AN OVERVIEW OF FOULING MECHANISMS, PREDICTION AND MITIGATION STRATEGIES FOR THERMAL DESALINATION PLANTS

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ABSTRACT

Despite technological advances of several desalination processes such as reverse osmosis, still considerable proportion of installed units are thermally driven processes which their efficiency can severely be reduced by the formation of fouling deposits on heat transfer surfaces. For many years, it has been practical strategy to avoid fouling rather than facing it. Some of these strategies are operating units at relatively low temperatures to prevent the supersaturation of saline waters, over-design of heat exchangers or over-dosage of antiscalants. Nonetheless such practices are now under scrutiny due to new environmental regulations and high costs of fuels and operation. This paper endeavours to address some of these concerns by highlighting governing fouling mechanisms and introduce some revolutionary prediction methods as well as new online mitigation methods and surface treatment based on ion implantation or sputtering techniques.

Keywords: Fouling, Scaling, Desalination, calcium phosphate and sulphate deposition

INTRODUCTION

The world faces an increasingly water crisis in recent years though more notably in arid regions and the present analyses do not present any better outlook for the future. A UN report [1] on sustainable water supply estimated that today more than 2 billion people are affected by water shortages in over 60 water scare countries (with less than 1000 m^3/y per capita). This has been in addition to the fact that per capita water supplies decreased by a third between 1970 and 1990. Much of the blame for global freshwater shortages, if not all, should be burdened by human activities as well as climate change that are categorically shown in Fig. 1.

The perspective particularly in the Middle East and North Africa is even gloomier where freshwater is already less than 1% of the world total accessible freshwater resources. Moreover, the quality of existing freshwater resources has badly been deteriorated which led to gradual increased in costs of freshwater production. This has resulted in giving new impetus to the widespread use of desalination plants.

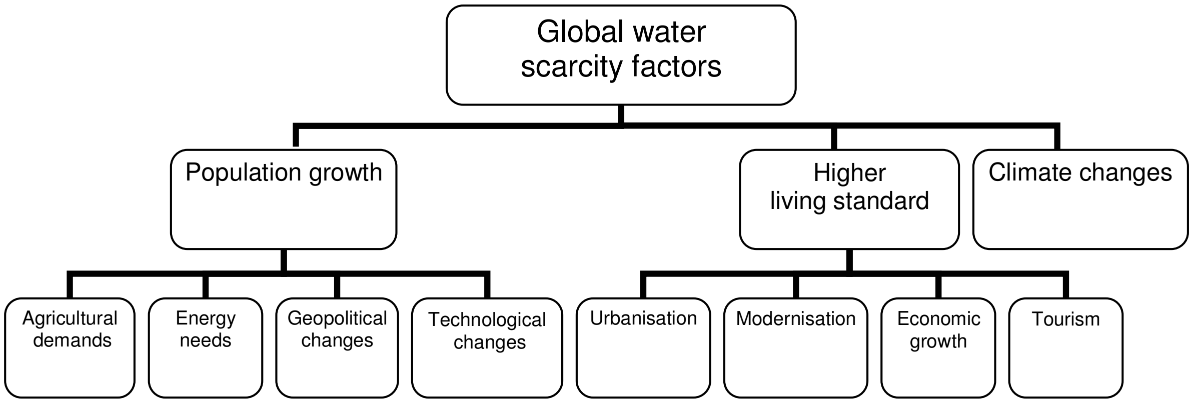

Fig. 1 Factors that led to global water scarcity.

Desalination is an old technique to convert saline water (e.g. seawater, brackish water or treated wastewater) into freshwater. The driving forces for desalination are either heat and mass transfer, or osmotic pressure as well as ionisation techniques. The Thermal driven units have been in existence for several hundreds years, if not thousands, but frequently considered as an expensive luxury technique due to high operational costs. It was only up to the past few decades that due to the increased demand for more potable water with the dramatic decline in the production costs due to tangible technological advancement, that helped its large scale commercial plants into realisation.

Fig. 2 categorises current approaches which are frequently being used for the desalination of seawater or brackish water. The first row generally divides energy resources into renewable and non-renewable energies. The second layer categorises different fuels and energies that could be utilised for conversion of saline water into potable water based on energy-driven resources stated in the preceding layer. In the latter row, three different techniques are visibly distinguished by the mechanisms that are used for water desalination. These are heat and mass transfer techniques such as MED, MSF and VC; chemical-physical techniques such as osmosis pressure or ionisation such as RO or ED; and finally a combination of some these techniques known as hybrid desalination units such as membrane-distillation which is still in research pilot stage.

The selection and utilisation of each of these methods are bound to pros and cons and depending upon numerous factors. For instance, parameters such as energy price and its availability, capacity of freshwater demand, socio-economical factors, environmental hazardous may have to be considered before a desalination technology could be picked up. Albeit, at present, RO emerges as leading and dominant technology trend, nevertheless 40-50% of installed desalination plants are still thermally driven units [2], though other reports show even higher share for thermal processes [3-4]. In addition, despite the technological superiority of RO, there are many instances where thermal desalination units are still economical due to cheap fuels or disposed energies in power plants which could be used in thermal water treatment processes.

The formation of deposit layer occurs in all desalination processes in spite of various pre-treatments which could cause substantial efficiency and production losses. For instance, Hanlon [5] reported that in a one million gallon/day desalination plant under normal concentration conditions a maximum of about 1400 kg calcium carbonate may be precipitated each day. Generally, fouling is faster in RO processes and easier to clean while in thermal processes it takes longer to form and harder to remove. Such characteristics are strong function of mechanisms that govern the fouling processes. This paper endeavours to give an update overview on the following topics in thermal desalination units:

- Dominant fouling mechanisms in thermal desalination plants such as crystallisation in form of $CaSO_4$ and $CaCO_3$ deposits and biofouling.
- Advanced numerical and phenomenological models to predict fouling behaviour e.g. computational fluid dynamics and intellectual correlation methods.
- Online mechanical mitigation strategies.
- Physical mitigation methods (surface treatment) i.e. modified ion implanted and sputtered surfaces and texture effects.

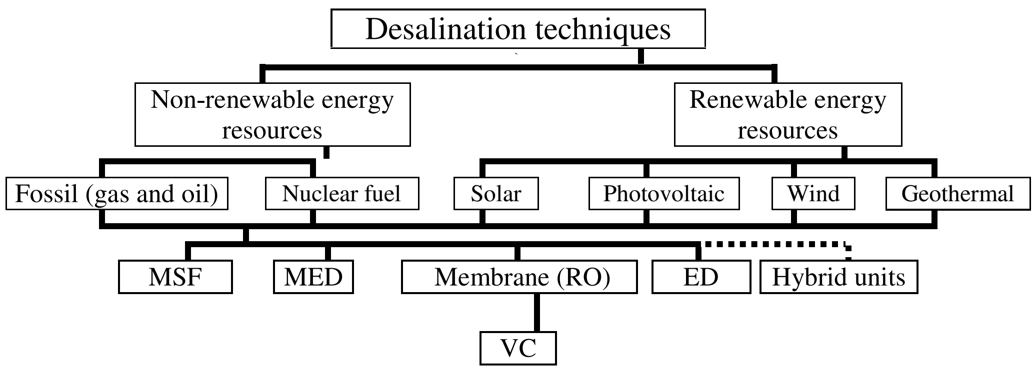

Fig. 2 Classification of different desalination units based on various energy resources.

ED	**E**lectro-**D**ialysis
MED	**M**ulti **E**ffect **D**istillation
MSF	**M**ulti **S**tage **F**lash
RO	**R**everse **O**smosis
VC	**V**apour **C**ompression

FOULING PROBLEM IN THERMAL DESALINATION UNITS

The utilisation of thermal desalination plants could severely be restricted due to:

1. Fouling and corrosion as a result of the deposition of unwanted materials on heat transfer surfaces.

2. Low efficiency on account of poor performance of energy conversion in plants such as MED and MSF and the old technologies that have been in practice for heat transfer and condensation.
3. Environmental impacts owing to green-house emission as a consequence of poor energy conversion and discharge of anti-foulant chemicals (fouling inhibitors).

Among these, the impact of deposit formation is far more severe which also could significantly influence the latter two causes. Thermal desalination in comparison to those of membrane desalination plants invariably faces a higher corrosive medium under usually extreme thermal conditions. Consequently, fouling has been major obstacle in operating thermal desalination units above 90^{o}C, a boundary that above this range the heat transfer efficiency is much higher. Apart from the seawater, the surface materials also have to operate in extreme conditions during chemical cleaning (removal of deposits). Fouling problems are one of the major reasons why MSF replaced MED in new desalination plants in the 1960s.

From economy point of view, the formation of process-related deposits on heat transfer surfaces bears an estimated enormous price tag of about 0.25% of the GDP of industrialized countries [6-7]. It also occurs in the majority of industrial heat exchangers (see Fig. 3). The cost of fouling is usually made up of heat exchanger over-design, fluid treatment, additional hardware, maintenance, shutdown, and cleaning, because only a combination of these measures will effectively reduce the fouling problem. In recent years, the importance of this phenomenon has received further attention due to the increasing cost of energy, climate changes as a result of energy conversion processes, technical advancement requiring more efficient thermal management, changes in the nature of feed materials and the adoption of restrictive environmental legislation.

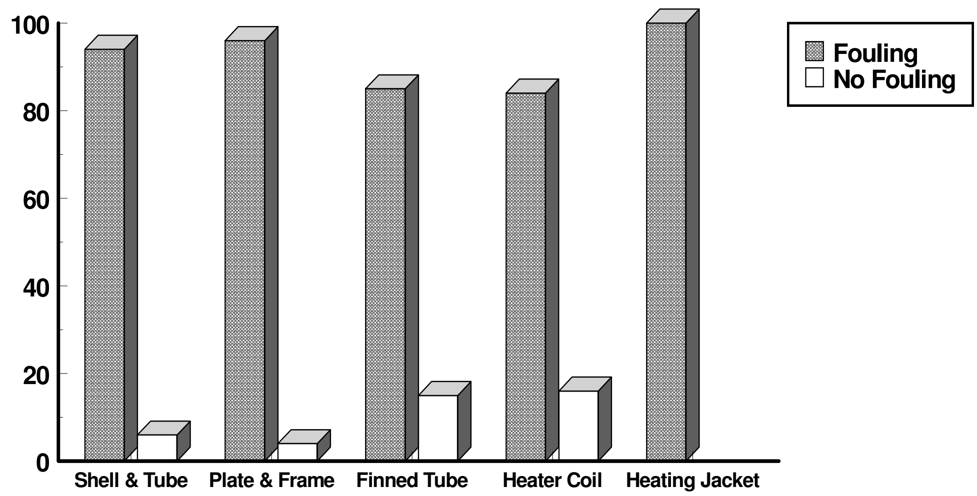

Fig. 3 Fouling problems in various heat exchanger types [7].

FOULING BEHAVIOUR AND MECHANISMS

Under Heat transfer fouling conditions, unwanted materials deposit on heated surfaces either from inorganic solutions with inverse solubility with temperature such as $CaSO_4$ and $CaCO_3$ when they become supersaturated or organic species in terms of biofouling. The deposit layer, with low thermal conductivity, decreases the overall heat transfer coefficient which may further lead to significant loss of thermal exchange capacity. Fouling generally behaves as a non-linear and unsteady-state process of an extremely complicated nature. It involves a considerable number of independent variables with poorly understood interaction. Some of these parameters are:

-Surface temperature
-Bulk temperature
-Bulk composition and chemistry
-Fluid velocity and turbulence
-Physical properties of the working fluid (viscosity, density)
-Surface specifications (material, surface finish and roughness)
-Physical properties of the deposit (density, thermal conductivity, stickability)
-Solubility equilibrium
-Chemical kinetics (chemical reaction)

Fouling is generally characterised in terms of a fouling resistance, R_f, which is a time-dependent function of the overall heat transfer coefficient U according:

$$R_f = \frac{1}{U_t} - \frac{1}{U_0} \tag{1}$$

The subscripts "t" and "0" denote conditions at any time and at the beginning of the experiment, when the heat transfer surface is considered to be clean. Based on this definition, the solid deposit per unit surface area of the fouling layer can be expressed as:

$$m_f = \rho_f \lambda_f R_f \tag{2}$$

If the density (ρ_f) and thermal conductivity (λ_f) of the fouling layer remain constant, R_f is thus directly proportional to m_f. This, already, is a fairly dubious assumption.

Usually, the deposition process is accompanied by a removal process due to the shear forces exerted by the fluid flow. The presence of particulate solids in the crystal lattice of the fouled layer, the increase of the thickness of the deposit and thermal stresses due to temperature gradients/transients make the fouling layer more fragile and accelerate the removal rate. The net rate of increase of the fouling layer is therefore:

$$\frac{d\,m_f}{d\,t} = \frac{d\,R_f}{d\,t}\left(\rho_f \lambda_f\right) = \dot{m}_d - \dot{m}_r \tag{3}$$

Subscripts “d” and “r” refer to deposit and removal, respectively. Under stagnant conditions where the fluid velocity is zero, the removal rate tends also to be negligible.

In addition fouling can occur due to different mechanisms in thermal desalination plants according to physical/chemical processes as described below:

Precipitation/crystallisation fouling is the prime fouling occurrence in thermal desalination units. It may occur on heated surfaces due to the presence of dissolved inorganic salts with inverse solubility with temperature under supersaturation conditions. In cases in which the deposit is a dense crystalline mass of inorganic salts especially for water, it is referred as scaling. Two prime chemicals that primarily, responsible for scaling, are $CaSO_4$ and $CaCO_3$. There are large of investigations that studied the fouling behaviour of each salt separately or as mix salt.

For each separate solution, investigations showed substantial influence of surface temperature, concentration, pH, and velocity. The major difference between the two salts is the effect of solubility index and surface temperature due to distinctive behaviour of solubility curves in which the calcium carbonate solubility increases after certain temperature. Helalizadeh et al. [8] investigated the precipitation fouling for mix salts. They found that deposit species do not necessarily precipitate entirely sequentially and independently of each other. The competitive precipitation may only take place the saturation index from the highest value to the lowest one. Moreover, there is a competition between ions for deposition, especially at higher degrees of supersaturation. This may be of particular interest in thermal desalination units which are often operated under 80-90^{o}C where calcium carbonate is the dominant deposition component.

Biofouling is referred to the development of organic films on heat transfer surfaces. It results from 1) microorganisms and their products (microbial fouling), 2) deposition and growth of macroorganisms such as barnacles, and c) assorted detritus. It can be seen in Table 1 that fouling resistance of biofilms is much less than calcium sulphate and calcium carbonate. The impact of fouling as heat transfer resistance can be realised when such data is compared with conductivities of stainless steel of 18 and copper of 400 W/mK, respectively.

Table 1 Thermal conductivity of typical deposits in thermal desalination plants [9].

Calcium Carbonate	2.9 W/mK
Calcium Sulphate	2.3 W/mK
Biofilm	0,7 W/mK

PREDICTION OF FOULING BEHAVIOUR

Several approaches are presently followed for the prediction of fouling behaviour. These may include, in order of decreasing practical application and increasing fundamental understanding:

1. Tabulated, time-independent fouling resistances (i.e. TEMA tables)
2. Rules of thumb (i.e. 25% overdesign)
3. Bench scale measurements under accelerated conditions
4. Empirical/ semi-theoretical correlations based on laboratory experiments
5. Numerical simulations (i.e. CFD)
6. Non-parametric function approximation methods
7. Application of the DLVO-theory to predict the deposit/surface interaction

1. Constant Fouling Resistances

The majority of heat exchangers today are designed using the 100 or so TEMA fouling resistances for tubular heat exchangers, which were first published more than 50 years ago. The application of these values has since been frequently criticized for a number of reasons, last but not least because they may lead to excessive and unnecessary overdesign. In the worst case, this may even lead to accelerated and enhanced fouling. The application of the TEMA fouling resistances does not consider any effects of operating conditions (flow velocity, temperature, foulant concentration) or flow geometry (baffles, corrugations) on the extent of fouling. Similar conclusions may be drawn for proportional overdesign.

2. Empirical/ Semi-Theoretical Correlations

Phenomenological/empirical models based on laboratory or pilot plant measurements may be useful as long as the actual fouling process is not significantly different in any major aspect. However, extrapolation to different conditions or general predictions are not possible, because the physical phenomena underlying fouling are so many and complex. They involve the physics of nucleation of crystals on the heat transfer surface, the chemistry of two-phase solid/liquid interfaces, the determination of local chemical, thermodynamic and hydrodynamic conditions. The wide range of possible processes has, even for scale formation alone, led to a substantial number of suggested models and correlations, which all include several simplifications and assumptions, and which often predict significantly different values and even trends.

For example, Jamialahmadi and Müller-Steinhagen (2003) compared the predictions of some of the more well-known models with experimental data for calcium sulphate and calcium carbonate which the dominant fouling species in thermal desalination units, as shown in Figures 4 and 5, respectively. Even though scaling data used for comparison and modelling have been for single component fouling under carefully controlled laboratory conditions in each case, the predicted trends and values vary quite substantially. Not the least of the many difficulties in the modelling of scaling is the generally unknown extent of the induction or initiation period. Moreover, while some of the investigated models show reasonable agreement with the laboratory measurements, none of them has been validated for industrial heat exchangers.

One of the reasons for the different predictions that can be found from published models are due to the way that conventional regression methods are used correlate experimental data, in particular inherent mathematical assumptions such as ignoring terms above the order of two in Taylor series or mandatory forms of final equations that are imposed on the experimental data.

Regression models can be partially theory-based or completely empirical. In both cases, it is not known a priori how many explanatory variables (independent variables, and/or their functions) and parameters have to be included in the model for obtaining an optimal regression model. An insufficient number of explanatory variables may result in an inaccurate model, which is characterised by a large variance. Some independent variables, which may have critical effects on the dependent variable, here fouling resistance under certain circumstances, may be left out of the correlation. On the other hand, including non-influential variables and/or variables which are collinear leads to an unstable model. Also, in conventional methods, values of the model parameters always contain consequences of the introduced assumptions and simplifications.

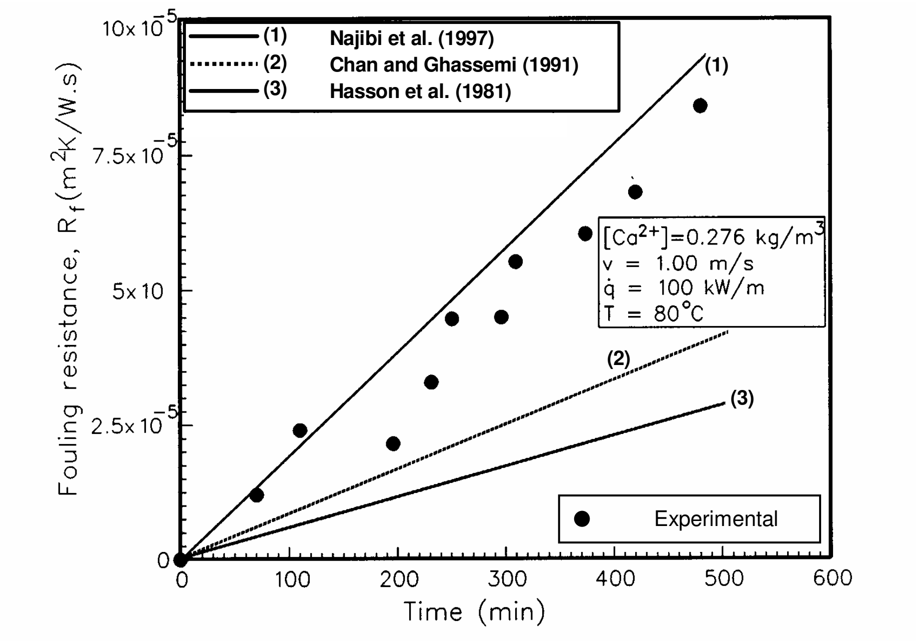

Fig. 4. Measured and predicted forced convective fouling resistances of calcium carbonate.

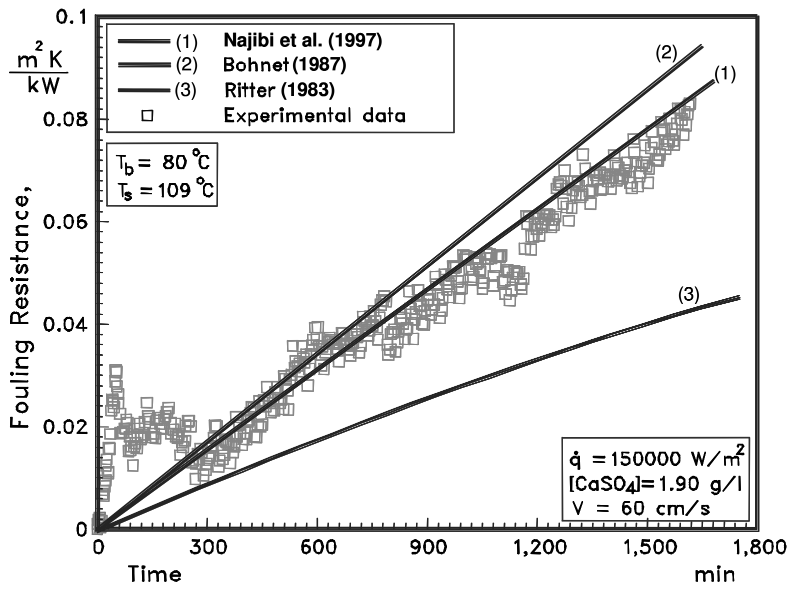

Fig. 5. Measured and predicted forced convective fouling resistances of calcium sulphate

3. Artificial Neural Network Architecture

Neural networks have rapidly become the focus of much attention, largely because of their capability to handle complicated and non-linear systems [11]. The applicability of neural networks is wide, ranging from function approximation to optimisation and process control. Neural networks are basically unsupervised methods because they can synthesise without detailed knowledge of the underlying process. This is certainly a benefit for modelling phenomena such as fouling in which the interaction of the dominant variables is not firmly established. The method can also be used for processing very substantial data sets, which is difficult for conventional approaches such as regression approaches. However, this approach has also some disadvantages as listed below:

- Slow rate of learning (usually requires a large number of iterations)
- Lack of first knowledge of the process
- Poor extrapolation
- Over-fitting
- Black-box behaviour with no meaning for net parameters

The construction of a neural function network in its most basic form involves three entirely different layers. The input layer is made of input nodes. The layer between the input and output layers is known as hidden layer, which may consist of only one or of several sub-layers. It has sufficient nodes, which serves a transformer of weights between the input and output layers. In some neural networks such as RBFs, only one hidden layer exists, which in contrast to the multi-layer perceptron, the transformation from input space to the hidden layer space is non-linear, whereas the transformation from the hidden layer space to the output space is linear. The output layer supplies the response of the network to the activation patterns applied to the input layer. A typical structural form of a neural network architecture with multiple inputs and one output is shown in Figure 4. Neural networks are generally developed in two phases, as follows:

1. The training or learning phase in which a set of known input-output patterns are presented to the network. The weights are adjusted between the nodes until the desired output is provided.
2. The generalisation phase in which the network is subjected to input patterns that it has not seen before, but whose outputs are known and the performance is monitored.

Input and output variables in designing the networks can be used in terms of normalised form and dimensional and/or dimensionless groups (more preferable for scale-up purposes). Selection of input and output variables and of the data set for training should be done carefully to cover the whole range of variables, since neural networks cannot be used reliably for extrapolations. In general, the majority of data are used for training of the network, and the remaining part for the generalisation phase.

Several investigators have successfully utilised neural networks for the prediction of fouling behaviour under subcooled flow boiling conditions and also for $CaSO_4$ precipitation in cooling towers [12-13]. The main aspects of these studies were as follows:

- Instead of a multi-layer perceptrons network of back-propagation, Radial Basis Functions (RBF) were utilised, which provided significantly better prediction.
- For the first time, a limited part of the prior process knowledge (e.g. specified gradient conditions) was used to strengthen the reliability of the resulting network. This strategy, which will be elaborated later, may prevent the resultant network from over-fitting the experimental data. However, its ability to extrapolate beyond the range of operational parameters was quite poor.
- Significantly more data-sets have been used for training the network than in previous investigations; nevertheless these are not yet sufficient for global prediction of crystallisation fouling.

Malayeri and Müller-Steinhagen [12] used radial basis function neural networks to interpolate within the then available range of experimental fouling data for fouling of $CaSO_4$ under subcooled flow boiling conditions, see Table 2.

Table 2 Range of operating parameters.

V [m s^{-1}]	T_b [^oC]	T_s [^oC]	C_b [g/L]	I [Mole/L]
0.5-2	65-95	95-140	1.6-2.7	0.05-0.3

In addition, some prior process knowledge has been introduced into the network to strengthen its reliability. Comparison with the experimental data revealed an average relative error of 14% for the training data and 17% for the unseen data. The model suggested by Najibi et al. [14] predicts the experimental data with an average relative error of 25%. Figure 6 illustrates a comparison of the network output against the experimental data, while Figure 7 shows the variation of fouling rate as a function of surface temperature. It is evident that predictions for higher surface temperatures are less accurate. This unsatisfactory performance of the network is attributed to those areas (i.e. induction period and high surface temperature) where not enough information about the underlying phenomena and/or insufficient experimental data were available. However, this preliminary work demonstrated that neural networks, in general, can be applied to the interpretation and analysis of fouling data.

Overall, these preliminary attempts highlight some important features of artificial neural networks (ANN) for analysis and prediction of experimental data, which gave rise to the following promising results:

- Accomplishment to correlate experimental data with the use of neural networks with good accuracy. The resulting networks could predict the objective function significantly better than the correlations of the individual researchers who had performed the experiments.
- The resulting networks not only quantitatively predicted objective functions with good accuracy but also captured the underlying mechanism of the processes, i.e. mass transfer control region at lower velocities and reaction control at higher surface temperatures during fouling under subcooled flow boiling conditions.
- The reliability of the resulting networks was confirmed when it was subjected to those data that had not been used before.
- The preliminary (and yet very limited) use of prior process knowledge, i.e. fouling curve trends and specified gradient conditions, in form of hybrid models instead of "black box" neural networks showed that predictability as well as reliability of the resulting network will be increased.

In addition, computational modelling and simulation techniques have also helped engineers to improve interpretation of on-line monitoring data and the prediction of optimum cleaning schedules for heat exchanger networks. In this strategy, artificial neural networks are employed to update continuously heat exchanger functioning modes and detective monitoring tools of when the deposition would occur [15].

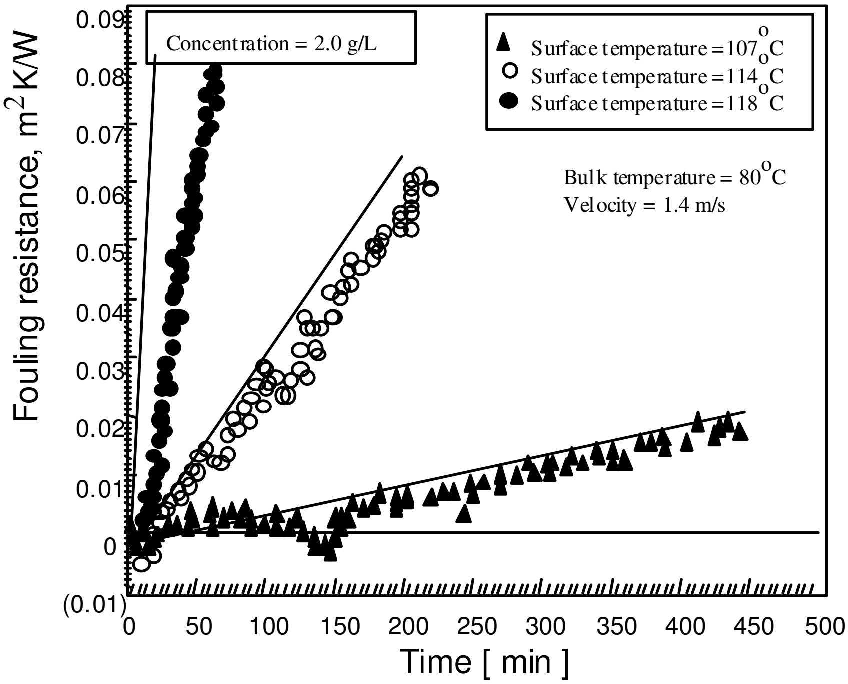

Fig. 6. Comparison of network output with experimental results.

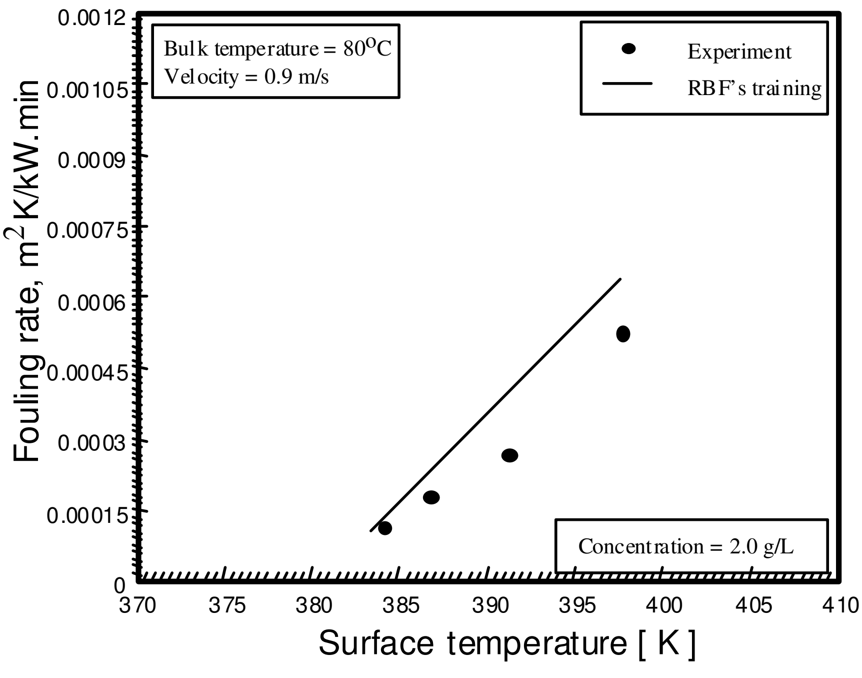

Fig. 7. Fouling rate as a function of surface temperature (experimental and network predictions).

SURFACE TREATMENT AND ONLINE MITIGATION STRATEGIES

Over the past decade, tangible progress has been made to develop advanced and effective mitigation strategies. During the last decade, new materials have been developed with significantly better resistance against fouling. Most materials are based on stainless steel, although for critical parts such as heat exchanger tubes often other metals such as titanium are used. The latter shows a very low fouling resistance even under extreme conditions of operation but are very expensive.

In addition, surface characteristics, mainly in terms of surface energy, are important parameters which until the mid 1990's have not been thoroughly investigated. In the past few years, however, several investigators demonstrated experimentally the significant effects of surface properties on fouling processes. In most, but certainly not all, cases lower surface energy resulted in reduced propensity of the surface to foul [16-17]. While there have been some successful attempts at fouling mitigation with modified surfaces, many problems remain unanswered such as irreproducibility of results and degradation of surface performance. Better understanding of the interactive forces between deposits and surfaces could provide the required insights into the adhesion mechanisms on modified surfaces.

For biofouling, the most widespread mitigation strategy is the use of chemical inhibitors containing substances like chlorine that are harmful to the environment. The use of harmful chemicals has to be reduced and eventually phased out due to the implementation of restrictive environmental legislations such as Water Framework Directive 60/2000/EC of the European Union. As a result, new efforts are dedicated at developing less-toxic substitute additives, optimisation of inhibitor dosing and hydrodynamic effects. For example, it was reported that tubes with inserts experience more severe biofouling than empty cylindrical tubes, while at the same time cleaning is more effective. In addition, there are efforts to reduce the stickability of the organic layers by modifying the polarisation of the heat transfer surface.

Tangible progress in the on-line mechanical mitigation of heat exchanger fouling is also reported when techniques such as gas/solid or liquid/solid fluidized beds [18], or tube inserts are exploited in chemical plants and refineries [19]. Not only have these methods been shown to reduce fouling, in many instances they also produced significantly enhanced heat transfer coefficients. Hence, such concepts may give rise to smaller heat exchangers, reduce energy consumption, increase heat transfer performance and reduce maintenance costs. Despite these advantages, installation occurs based on field experience following a time consuming and costly trial and error approach.

CONCLUDING REMARKS

The gap between demand for freshwater and supply is increasingly widening. Therefore, there is a need to accelerate the development of new and reliable water desalination technologies as well as to increase the efficiency of already installed plants. Nevertheless, in parallel to this, it is necessary to put much stronger efforts in enhancement of heat transfer and fouling more rigorously.

In the meantime, in recent years, substantial progresses in academic fouling research are made such as fundamental mechanisms that govern fouling behaviour, innovative anti-fouling surfaces and online mechanical mitigation tools. However, much of these results have not commercially been materialised yet due to lack of enough interaction and exchange of information with industry. This paper highlights some of recent advances in fouling research and addresses the areas that require closer industrial and academic research collaboration.

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NOMENCLATURE

C concentration, g/L
I Ion strength, mole/L
m_f mass of deposition per unit area, kg/m^2
$\dot{m}_d$ deposition rate, kg/m^2.s
$\dot{m}_r$ removal rate, kg/m^2.s
q heat flux, W/m^2.K
R_f fouling resistance, m^2.K/W
$\dot{R}_f$ fouling rate, m^2.K/W.s
t time, s
T_b bulk temperature, K
T_s surface temperature, K
U_0 overall clean heat transfer coefficient at time zero, W/m^{2}K
U_t overall heat transfer coefficient at any time, W/m^{2}K
V fluid velocity, m/s

Greek symbols

λ thermal conductivity of solution, W/m.K
λ_f thermal conductivity of fouling layer, W/m.K
ρ_f density of fouling layer, kg/m^3

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