Effect and thermophysical properties identification of tartar deposited on heat exchanger tubes

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Abstract :

Despite great technical achievement in the design and manufacture of heat exchangers in the past two decades, the problem of deposited fouling on the internal surfaces of tubes is found and stills one of the unresolved problems in thermal science. This paper deals with a process of thermophysical properties estimation for a deposited fouling on the internal surface of a heat exchanger. The experimental bench uses a photothermal method using a crenel heat excitation. The thermal properties of the sample are identified by the minimization of the cost function that compares the measured temperature to the response of a direct model function of thermophysical parameters with the Gauss-Newton algorithm. And the harmful effects of the deposited fouling on the thermal efficiency of a flat plate solar collector are studied.

Résumé:
Le problème du tartre se pose avec plus ou moins d'acuité selon la dureté de l'eau distribuée (teneur en calcaire). Selon les endroits cette dureté occasionne un entartrage important des installations. Le calcaire entartre rapidement l'échangeur de chaleur où il cause deux problèmes importants : des bruits et un accroissement de la consommation en énergie. Dans cette étude, nous nous proposons, en première partie, de déterminer les propriétés thermophysiques du tartre accumulé dans un échangeur en se basant sur méthode inverse utilisant l'algorithme de Gauss-Newton. Le dispositif expérimental de caractérisation utilisé est celui de la méthode flash à longue durée. En une deuxième partie, nous étudions les effets du tartre sur le rendement thermique d'capteur solaire plan.

Nomenclature

a:Thermal diffusivity	($m^2.s^{-1}$)	T_i, T_o: inlet, outlet fluid temperature	(K)
ρC_p volumetric heat capacity	($KJ/m^3.K$)	t_c :heating time	(s)
F_R: collector overall heat removal transfer factor		T_m: mean fluid temperature	(K)
G: global solar radiation incident on the collector	($W.m^{-2}$)	λ: Thermal conductivity	($W.m^{-1}.K^{-1}$)
θ_f: Laplace temperature on the front face	(k.s)	Ψ: Heat flux density	($W.m^{-2}$)
θ_r: Laplace temperature on the rear face	(k.s)	T_a :The surrounding air temperature	(K)

1. Introduction:

At high temperature, the circulation of fluid in heat exchangers provides a tendency for tartar accumulation to take place on the internal surface of pipes. From thermophysical point of view, the accumulation of tartar has harmful effects on the heat exchanger efficiency. Indeed it increases the energizing consumption. In this work, we present a theoretical and an experimental study allowing the identification of the thermophysical properties of a bi-layer system composed of a heat exchanger section and the tartar deposited on. The experimental bench uses a photothermal method using a crenel heat excitation. The system under investigation is submitted to a crenel heat flux on the front face. The temperature response, during and after irradiation, is measured at the opposite face using a thermocouple. The identification of thermophysical properties is performed by an iterative procedure based on minimizing the ordinary least squares function comparing the measured temperatures on the rear face of the bi-layer system during the crenel heating to the response of a theoretical model with the Gauss-Newton method. The optimization algorithm developed to solve the problem, is efficient and stable. To study the effect of the deposited fouling formation, a set of measures of the thermal efficiency of a flat plate solar collector is realized. It has been shown that the deposited fouling decreases the thermal efficiency till 10%.

2. Fouling in heat exchangers

Fouling is a general term that includes any kind of deposit of extraneous material that appears upon the heat transfer surface during the lifetime of the heat exchanger. The problem of fouling on heat exchanger surfaces still remains one of the major unresolved problems in thermal Science.
There are several different basic mechanisms by which fouling deposits may be created and each of them in general depends upon several variables. In this section we will identify the major mechanisms of fouling and the more important variables upon which they depend:

- **Sedimentation:** Many streams and particularly cooling water contain solid particles which can settle out upon the heat transfer surface.
- **Crystallization of salts:** is occurred when a stream encounters a wall at a temperature above that corresponding to saturation for the dissolved salt, the salt will crystallize on the surface.
- **Coking:** In some cases the fouling is generated by chemical reactions that produce a solid phase at or near the surface of tubes.
- Corrosion is a general term that indicates the conversion of a metal into a soluble compound. There are two types of corrosion: the oxygen pitting corrosion, seen on the tubes section, and low pH corrosion, seen in the condensate return system.
- **Combined mechanisms**. Most of the above fouling processes can occur in combination. It is therefore common to find deposits composed of crystals resulting from salts crystallization with finely divided sediments.

Whatever the exact nature of the deposits, an additional thermal resistance to heat transfer is introduced and the operational capability of the heat exchanger is correspondingly reduced. The aim of this work is to identify this added thermal resistance and thermophysical properties of the deposited fouling on the internal surface of heat exchangers.

3. System description and mathematical model

The system under investigation is a section (figure1) of a heat exchanger of copper with a thin layer of fouling deposited on. To determine the thermal properties of this fouling accumulation of thickness e_1, the system is submitted on the upper face to a finite width pulse heat flux *Q(t)* as shown in figure 2:

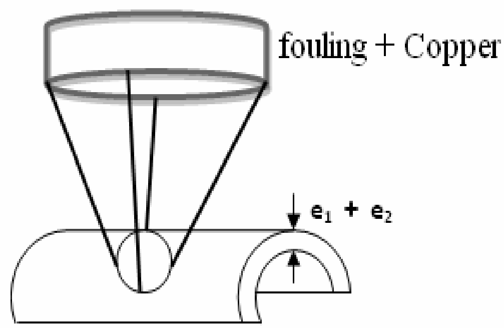

Figure 1. Section of the heat exchanger

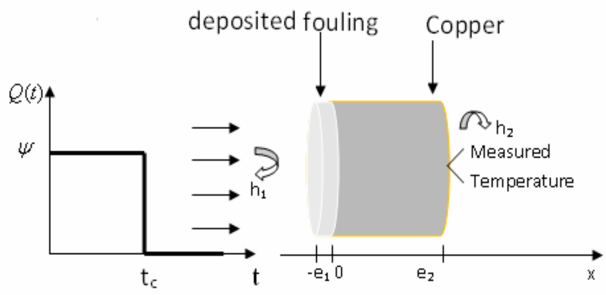

Figure 2. Principle of the method

The model assumes one-dimensional heat flux through a two-layer sample constituted by two materials of thickness e_1 and e_2. Their interface is characterized by an imperfect contact (thermal contact resistance R_c). Taking into account that we work at ambient temperature, we have used the approximation of equal heat transfer coefficient on the two sample faces ($h_1 = h_2 = h$).The transient temperature distribution in the sample can be obtained by solving the one dimensional heat equation for each layer:

$$\lambda_i \frac{\partial^2 T_i(x,t)}{\partial x^2} = \rho_i C_{pi} \frac{\partial T_i(x,t)}{\partial t}, \qquad i = 1,\ 2 \tag{1}$$

Where T_i is the temperature of layer i.
The mathematical model describing the temperature evolution at the rear face of the system under investigation can be obtained by the thermal quadripoles method. The entire system can be described in Laplace space as:

$$\begin{bmatrix} \theta_f \\ \frac{\psi(1-\exp(-pt_c))}{p} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ h_1 & 1 \end{bmatrix} \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} 1 & R_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ h_2 & 1 \end{bmatrix} \begin{bmatrix} \theta_r \\ 0 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \theta_r \\ 0 \end{bmatrix} \tag{2}$$

Here θ_f and θ_r are the Laplace transforms of the sample front and rear face temperatures, respectively. The coefficients A_i, B_i, C_i and D_i depend on the Laplace parameter p, on the thickness e_i of the layer i, and on the thermophysical properties of the material:

$$A_i = D_i = \cosh(\alpha_i e_i)\ ,\ C_i = \lambda_i \alpha_i \sinh(\alpha_i e_i),\ B_i = \frac{1}{\lambda_i \alpha_i} \sinh(\alpha_i e_i)\ ,\ \alpha_i = \sqrt{\frac{p}{a_i}} \qquad 3)$$

In the Laplace space, the rear face temperature is given by:

$$\theta_r(p) = \frac{\Psi}{pC}\left[1-\exp(-pt_c)\right] \tag{4}$$

The rear face temperature in Laplace space for a crenel heating excitation is given by:

$$\theta_r = \frac{\beta_3}{\beta_1^2 s_1^2} \frac{\left(1-\exp(-s_1^2 t_c^*)\right)}{(\delta+\varphi+\phi)} \tag{6}$$

Where: $$\delta = [s_1.ch(s_2)sh(s_1) + \beta_4.\beta_5.s_1^2.sh(s_2)sh(s_1) + \beta_5.s_1.ch(s_1)sh(s_2)] \tag{7}$$

$$\varphi = \beta_2{}^2[\frac{1}{\beta_5 s_1} ch(s_1)sh(s_2) + \beta_4.ch(s_1)ch(s_2) + \frac{1}{s_1} sh(s_1)ch(s_2)] \tag{8}$$

$$\phi = \beta_2[2ch(s_1)ch(s_2) + \beta_4\beta_5 s_1.ch(s_1)sh(s_2) + (\beta_5 + \frac{1}{\beta_5})sh(s_1)sh(s_2) + \beta_4 s_1.sh(s_1)ch(s_2)] \tag{9}$$

The dimensionless parameters are defined by:

$$s_1 = \sqrt{\frac{p}{\beta_1}},\ \beta_1 = \frac{a_1}{e_1^2},\ s_2 = \sqrt{\frac{p}{a_2}} e_2,\ t_c^* = \beta_1 t_c,\ \beta_2 = \frac{he_1}{\lambda_1},\ \beta_3 = \frac{\psi}{\rho_1 C_{p1} e_1},\ \beta_4 = \frac{R_c \lambda_1}{e_1},\ \beta_5 = \left(\frac{\lambda_2 \rho_2 C_{p2}}{\lambda_1 \rho_1 C_{p1}}\right)^{1/2} \tag{10}$$

The variation of the reduced temperature $T_{crenel}(t,\beta)$ with time in the usual space domain is calculated using the numerical algorithm proposed by Graver-Stehfest of θ_r [1]:

$$T_{crenel}(t,\beta) = \frac{Ln(2)}{t} \sum_{i=1}^{n} V_i \theta_r \left(\frac{iLn(2)}{t}\right) \tag{11}$$

Where V_i are the Graver-Stehfest function's coefficients, and $\beta = [\beta_1, \beta_2, \beta_3, \beta_4, \beta_5]$ is the vector of unknown parameters to be estimated using the Gauss-Newton method.

4. Experimental setup:

The experimental apparatus is schematically shown in figure 3.It involves a stabilized power, a heat source, a sample to be characterized, a thermocouple, a data acquisition system and a computer.

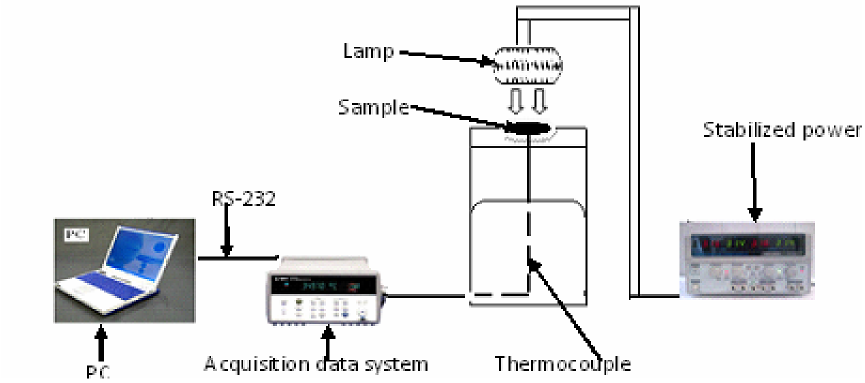

Figure 3. Experimental setup

As noted above in the second section 2, the investigated sample, composed of two layers, is a section of a heat exchanger with fouling deposited on. The first layer is composed of the fouling of thickness e_1 = 0.1mm, the second layer is the copper of the heat exchanger of thickness e_2=1mm. The sample's sides were insulated while a finite width pulse of heat flux equal to 1kw.m^{-2} of about 15 s delivered by a halogen lamp was applied across the entire top surface using a halogen lamp during 15s. The experimental temperature, $T_{measured}$, at the rear face of the sample is measured by a K-type thermocouple.

5. Inverse parameter estimation method: use of the Gauss-Newton method:

There are many methods to minimize linear or non-linear functions, the Gauss-Newton method is one of the simplest methods. It is an iterative procedure based on the minimization of a cost function. The unknown parameters are estimated from adjusting the theoretical temperature history obtained from a mathematical model to the measured temperature history. This can be achieved from the minimization of the gap between the measured and the calculated temperature [2, 3]:

$$S(\beta) = \sum_{i=1}^{n} (T_{measured} - T_{crenel}(t,\beta))^2 \qquad (12)$$

The cost function $S(\beta)$ is minimized by differentiating equation (12) with respect to each of the unknown vector $\beta_j = (\beta_1, \beta_2, \beta_3, \beta_4, \beta_5)$ and then setting the resulting expression equal to zero. Using the Gauss-Newton iterative procedure, the unknown parameters are given by the following expression:

$$\beta^{k+1} = \beta^k + [X^T X]^{-1} X^T [T_{measured} - T_{crenel}] \qquad (13)$$

Where $X = \dfrac{\partial T_{crenel}(t,\beta)}{\partial \beta}$

In this parameters' estimation, the thermophysical parameters of the second layer of copper are fixed. Using the definition given in equation (10), the unknown dimensional parameters of the fouling can be calculated. Their values are given in table 1.

Table 1. Calculated dimensional parameters

Parameters	$a_1 (m^2.s^{-1})$	$\rho_1 C_{p1}$ (KJ/m³.K)	$\lambda_1 (W.m^{-1}.K^{-1})$	h $(W.m^{-2}.K^{-1})$	R_c $(W.m^{-2}.K^{-1})$
values	0.87 10^{-6}	2070	1.8	17	2 10^{-5}
Relative uncertainty %	2.072	4.790	6.862	8.29	14.842

The quality of the estimation is analyzed, by comparing the experimental response and the calculated temperature. Figure 4 presents comparisons between the measurements and the optimal model using the estimated parameters.

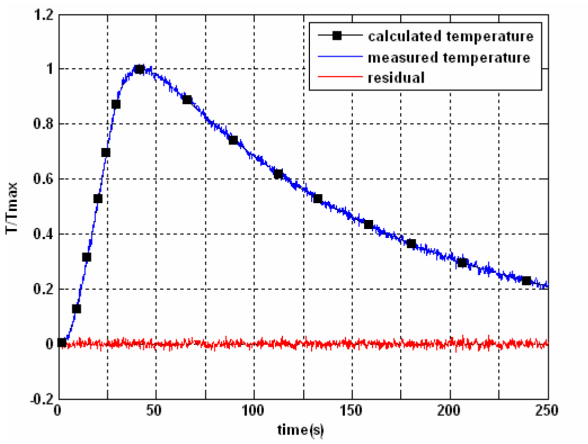

Figure 4. Comparison between measured and calculated temperature

The figure shows a good agreement between the measured and calculated temperatures.

6. Effect of the deposited fouling on the heat transfer

As noted above the consequence of fouling is to form an essentially solid deposit upon the surface, through which heat must be transferred by conduction. If we knew both the thickness and the thermal conductivity of the fouling, we could treat the heat transfer problem simply as another conduction resistance in series with the wall (figure 5):

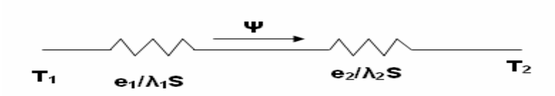

Figure 5. Global thermal resistance

Then the global thermal resistance is given by the following relation:

$$R_{Th} = \frac{e_1}{\lambda_1} + \frac{e_2}{\lambda_2} = 0.0581.10^{-3} W^{-1}.K.m^2 \quad (14)$$

We remark thus, during the operational lifetime the thermal resistance is multiplied by twenty six times of its initial value. In order to evaluate the effect of the additional thermal resistance on the heat transfer efficiency, experimental measurements are carried out on a flat plate solar collector before and after its descaling. The measurement procedure follows the recommendation for Tunisian solar collector test method [4]. The heat thermal efficiency η of the collector is determined by the two following empiric relation [5, 6]:

$$\eta = F_R \ (\eta_0 - u_1 T_{st} - u_2 T_{st}^2) \quad (15)$$

Where $T_{st} = (T_m - T_a)/G$, $T_m = (T_i + T_o)/2$ is the mean fluid temperature, and $G = 800 W.m^{-2}$ is the global solar radiation incident on the collector.

The values of u_1, u_2 and F_R are experimentally derived constants and η_0 is the collector transmissivity-absorptivity product [7]. The results of measurement are presented in table 2.

Table2. Thermal efficiency of a tested flat plate collectors before and after scaling its fluid conduit

Fluid conduit	Thermal efficiency (η)
With fouling	0.465
Cleaned	0.520

Results show clearly that the thermal efficiency and the heat loss transfer coefficient depend on the statement fluid tubes. The maintenance of fluid circulating tubes can increase the thermal efficiency until 10%.The designer must take into account the effect of fouling upon heat exchanger efficiency during the operational lifetime and make previsions in his design for a sufficient extra capacity to insure that the exchanger will meet process that will perturb its primordial role.

7. Conclusion :

The determination of thermophysical properties from an inverse method is an attractive technique both from the experimental and methodological point of view, because of its accuracy and short time for parameters estimation. Therefore, an inverse method for the determination of the thermophysical properties of the fouling deposited on the internal surface of fluid circulating tubes has been described. The method consists in minimizing the gap between a measured temperature and a calculated one which has been developed using the quadrupoles formalism. Estimated parameters are obtained with high accuracy. The damaging effect of the deposited fouling on the thermal efficiency of a flat plat solar collector is studied, and it has been shown that its maximum efficiency is restored after its cleaning.

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