially in the filtration of wastewater which change the membrane performance in a negative way, attributable to the concentration polarization and membrane fouling. Hereby, in-depth analysis of flux decline phenomena is very vital for accomplishment of efficient and economical process design in order to scale up the membrane systems. It should be noted that flux values in a cross-flow UF process extremely dependent on various process variables such as CFV, TMP, kind of membrane (pore size and chemical composition, etc.) and physico-chemical properties of feed streams. Presently, quantification of the effects of basic parameters such as CFV, TMP, temperature, pH, molecular size of solutes, etc. on membrane fouling, which cause the decline in permeate flux, in UF is not completely understood. Accordingly, technologically and economically speaking, developing a robust dynamic predictive/simulative modeling of permeate flux decline

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Nomenclature

Acronyms

ANN	artificial neural network
API	American petroleum institute
FFNN	Feed-Forward Neural Network
GA	genetic algorithm
MSE	mean square error
MSRE	mean squared relative error
MWCO	molecular weight cut off
NMSE	normalized mean squared error
PV	pervaporation
PAN	polyacrylonitrile
PES	polyethersulfone
PS	polysulfones
PP	polypropylene
PVDF	polyvinylidene fluoride
SEM	scanning electron microscopy
SSE	sum-squared error
TOC	total organic carbon
TSS	total suspended solids

Symbols used

A	membrane area (m^2)
b	threshold (bias)
CFV	cross-flow velocity(m/s)
J	filtration flux (L/m^2 h)
N	number of data points
o	neuron's output
pH	(–)
S	neuron's net input signal
t	Filtration time (h)
T	temperature (°C)
TMP	trans-membrane pressure (bar)
V	filtrate volume (L)
w	weight
x	input signal (vector)

Greek symbols

φ	activation function
σ^2	variance of experimental data

Subscripts

j	input j
k	kth hidden neuron in first layer
m	number of neuron in the input layer

in cross-flow UF membrane filtration is of fundamental importance issue.

Currently, a completely knowledge-based approach (parametric or theoretical model) quantitatively approved, in which the detailed knowledge of the mass, momentum, and energy balances, and other chemical engineering principles, is a necessity [8], is not available that describe UF process dynamics very accurately, which is needed by engineers in design, simulation and operation of such processes [3,9] because the accuracy of theoretical modeling has been hampered by insufficient understanding regarding the complexity of the microscale phenomena occurring during the filtration processes [10] and also the model becomes mathematically complex and computationally intensive, and large number of experiments needed to acquire the requisite process data [8]. Moreover, the effects of process conditions on permeate flux and its dynamic behavior is usually non-linear in nature that poses additional difficulties for the development and solution of the resultant non-linear theoretical models [8].

Thus, it becomes necessary to explore alternative approaches to the parametric models which are based on fundamental knowledge of the process. Hereby, in such circumstances it is preferable to employ non-parametric methods such as computational intelligence paradigms, to represent such a complex relationship.

Recently, ANNs have been found to be potentially reliable and attractive tools for the steady state/dynamic process modeling in circumstances where the development of the theoretical or classical regression models becomes either impractical or cumbersome [8]. This is mainly owing to its capability to model ill-defined, vague, and non-linear issues [11]. It should be noted that an important feature of this methodology, as a subclass of non-parametric methods, is that it does not require much theoretical knowledge or human experience during the training process. Therefore, prior knowledge about what happens during the process such as the intrinsic nature of membranes, the effect of environment, the behavior of particles being separated and the complex nature of cake layer that forms during filtration and its dependence on hydrodynamic and electrostatic phenomena [12] is not required and the model is trained exclusively on the basis of the experimental data. Definitely, ANNs, as one of renowned examples of computational intelligence approaches, have received considerable research attention in many membrane processing applications [13], especially when the focus is placed on predicting the flux decline [10,12,14–32]. The ANN application of the findings of these articles is summarized in Table 1.

Utilizing an appropriate optimization paradigm in combination with the process model is very useful and helps designers to discern optimal process input parameters result in maximization or minimization a specified-objective function. There are a number of important requirements (such as smoothness, continuity, and differentiability criteria) that the objective function should simultaneously satisfy while employing most of deterministic gradient-based methods. Although it is possible to write the closed-form expression of the input–output relationship approximated by ANN, the mapping executed attains a complicated non-linear feature that cannot be guaranteed to simultaneously meet the smoothness, continuity, and differentiability criteria for the objective function [8,33]. Therefore, it becomes necessary to explore optimization paradigms that do not impose strict preconditions on the form of the objective function.

GA, which is stochastic population-based search method for an optimal solution to a given problem, can be considered as a viable alternative to conventional deterministic techniques and potential candidate for optimizing the ANN-based models, on account of its efficacy does not hampered by the features of the objective function with great severity. According to the literature [8,34], the key features of GAs are as follows (i) they require only scalar values and not the second- and/or first-order derivatives of the objective function; (ii) they are capable of handling non-linear and noisy objective functions; (iii) they perform global searches and thus are more likely to arrive at or near the global optimum; (iv) they do not impose preconditions, such as smoothness, differentiability, and continuity, on the form of the objective function. These attractive features extend GAs ability to a wide range of applications.

The ANN–GA methodology is a robust modeling and optimization formalism for complicated processes and may be superior to other methods such as the response surface methodology [34,35] as, several researchers successfully utilized the ANN–GA to get