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Model for fouling deposition on power plant steam condensers cooled with seawater: Effect of water velocity and tube material

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Abstract

A kinetic model for fouling evolution prediction is proposed. The model suggested in this paper represents fouling evolution *versus* time, and is a modification of the model defined by Konak [A.R. Konak, Prediction of fouling curves in heat transfer equipment, Trans. Inst. Chem. Eng. 51 (1973) 377]. The proposed model is a combination of the first order equation and the driving force concept employed by Konak. It is also a new expression of the classic logistic equation proposed by Verhulst in 1839 to interpret biological population growth data. The new model has the additional advantage that its kinetic parameters, the maximum asymptotic limit of the thermal resistance ($R_{f\infty}$) and the rate at which that maximum value is reached (k), present a clear physical significance. As application and validation of the model performance, the effects of water velocity and tube material on fouling deposition have been tested and modeled. It can be concluded that the maximum asymptotic limit of the thermal resistance decreases as velocity increases. After the application of the model it can also be concluded that for all seasons of the year, titanium tubes are more prone to be fouled, although the process is slower, than with brass tubes.

Keywords: Fouling; Kinetic model; Cooling water; Steam condenser; Seawater

1. Introduction

All the materials exposed to the water suffer the well-known phenomenon of fouling, consisting of the formation of a film that covers the surfaces in contact with the water.

This fouling can be of different nature according to the phenomena that take part in its genesis. Three types of fouling are usually considered: biological, corrosion and precipitation fouling [1]. When seawater is the cooling fluid the phenomenon is accentuated fundamentally due to the strong corrosive nature of salt water and to its elevated biological activity [2]. In general, fouling causes important operation and maintenance problems in facilities in contact with seawater, among them, those of the maritime sector, aquaculture, offshore utilities, etc.

The formation of fouling in heat exchangers of coastal power plants using sea water for cooling purposes has special economic significance [3–5]. In power station condensers, fouling is formed inside the condenser tubes, reducing heat transfer between the hot fluid (steam that condenses in the external surface of the tubes) and the cold sink (sea water flowing through the tubes). This fouling has negative consequences in the efficiency of the power plant and therefore in its economic balance [6,7].

For all the above reasons the designing and operating of heat exchanger must contemplate and estimate the fouling resistance to the heat transfer. The traditional method is the utilization of fouling resistance tables from the bibliography [8]. But these tables show a range of fouling resistance, calculated in very specific conditions that cannot be extrapolated to any other situation. Therefore, the

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Nomenclature

A_o	surface of tube wall (m^2)
C_p	specific heat capacity of seawater at bulk temperature ($J\,kg^{-1}\,K^{-1}$)
d_i	diameter of tube (m)
k'	rate constant of Konak model
k	rate constant of proposed model ($W\,m^{-2}\,K^{-1}\,d^{-1}$)
R	overall heat transfer resistance referred to outside surface of tube ($m^2\,K\,W^{-1}$)
R_f	thermal resistance of fouling layer at time t ($m^2\,K\,W^{-1}$)
$R_{f\infty}$	thermal resistance of fouling layer at time ∞ ($m^2\,K\,W^{-1}$)
R_{f0}	thermal resistance of fouling layer at time 0 ($m^2\,K\,W^{-1}$)
t	time (d)
$t_{1/2}$	time estimated for developing half of the fouling layer (d)
T	temperature (K)
U	overall heat transfer coefficient referred to outside surface ($W\,m^{-2}\,K^{-1}$)
v	cooling seawater velocity ($m\,s^{-1}$)
ρ	seawater density ($kg\,m^{-3}$)

Subscripts

cwo	cooling water outlet
cwi	cooling water inlet
hwi	hot water inlet
hwo	hot water outlet
i	inside
o	outside

determination of the actual fouling resistance has great relevance for each heat exchanger in its particular localization and with the actual operating conditions.

One of the possible strategies for monitoring and detection of the produced fouling is referred to as *side-stream monitoring*, consisting of a device located in parallel with the industrial plant and that, using the same water source, allows an estimation of the fouling produced in this side stream and subsequently to extrapolate to the main stream [7,9]. Although the cost of this type of device is high it offers opportunities for improved heat transfer efficiency and substantial financial saving. In recent years, some side-stream monitoring devices have been made [10] (an EPRI report (1985) do a status survey of 18 biofouling detection devices), but few of them are ready to employ seawater as a cooling fluid, due to the corrosive nature and high biological activity of the seawater.

In order to minimize this undesirable phenomenon, biocides are usually employed as antifouling agents not for avoiding but for reducing fouling accumulation. Chlorine is the more commonly used antifouling agent due to its low cost (frequently electrolytically generated from seawater) and high effectiveness [11]. Nevertheless, the important toxic effect of chlorine and of its reaction products from contact with the seawater (chloramines, haloforms, etc.) is also known. For that reason it is important to optimize the amount of chlorine used in once-through cooling systems – typical in coastal power stations – using huge water volumes (ranging between 10 and 50 m^3/s) and where chlorine amounts in the outfall are also very important [12].

In order to carry out a study on the optimization of antifouling treatment it is necessary to consider the factors that influence their formation and development. Essentially these factors are going to depend on the physical, chemical and biological characteristics of the water and the design and operating conditions of the heat exchanger (material and roughness of the tubes, flow velocity and temperature) [7,13]. Since these characteristics are very dependent on the location and design of the power plant, *in situ* studies are recommended to take into account, as far as possible, the environmental factors and site-specific conditions. The knowledge of the progression and mechanisms of formation of fouling will allow a design of an appropriate fouling mitigation strategy to be made.

The modeling of fouling deposition has great relevance due to the negative effect of the fouling layer over the condenser performance [5,14]. An appropriate model is useful for both, designers and condenser operators. In accordance with that, several models have been proposed in the literature. Zubair et al. [15] presented a review of models for predicting some fouling processes which occurred in various industrial practices: linear, power-law, falling-rate and asymptotic models. For modelling the fouling development in steam condensers, most authors propose asymptotic models, in view of the fact that when the steady state is reached an asymptotic value for the thermal resistance is achieved. One of the first and simplest models for interpreting the fouling process was proposed by Kern and Seaton [16], corresponding to the following expression:

$$R_f = R_{f\infty}(1 - e^{-k\cdot t}) \quad (1)$$

Later, in 1973, Konak [17] proposed a generalised equation for asymptotic fouling based on the driving force concept for deposit development. As the driving force, he suggested the nth power of the difference between the asymptotic fouling resistance and the fouling resistance at time t.

$$\frac{dR_f}{dt} = k'(R_{f\infty} - R_f)^n \quad (2)$$

When $n = 1$, integration of the Konak equation is equivalent to the Kern and Seaton model. Both models that were proposed for inorganic fouling, assume that the rate of fouling growth is constantly decreasing from the clean tube condition until the asymptotic period is reached. Nevertheless, experimental evidence [18–20] shows that the progression of biological fouling follows a sigmoidal curve, with an initial period of low rate and after this induction period, undergoes an exponential growth before achieving the stabilization stage.

This research work deals with the modeling of fouling deposition. A model is proposed to predict the maximum value of the thermal resistance of the fouling layer in different conditions. To apply and validate the model performance, the effects of water velocity and tube material have been assessed and incorporated in an appropriate model. The experimental work took place *in situ* employing a pilot plant located in "Los Barrios" coal power station, (Bay of Algeciras, Southern tip of Spain).

2. Material and methods

2.1. Experimental system

The pilot plant basically consists of a shell-and-tube heat exchanger 3100 mm in length and specially designed to avoid galvanic corrosion. For this reason PVC has been employed for all the ancillary piping and fittings in contact with seawater, as well as for the main heat exchanger (excluding, obviously, the tubes to be tested). In order to simulate power plant condenser conditions, five metallic tubes were heated on the shell side by a fresh-water closed system to maintain a tube surface temperature equal to that in the real condenser. The hot water temperature set point was 35 °C with a difference through the shell of only 0.4 °C, this being achieved by employing a flow rate of 35 m^3/h through the shell, giving a high thermal capacitance to the hot fluid. Cooling sea water flows in one pass through the heated tubes, as fouling is formed on the inside surface and its flow rate is automatically regulated to maintain a prescribed flow velocity. Flow-meter sensors were calibrated periodically to ensure a relative error not greater than 5%. Temperature sensors are 0.1 °C accurate, and were also frequently intercalibrated; then, the observed measurements were corrected accordingly.

Taking into account that the type and rate of fouling will be dependent on the specific characteristics of the cooling water, climatology and other operating conditions of every industrial cooling water system, *in situ* studies must be made. Consequently, the pilot plant was arranged for side-stream monitoring in parallel with the real system at "Los Barrios" 550 MWe power plant (Bay of Algeciras, Southern tip of Spain).

The design of the pilot plant facilitates studies with different tube materials, diameters, flow rates, biocides and dosage patterns. This is very useful for optimizing and monitoring biofouling control procedures. Wireless remote control, monitoring and data transmission from the pilot plant can be carried out via a modem.

The complete description and detailed characteristics of the pilot plant and different components can be found in [18,19], therefore only the most important features are highlighted here.

2.2. Experimental method

In order to obtain a better understanding of the fouling progression, a set of experiments has been designed. Tests over a period of about 90 days have been carried out to evaluate the effect of flow rates on biofilm development.

Flow velocity was maintained nearly constant throughout the experiments, with a Coefficient of Variation (standard deviation/average value) less than 10%. Due to the mild weather in the area, temperature registered low seasonal variations, the average inlet temperature during each experiment ranging between 15 and 19 °C, with a Coefficient of Variation less than 10% for each seasonal experiment. Other physical and chemical properties of the cooling water, as pH, conductivity and salinity registered minimal variations. Such stable environmental conditions together with the capabilities of the experimental pilot plant, helped obtain meaningful and congruent data.

Throughout the experiments, the signals of the sensors were automatically recorded: cooling water temperature (in and out), flow rate and pressure drop, as well as the inlet and outlet bulk temperatures in the heating water shell. From all these measured variables, on-line instantaneous data was obtained for computing the increment of heat transfer resistance due to fouling development.

The overall heat transfer resistance (sum of conductive and convective resistances) is expressed by the reciprocal of the overall heat transfer coefficient and can be easily determined for each tube in accordance with the following equation:

$$R = U^{-1} = \frac{A_o \cdot [(T_{hwo} - T_{cwi}) + (T_{cwo} - T_{cwi})]}{\frac{\pi}{4} \cdot d_i^2 \cdot v \cdot \rho \cdot C_p \cdot (T_{cwo} - T_{cwi}) \cdot \ln \frac{T_{hwo} - T_{cwi}}{T_{hwi} - T_{cwo}}} \quad (3)$$

The resistance due to fouling is then determined by calculating the difference in R between fouled and clean conditions.

This experimental data was then fitted to the proposed model. To simplify the problem, the tests were made in the absence of antifouling treatment, so that the natural process of fouling deposition could be reproduced.

In order to check the effect of flow velocity on fouling deposition, an experiment was initiated with commercially clean tubes, each one working with increasing flow velocities: 84%, 100%, 132% and 163% with respect to the established flow velocity in the industrial plant (1.85 m/s).

To understand the effect of tube material on fouling progression, four experiments, one for each season, have been carried out with aluminium brass tubes. After that, another four seasonal experiments were conducted with titanium tubes, and then the evolution of the fouling resistance for both materials at the same nominal flow velocity (1.85 m/s) was compared.

2.3. Results and discussion

A suitable model must have the following characteristics:

- accurate fitting to experimental data;
- simplicity of the mathematical equation as well as in application to experimental data;
- physical significance, making it possible to interpret the values of the kinetic parameters of the model.

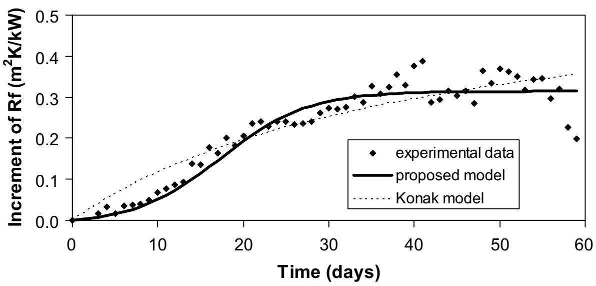

Fig. 1. Example of proposed model and its fitting to experimental data.

As the pilot plant has temperature and flow sensors, it permits on-line calculation of the overall heat transfer resistance from the beginning of an experiment (clean tubes) to the end, when the fouling layer has reached the stationary equilibrium. Fig. 1 shows the typical sigmoidal shape of this curve. During the induction period, the tubes underwent little fouling accumulation, later a fast growth of the fouling layer occurred, and finally a stabilization period was reached when attachment and detachment rates were similar.

After the application of the Konak model to the experimental data, it was observed that it did not fit correctly to the data (Fig. 1). So, it was decided to modify the model,

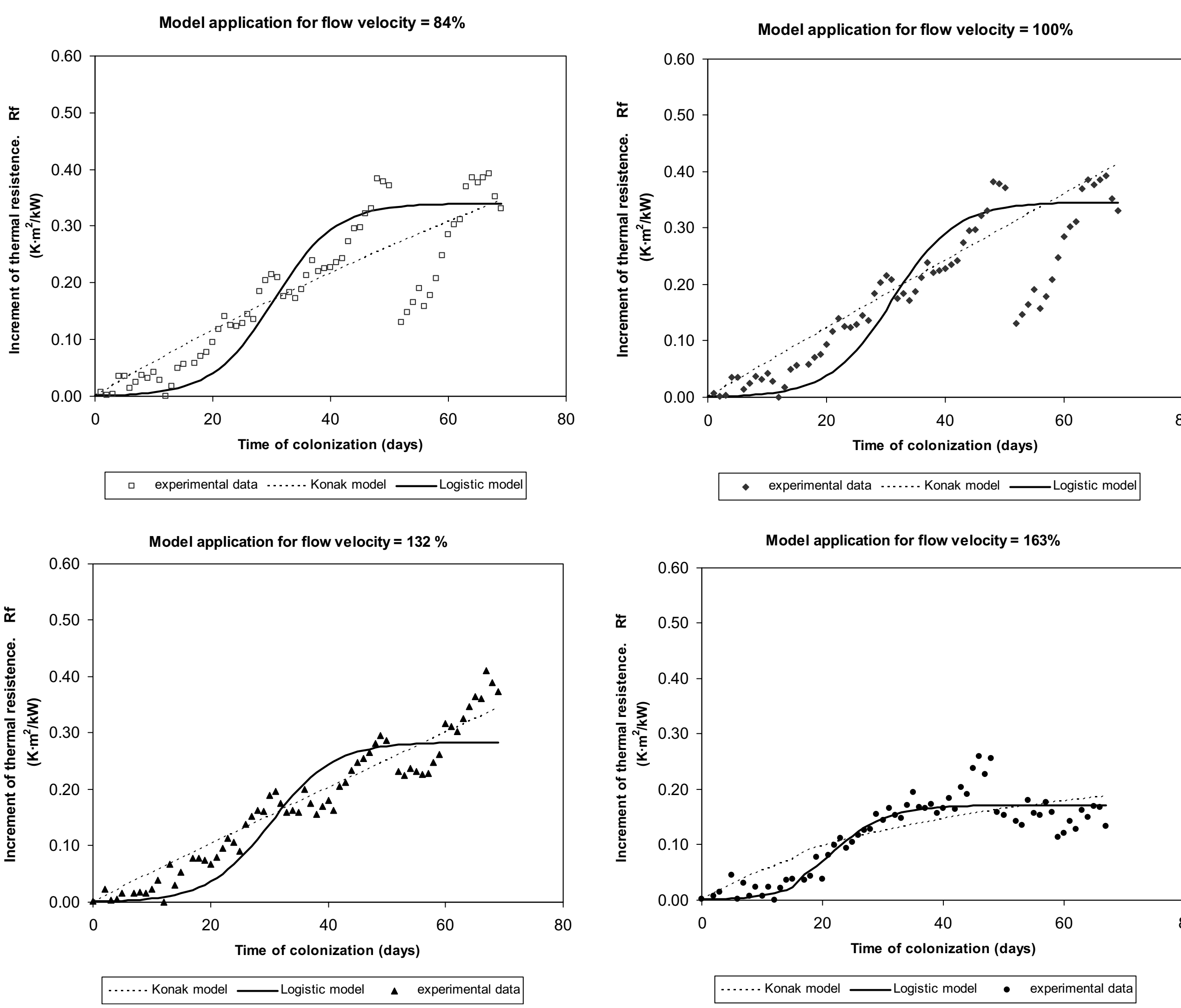

Fig. 2. Thermal resistance increment *versus* time for four flow velocities: 84%, 100%, 132% and 163% with respect to the nominal plant water velocity (1.85 m/s).

but without increasing the number of parameters. The new model is represented by Eq. (4). The proposed model after this study, representing fouling evolution *versus* time, is a modification of the model proposed by Konak [17]

$$\frac{dR_f}{dt} = k(R_{f\infty} - R_f) \cdot R_f \quad (4)$$

This relationship is simply a combination of the first order equation and the driving force concept employed by Konak. The equation is not a new one, because it coincides, in its mathematical form, with the logistic equation proposed by Verhulst [21] to interpret biological population growth. Nevertheless, the originality of this work could be its innovative application to fouling evolution prediction. The model has the advantage that both kinetic parameters: $R_{f\infty}$ and (k), have a clear physical significance.

Table 1
Kinetic and statistical parameters of the proposed model resulting from experiments carried out with different flow velocities

% of velocity (respect 1.85 m/s)	$R_{f\infty}$ (m^2 K/kW)	k (kW/m^2 K d)	$t_{1/2}$ (days)	$\sum(\text{Pred} - \text{Obs})^2$	r^2
84	0.340	0.564	30.41	0.311	0.768
100	0.346	0.542	31.16	0.378	0.755
132	0.284	0.657	30.32	0.145	0.849
163	0.171	1.270	23.66	0.047	0.855

On one hand, $R_{f\infty}$ is the maximum limit of the fouling resistance, and on the other hand k represents the rate at which that value is reached.

It can be seen in Fig. 1 that this proposed model fits more correctly to the data than the model proposed by Konak, since this model does not consider the existence of the induction period.

By integration of Eq. (4), we obtain

$$\ln\frac{R_f[R_{f0} - R_{f\infty}]}{R_{f0}[R_f - R_{f\infty}]} = k \cdot R_{f\infty} \cdot t \quad (5)$$

From Eq. (5), it is possible to express the variable R_f in terms of the kinetic parameters k, $R_{f\infty}$ and R_{f0} (initial value of R_f) and time (Eq. (6)) and, as a result, using non-linear regression, both parameters, $R_{f\infty}$ and k can be obtained

$$R_f = \frac{R_{f\infty}}{1 + \left[\frac{R_{f\infty}}{R_{f0}} - 1\right] \cdot e^{-k \cdot R_{f\infty} \cdot t}} \quad (6)$$

Once the above expression is obtained, some calculations of interest can be made. For example, the value of $t_{1/2}$ (time necessary for the accumulation of half of the fouling layer at which R_f is $(R_{f\infty} - R_{f0})/2$) may be obtained. This parameter has a clear physical significance as it provides information about the time for fouling formation, resulting in a useful parameter for the design and operation of steam condensers and many other types of heat exchangers. The time $t_{1/2}$, mathematically, corresponds with the inflexion point of the s-shaped curve (Eq. (7))

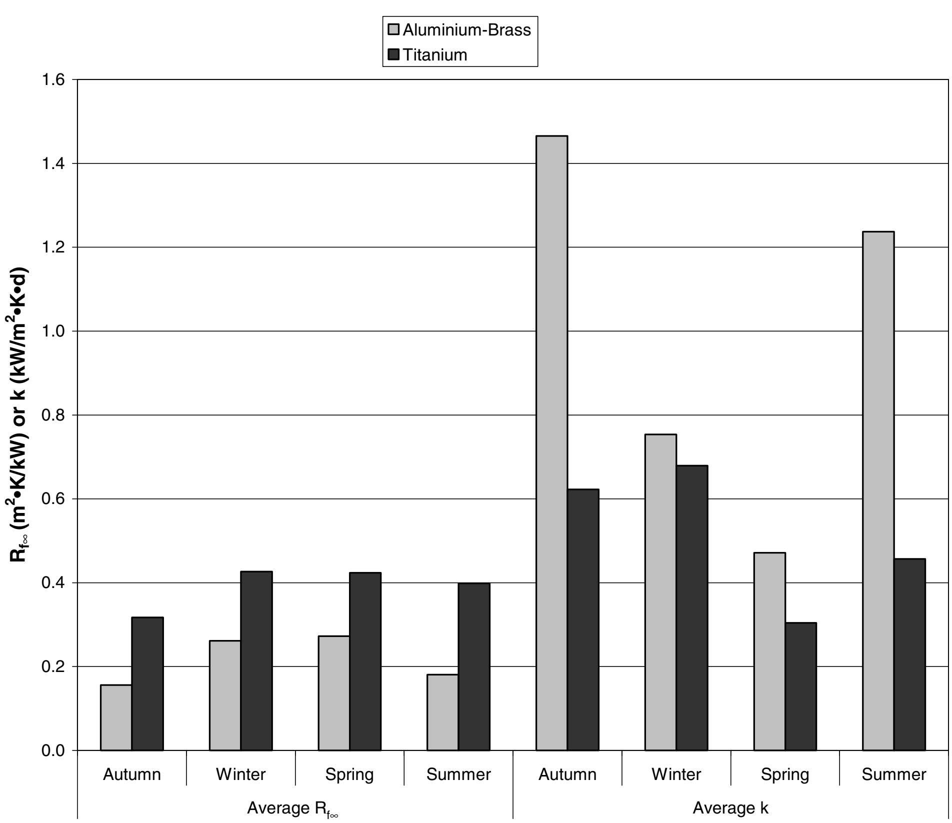

Fig. 3. Asymptotic maximum thermal resistance increment ($R_{f\infty}$) and kinetic constant rate (k) for two tube materials and four seasons.

$$t_{1/2} = \frac{\ln\left[\frac{R_{f\infty}}{R_{f0}} + 1\right]}{k \cdot R_{f\infty}} \quad (7)$$

Also it is possible to obtain from Eq. (6), the time required to reach a limit value of R_f, in order to optimize the cleaning schedule of the equipment.

In the autumn of 2004, an experiment was carried out using four test tubes of the pilot plant. The material of the tubes was titanium grade 2, and the inner and outer diameters were 12 and 15 mm, respectively. For each tube a water velocity was initially established and automatically maintained throughout the experiment by the PLC of the pilot plant. The deposition of fouling *versus* time was monitored on-line, from the thermal resistance increment which was continuously recorded and plotted. Typical sigmoidal curves were obtained and then both kinetic models described above (logistic and Konak models) were applied to the data by non-linear regression. It can be seen in Fig. 2, that the Konak model, although fitted to the set of experimental data reasonably well, did not predict either the initial induction period or the final asymptotic value, adequately. Nevertheless, the logistic model, predicted the complete process of fouling development correctly. One of the advantages of this model is its capability of discerning the data oscillations and predicting, for each set of data, the maximum asymptotic R_f value. This data oscillation was produced by massive mature biofilm detachment and subsequent new biofilm regrowth. Fig. 2 also shows that these marked drops and rapid recoveries were less marked when flow velocity increased. This can be explained because the higher fluid shear was compensated by a higher bond resistance of the fouling, and therefore biofilm is more stable.

In Table 1 the kinetic parameters of the logistic model were recorded. It may be seen that both parameters, k and $R_{f\infty}$, undergo a reasonable variation with respect to the water velocity. In this way, $R_{f\infty}$, does not change significantly when velocities range between 86% and 100%, but clearly it decreases for water velocities higher than 1.85 m/s. With the highest tested velocity (163%) a 50% reduction in $R_{f\infty}$ was obtained (see Table 1). This means that the heat transfer resistance will be lower if the condenser operates with higher water velocities, although with the handicap of a greater pumping power consumption (the specific economic evaluation is not the objective of this study which only proposes a versatile model for fouling prediction).

Parameter k represents the kinetic constant rate that expresses the overall velocity of the main processes involved in fouling development: adsorption, sedimentation, reaction and biological growth. Therefore, a higher value indicates a more reactive fouling, and so the steady state or stabilization period will be achieved sooner than in the case of a lower value of k. In Table 1 it can be seen that, in particular, for the nominal flow velocity (1.85 m/s)

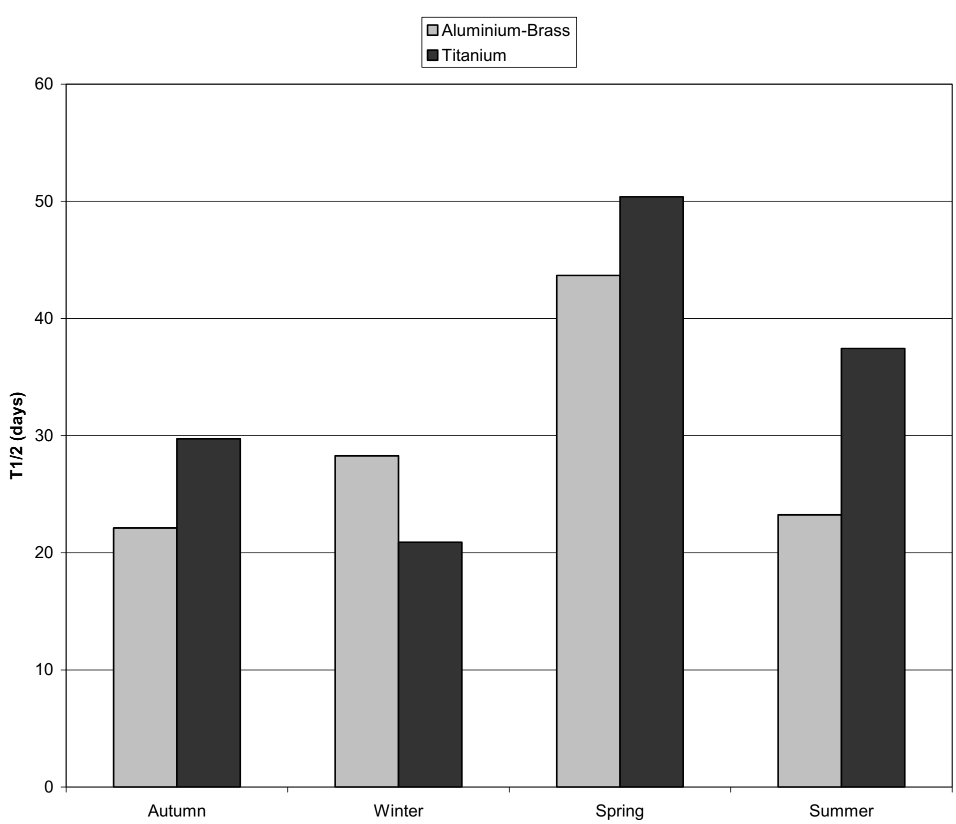

Fig. 4. Time for developing half of the fouling layer ($t_{1/2}$) for two tube materials and four seasons.

the minimum fouling reactivity is obtained, while higher values for k are obtained by modifying the cooling water velocity.

Finally, the $t_{1/2}$ shows very similar behaviour to k. The maximum value (corresponding to a longer period for fouling development) is achieved for the nominal seawater velocity, whereas for the maximum velocity, the time in question is significantly reduced.

Comparisons have been made between the thermal resistance curves obtained from experiments done with different tube materials: aluminium, brass and titanium. These experiments have been carried out for the four seasons of the year. After applying the model, the kinetic constants are obtained. In Fig. 3 it can be seen that when the tubes are of titanium, the maximum asymptotic thermal resistance obtained is clearly higher in all cases than when brass tubes are used. This fact could be attributed to the non-toxic characteristics of titanium, whereas brass allows greater fouling development.

Conversely, the brass tubes result in higher values of k and lower values of $t_{1/2}$ (except in winter), indicating that, in general, the fouling deposition and steady state is reached in a shorter period of time than using titanium tubes. As it can be seen in Figs. 3 and 4, may be concluded that titanium tubes are more prone to fouling, although the fouling process is slower than with brass tubes.

3. Conclusions

A kinetic model for fouling prediction is proposed. The model is based on the model proposed Konak, but fits better to the experimental data because it takes into account the induction period due to the biological contribution to the fouling process. The induction period is of vital importance in the industrial heat transfer process studied. Besides, it has the additional advantage that both its kinetic parameters, $R_{f\infty}$ and k, have a clear physical significance. On one hand, $R_{f\infty}$ is the highest limit of the R_f variable (the thermal resistance due to fouling layer) and on the other hand, k represents the reactivity of the process and, consequently, the rate at which that maximum value is reached. Another benefit of the new model is that the differential equation of the model has an analytical solution, allowing, by non-linear regression, to easily obtain the kinetic parameters, $R_{f\infty}$ and k, and from both $t_{1/2}$, the time estimated for developing the half of the fouling layer.

To validate the model, it was applied to experimental data from fouling deposition experiments carried out changing water flow velocity and tube material.

It may be concluded that $R_{f\infty}$, does not undergo a significant change when flow velocity ranges from 86% to 100% of the nominal value (1.85 m/s), whereas it decreases when velocity increases above this figure, diminishing up to 50% when the flow velocity is increased by 63%. The parameters k and $t_{1/2}$ are related to the kinetic constant rate, and they indicate the velocity and the time required for the fouling layer development. From these parameters it is possible to conclude that the nominal flow velocity (1.85 m/s) is the optimum one, given that, with that condition the fouling deposition occurred at a slower rate.

The application of the model also shows that titanium tubes have a higher maximum asymptotic value of the thermal resistance than brass tubes. Conversely, the brass tubes have superior values of k, indicating that the fouling deposition and steady state are reached in a shorter period than with titanium tubes. These facts are true, as general rule, for all seasons and so we can conclude that titanium tubes are more prone to fouling, although the fouling process is slower than with brass tubes.

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