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A risk based heat exchanger analysis subject to fouling Part II: Economics of heat exchangers cleaning

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Abstract

Fouling is one of the major uncertainties associated with the operation and maintenance of heat exchangers in the power and process industries. The decision regarding periodic maintenance (cleaning) to meet the target performance level is generally based on both thermal and economic behavior of the process. In this paper, we present a cost model, which includes the risk level and the scatter parameter of random fouling growth models. Four models, namely linear, power law, falling rate and asymptotic fouling growth are integrated in the model. The non-dimensional cost function Γ as a function of reduced time t/M is examined by considering the dimensionless cost parameters γ_1, γ_2 and γ_3, representing additional fuel cost, antifoulant cost and miscellaneous costs, respectively. These dimensionless cost elements are examined for a heat exchanger that is used in a crude oil preheat train. The results are presented in terms of risk level p and scatter parameter $\sqrt{\alpha}$ for the underlying fouling models. Furthermore, a simplified closed-form solution is also obtained to study the optimal cycle time, representing minimum cost of operation and maintenance of heat exchangers.

1. Introduction

The decisions regarding cleaning or replacement of heat exchanger tubes subject to fouling in industrial applications is based on thermoeconomic analysis. Crittenden and Khater [1] showed that if the fouling resistance–time curve can be predicted, the optimum number of plant shutdowns per year may be determined by balancing investment costs against plant cleaning costs and loss of revenue during the shutdown period. Epstein [2] derived an analytical expression for maximum production, minimum cost evaporation cycles based on the Hasson–Retizer scale formation model. Ma and Epstein [3] developed a graphical procedure for predicting the maximum production and minimum cost cycles for falling rate processes in which the cleaning time depends linearly on

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Nomenclature

A	=External heat exchanger surface (m^2)
C_A	=Cost of additional fuel consumption ($)
$C_A{}'$	=Cost of additional fuel consumption per day ($.day^{-1})
C_H	=Cost of fuel consumption ($)
C_S	=Cost of steam consumption ($)
C_{AF}	=Cost of antifoulant ($)
$C_{AF}{}'$	=Cost of antifoulant per day ($ day^{-1})
C_C	=Cost of heat exchanger cleaning ($)
$C_C{}'$	=Cost of heat exchanger cleaning per day ($ day^{-1})
C_M	=Miscellaneous cost ($)
C_T	=Total cost ($)
ΔH	=Change in enthalpy (kJ kg^{-1})
k_H	=Cost of additional fuel consumed ($ W^{-1} day^{-1})
k_S	=Cost of additional steam used ($ .W^{-1} day^{-1})
$\dot{m}$	=Mass flow rate (kg h^{-1})
NTU	=Number of transfer units
p	=Risk level, $p=P(R_f(t)\leq R_{f,c})$
$\dot{Q}$	=Heat transfer rate (W or MW)
R_f	=Fouling resistance (m^2 K W^{-1})
R_f^*	=Asymptotic fouling resistance (m^2 K W^{-1})
t	=Time (days)
t_{down}	=Down time (days)
T	=Temperature (K)
T_0	=Cycle time (days)
T_0^*	=Optimum cycle time (days)
U	=Overall heat-transfer coefficient (W m^{-2} K^{-1})
$\sqrt{\alpha}$	=Scatter parameter for the fouling model
γ_1	=Dimensionless fuel cost
γ_2	=Dimensionless antifoulant cost
γ_3	=Dimensionless miscellaneous cost
Γ	=Dimensionless total cost
ε	=Heat exchanger effectiveness
$\varepsilon(0)$	=Effectiveness of the heat exchanger at time t=0
$\Phi(\ )$	=Standard normal cumulative distribution function

the cycle throughput. Curlett and Impagliazzo [4] made an analysis of a power plant to predict the effect of condenser tube fouling on thermoeconomic performance of the plant. They showed that the cost of condenser tube fouling was of the order of $1 million per annum for a 600-MW coal-fired power plant when the fouling resistance was increased by four times than that of the design value. Barton [5] presented an objective function to minimize both the cost of cleaning and the heat loss associated with the higher pyrolysis gas exit temperatures required by coke deposition on the transfer-line heat exchanger. Casado [6] developed a cost-based optimization model to calculate the optimum operation of a shell-and-tube heat exchanger in a crude oil preheat train. Sheikh et al. [7] further generalized the Casado's analysis by incorporating the stochastic nature of the linear fouling growth law as discussed by Zubair et al. [8,9]. This paper further expands on the analysis by incorporating power-law, falling rate and asymptotic random falling growth laws, which are discussed in the companion paper. In this regard, we first discuss economic aspects of heat exchanger fouling, which is followed by the risk-based thermoeconomic analysis of a heat exchanger.

2. Economic aspects of fouling

2.1. At design stage

Since fouling of heat-transfer equipment (HTE) reduces the thermal efficiency of the equipment, an allowance needs to be introduced to compensate for the additional heat-transfer resistance due to the anticipated deposit. This means an increase in the heat-transfer area with a corresponding increase in the installed capital cost. TEMA [10] recommendations for the fouling allowance are often used at the design stage. This design allowance is usually a fixed value, which generally represents an asymptotic value of fouling resistance, assuming the underlying fouling process will follow an asymptotic law. However, if the fouling growth is linear with respect to time, or according to a power law or falling rate, there will be no asymptotic value. In such case, this fouling allowance at design stage may be treated as a critical fouling resistance $R_{f,c}$, introduced earlier in the companion paper. The designer may have a perception that a certain time will be needed to reach this critical level of fouling and thus recommend the time between cleaning to the user. In actual operation, there is often an uncertainty concerning the extent of fouling, which can be incorporated at the design stage [11,12]. It is thus important to emphasize that incorporating additional heat-transfer area does not always solve the fouling problem, but it may itself increase the problem of fouling, by introducing the changes, such as a decrease in the velocity as compared to the design value thus accelerating the fouling growth rate.

In some power and process industries, continuous operation is vital, i.e. the heat exchanger need to be operated with highest possible availability, i.e. uptime/(uptime+downtime) must approach 1. In these cases, a particular heat exchanger may be duplicated (i.e. a standby unit is provided), so that when one exchanger becomes excessively fouled, it can be taken out of operation for cleaning and the second exchanger can be brought into service to continuously maintain the production. This provision of a standby (or duplicate) equipment further add to the capital cost of the plant.

The corrosion of a heat exchanger surface is also generally attributed to fouling. To minimize the corrosion as well as to avoid the possibility of developing a pitting phenomenon, often more expensive materials are needed for construction, such as using titanium plates or tubes as compared to ordinary carbon steel. It is therefore expected that the cost of heat exchanger will become many times greater than that of carbon steel heat exchangers. Once the heat exchanger is designed, constructed and commissioned, the user has to live with the economic impact of its operation and maintenance during its useful life that typically may be 20–30 years.

2.2. At operational stage

2.2.1. Operation and maintenance

If the fouling problem is not properly anticipated and allowed for at the design stage, the effects of the subsequent fouling during operation may result in additional downtime and maintenance costs, over and above those considered in the original design. The cost penalties for interrupted production and maintenance may be high unless a duplicate heat exchanger is installed. For example, Bott [13] indicated that in one application, the feed pre-heaters to a distillation column, exchanging heat with the bottom product, had to be stripped down and cleaned once a week, whereas the original specification called for cleaning once every six months. In addition to maintenance costs, the repeated dismantling and re-assembly of the equipment may result in a rapid deterioration of the equipment, thus a reduction of useful life of the equipment.

2.2.2. Loss of production

In many heat exchanger applications, where the fouling potential of the particular fluid stream is not properly recognized or inadequately allowed for in the design, frequent cleaning may be required. Unexpected shutdown, possibly at short notice, may have a significant effect on production schedules and overall output. In some instances it may be possible to bypass the particular heat exchanger (as discussed earlier) while production is maintained, but in others the heat exchanger will be an important part of the plant. Unplanned shutdowns, particularly, can lead to an overall loss of production, which in turn represents a loss of profits to the company.

2.2.3. Cleaning

The cleaning of heat exchangers involves labor costs, but also requires special equipment, particularly if chemical cleaning is required. Additional circuitry involving pumps and tanks may be required, chemicals have to be purchased, and the cleaning process may produce an effluent that will require treatment before disposal due to environmental consideration. These costs can be heavy. More conventional cleaning processes, such as water jetting or circulation of sponge balls, will also require capital outlay in addition to the labor costs involved. The removal of hard deposits from the inside of tubes may require drilling the individual tubes, which may damage the tubes.

2.2.4. Utilization of energy

The reduced heat transfer in a particular heat exchanger due to fouling may increase the overall energy requirement for the process. The shortfall in energy recovery in the exchanger will have to be made up by an increased use of purchased primary energy. For example, Bott [13] indicated that there is an opportunity to utilize waste heat in domestic refuse incineration, where the heat produced by the burning process may be used to produce steam, which is subsequently exported. The income from the sale of the steam offsets the costs of collection, incineration, and final disposal of the ash and other non-combustible material. The gradual fouling of the heat exchangers associated with the steam raising causes a gradual (sometimes-rapid) reduction in steam produced and, therefore, reduced income.

2.2.5. Use of antifoulants

It is possible to mitigate fouling in heat exchangers by adding chemical inhibitors to the fluid stream responsible for the fouling. Extra costs associated with the capital cost of the dosing equipment and the cost of the chemicals will occur. These additives are usually grouped under the general heading of antifoulants. The use of these chemicals must result in cost savings for particular applications; otherwise they will not be appropriate. For the crude unit in a typical petroleum refinery, van Nostrand et al. [14] showed that the use of antifoulant chemicals was justified.

3. Risk-based economic analysis

The costs associated with the fouling can be broadly grouped in the following cost elements in view of the economic aspects discussed earlier in Section 2. Here, these cost elements are discussed as a function of risk level p and scatter parameter $\sqrt{\alpha}$ for given random fouling models that are discussed in the companion paper. In this regard, we consider a simplified schematic of a heat exchanger in a preheat train, as shown in Fig. 1. The relevant properties along with different unit cost parameters of the heat exchanger are shown in Table 1.

3.1. Additional fuel cost due to drop in effectiveness

For a continuous operation between 0 and $t=t(p,\sqrt{\alpha})$ days, where t represents a cleaning cycle corresponding to a risk level p and scatter parameter $\sqrt{\alpha}$, the costs associated with additional fuel consumption can he expressed in terms of cost constant k_H (in \$/W day) as

$$C_H(t,p;\sqrt{\alpha})=k_h\dot{Q}_{max}\left(\varepsilon_n(0)t-\int_0^t \varepsilon_n(t,p;\sqrt{\alpha})\,dt\right), \tag{1}$$

where the symbols are defined in the nomenclature section.

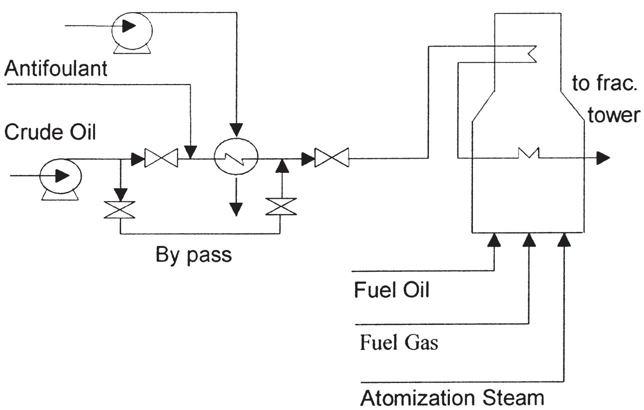

Fig. 1. A simplified crude oil preheat train.

Table 1
The relevant thermal-cost parameters for the fluid streams in the heat exchanger

1	Time for cleaning	$0.1\times M^{a}$ days
2	Total heat transfer area of the heat exchanger, A	1070 m^2
3	Maximum heat transfer duty, $\dot{Q}_{max}$	27.40 MW
4	Number of shell passes, n	3
5	Number of tube passes per shell	2
6	Inlet temperature (cold stream), $T_{c,i}$	325.78 K
7	Inlet temperature (hot stream), $T_{h,i}$	478.00 K
8	Cold-side mass-flow rate, $\dot{m}_c$	424,922 kg/h
9	Hot-side mass-flow rate, $\dot{m}_h$	230,600 kg/h
10	Overall heat transfer coefficient, U_c	145.66 W/m^2 K
11	Critical fouling resistance[b], $R_{f,c}$	2.55×10^{-3} m^2 K/W
12	Initial outlet temperature (cold stream), $T_{c,o}$ (0)	452.20 K
13	Initial outlet temperature (hot stream), $T_{h,o}$ (0)	401.20 K
14	Cost of heat exchanger cleaning per day, $C_C{}'$	677 $/day
15	Cost of additional fuel consumed during heat exchanger cleaning per day, $C_A{}'$	2.095 $/day
16	Miscellaneous cost, C_M	0.00$
	Unit cost of additional steam used, k_S	2.28 $/MW day
17	Unit cost of additional fuel consumed, k_H	300.00 $/MW day

[a] M=100 days for the falling rate model, while for other models is not needed.
[b] For an asymptotic fouling model, $R_{f,c}$=0.95 R_f^*.

3.2. Additional steam cost due to extra fuel consumption

If the rate of steam generation holds a constant relationship with the fuel oil consumption, the costs associated with additional steam can be written in terms of cost constant k_S (in $/W day) as

$$C_S(t,p;\sqrt{\alpha})=k_S\dot{Q}_{max}\left(\varepsilon_n(0)t-\int_0^t \varepsilon_n(t,p;\sqrt{\alpha})\,dt\right). \tag{2}$$

3.3. Antifoulant cost

If the antifoulant is used at constant rate then its associated cost is given by

$$C_{AF}(t,p;\sqrt{\alpha})=C_{AF}{}'t(p,\sqrt{\alpha}). \tag{3}$$

3.4. Cleaning cost

If $C_C{}'$ is the daily cleaning cost during the shut down period, then the total cleaning cost per cycle can be expressed as

$$C_C = C_C' t_{down}. \tag{4}$$

3.5. Additional cost of fuel in the heater during cleaning

If the exchanger's process unit is not stopped (i.e. the exchanger is bypassed), the fired heater will burn an additional amount of fuel necessary to release the heat duty equivalent to the clean exchanger. This cost may be expressed as

$$C_A = C_A' t_{down}. \tag{5}$$

3.6. Miscellaneous costs

Finally, other costs related indirectly to fouling for each cycle are included here as C_M. These include the cleaning program, the shutdown and start up of the process unit, the crude oil filters maintenance, the anti-foulant injection system maintenance, etc.

4. Cost objective function

The operating cycle of the heat exchanger consists of the uptime $t=t(p,\sqrt{\alpha})$ that has an associated risk level p, scatter parameter $\sqrt{\alpha}$ and fixed downtime t_{down}, i.e. $t_{cycle}=T_0=t(p,\sqrt{\alpha})+t_{down}$. Also, the total fouling cost (in \$) through an operation cycle can be written as

$$C_T(t,p;\sqrt{\alpha}) = C_H(t,p;\sqrt{\alpha}) + C_S(t,p;\sqrt{\alpha}) + C_{AF}(t,p;\sqrt{\alpha}) + C_C + C_A + C_M. \tag{6}$$

Making appropriate substitutions and calculating for daily costs, we can express the total cost per unit cycle time as

$$\frac{C_T(t,p;\sqrt{\alpha})}{T_0} = \frac{1}{T_0}\left\{(k_H+k_S)\dot{Q}_{max}\left(\varepsilon_n(0)t_p - \int_0^t \varepsilon_n(t)\,dt\right) + C_{AF}'t + (C_C' + C_A')t_{down} + C_M\right\}. \tag{7}$$

Simplifying the above equation and dividing throughout by ($C_L=C_C'+C_A'+C_M/t_{down}$), we get the dimensionless total cost as

$$\frac{C_T(t,p;\sqrt{\alpha})}{C_L T_0} = \frac{1}{T_0}\left\{\frac{(k_H+k_S)\dot{Q}_{max}}{C_L}\left(\varepsilon_n(0)t_p - \int_0^t \varepsilon_n(t)\,dt\right) + \frac{C_{AF}'t}{C_L} + t_{down}\right\} \tag{8}$$

or in a simplified form, we can write as

$$\Gamma = \frac{C_T(t,p;\sqrt{\alpha})}{C_L T_0} = \frac{\gamma_1}{T_0}\left(\varepsilon_n(0)t - \int_0^t \varepsilon_n(t)\,dt\right) + \gamma_2\left(\frac{t}{T_0}\right) + \gamma_3\frac{t_{down}}{T_0}, \tag{9}$$

where $\gamma_1=\dot{Q}_{\max}(k_M+k_S)/C_L$, $\gamma_2=C_{AH}'/C_L$, $\gamma_3=1$ and $C_L=C_A'+C_C'+C_M/t_{down}$. It should be noted that γ_1, γ_2 and γ_3 represent dimensionless additional fuel, antifoulant, and miscellaneous costs, respectively.

5. Results and discussion

The time and risk-based thermal effectiveness $\varepsilon_n(t,p;\sqrt{\alpha})$ is calculated based on the procedure discussed earlier in the companion paper using linear, power-law, falling rate and asymptotic random fouling growth laws. These values of effectiveness are substituted in Eq. (9) to calculate the total dimensionless cost for a given cycle time Γ as a function of reduced time t/M and risk level p for the conditions given in Table 1 and scatter parameter $\sqrt{\alpha}=0.30$. The results are presented in Fig. 2(a)–(d) for the linear, power-law, falling rate and exponential fouling models, respectively. The line A–A on these plots indicate the total cost corresponding to the critical level of fouling for a given risk level. These figures demonstrate that the minimum cost of operation and maintenance is a function of the risk level p, indicating higher costs for a low risk level (or high reliability) case. In addition, we note that the minimum cost points occur before the time to reach the critical-level of fouling (refer to line AA on these plots), and this time is very small as well as there is a significant scatter with risk level for the falling rate model when compared to the linear fouling case. For example, if the user of HTE would prefer to schedule maintenance based on the minimum cost criterion then the interval between the cleaning cycles will be small compared to the critical fouling case.

Fig. 3(a)–(d) show the effect of down time t_{down} on the total dimensionless cost for the deterministic case ($p=0.50$), with unit cost constants for the crude oil exchanger given in Table 1. These cost constants are similar to those considered by Casado [6] and Sheikh et al. [7] in their investigations. As expected, the figures show that there is a strong relationship between t_{down} and the total cost, particularly in the region where the cost of operation and maintenance is minimum. We also notice that a somewhat high optimum operating cost is indicated with t_{down}. Furthermore, in the optimum region a falling rate model [refer to Fig. 3(c)] indicates that the total cost is relatively sensitive to the cycle downtime when compared to the cost curves for other fouling models.

The effect of miscellaneous cost parameter C_M representing various off-line cleaning related costs, is presented in Fig. 4(a)–(d) for $p=0.50$. We find that the optimum reduced time t/M is a strong function of C_M for all the fouling models considered in this study. These curves show that for $C_M>\$100$, the optimum cost of operation and maintenance is very close to the median time, i.e. the time corresponding to the given critical fouling resistance $R_{f,c}$, which is discussed in somewhat more detail in the companion paper. In addition, the figures show that the optimum dimensionless cost, decreases with C_M.

The effect of different terms in the cost equation, given by Eq. (9) are shown for the deterministic case, in Fig. 5(a)–(d) for all the fouling growth models. In these figures curve Γ_1, represents dimensionless cost due to degradation in heat exchanger performance, curve Γ_2 shows the dimensionless antifoulant cost and curve Γ_3 dimensionless off-line cleaning and other miscellaneous costs. All theses figures show that the first term in the cost equation, representing the extra energy consumption due to fouling, dominate. The variation of this dimensionless cost component is

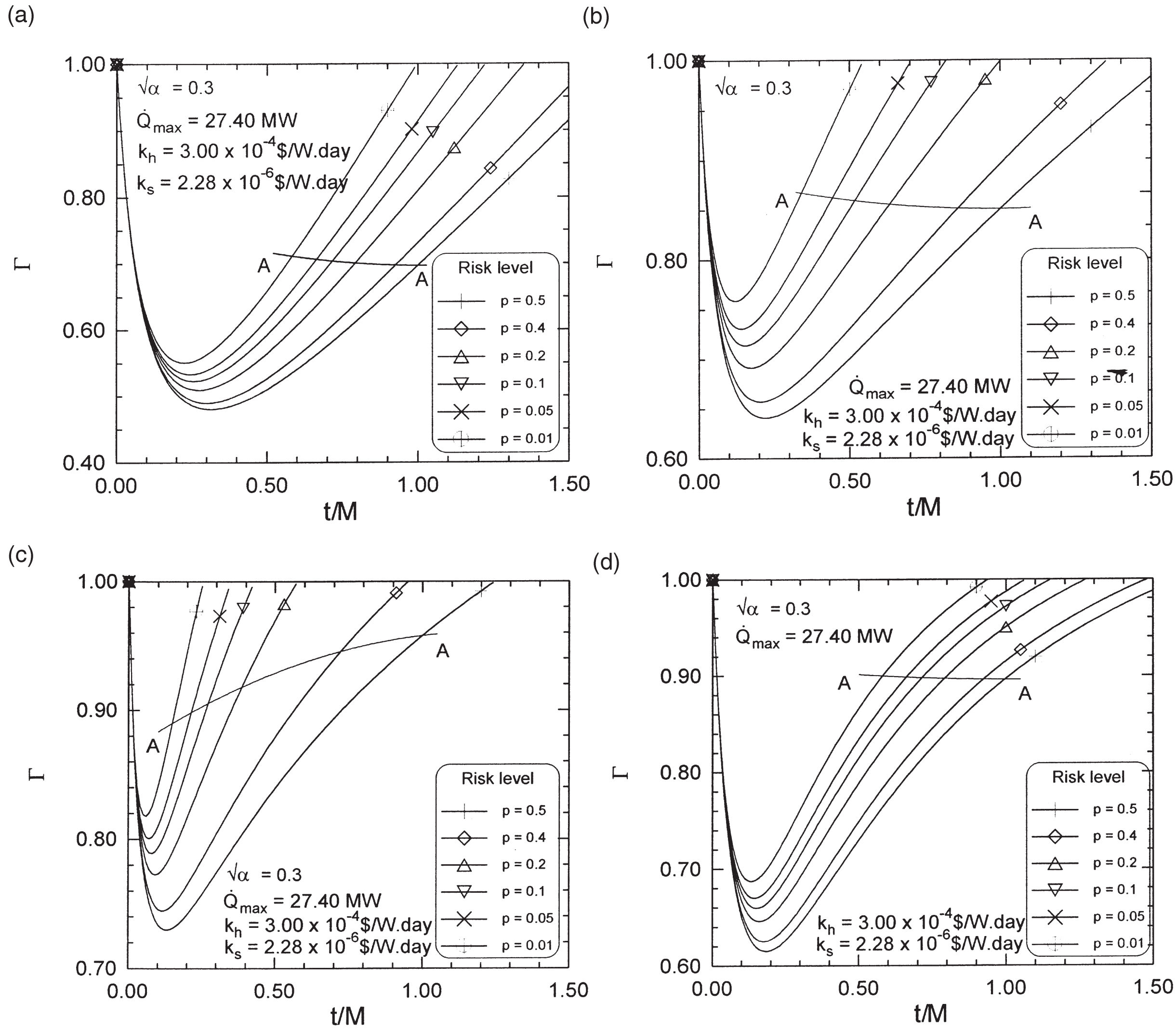

Fig. 2. Dimensionless total cost vs dimensionless operating time with different values of risk level p and scatter parameter $\sqrt{\alpha}$=0.30 (a) linear; (b) power-law with exponent n=0.50; (c) falling rate; and (d) exponential fouling growth models.

somewhat linear for the linear fouling model, while for other fouling models the figures show a non-linear behavior with the reduced time.

5.1. A closed form solution

A careful examination of Fig. 6(a)–(d) as well as several simulations reveal a somewhat straightforward behavior of the term involving the integral occurring in Eq. (7). In these figures, we present the integral term given by

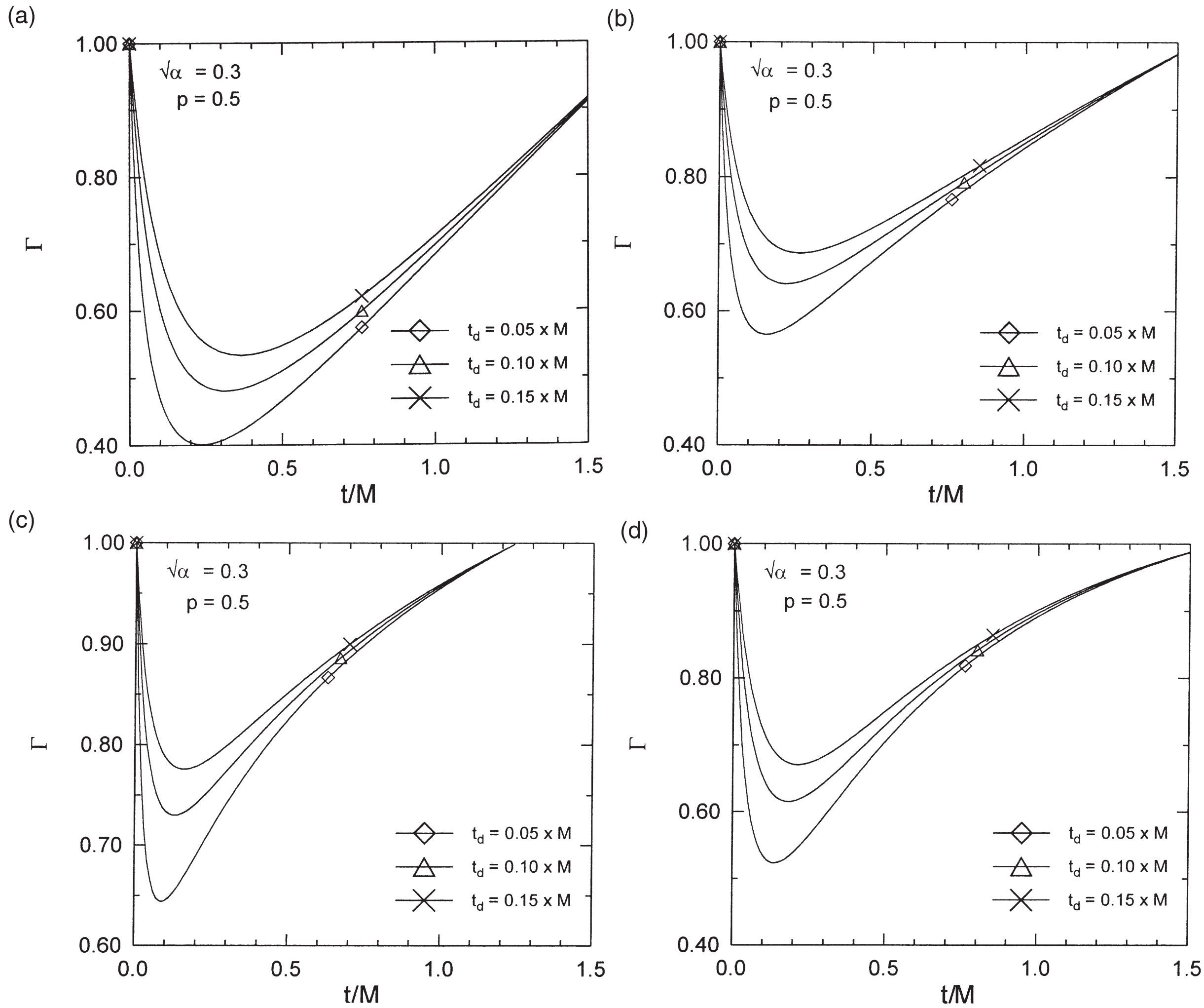

Fig. 3. The effect of down time t_{down} on the total dimensionless cost for a deterministic case p=0.50 (a) linear; (b) power-law with exponent n=0.50; (c) falling rate; and (d) exponential fouling growth models.

$$I(t/M,p;\sqrt{\alpha})=M\left(\varepsilon_n(0)(t/M)-\int_0^{t/M}\varepsilon_n(t,p;\sqrt{\alpha})\,\mathrm{d}t\right), \tag{10a}$$

as a function of reduced time t/M, risk level p and $\sqrt{\alpha}$=0.30 for M=1 in the case of linear, power law and exponential models; while M=100 for the falling rate model. Based on the data shown in these figures, it can easily be demonstrated by a standard regression analysis that the above integral can be approximated in terms of the reduced time t/M as

$$I(t/M,p;\sqrt{\alpha})=M\left(\varepsilon_n(0)(t/M)-\int_0^{t/M}\varepsilon_n(t,p;\sqrt{\alpha})\,\mathrm{d}t\right)\cong A_1(t/M)^2=At^2. \tag{10b}$$

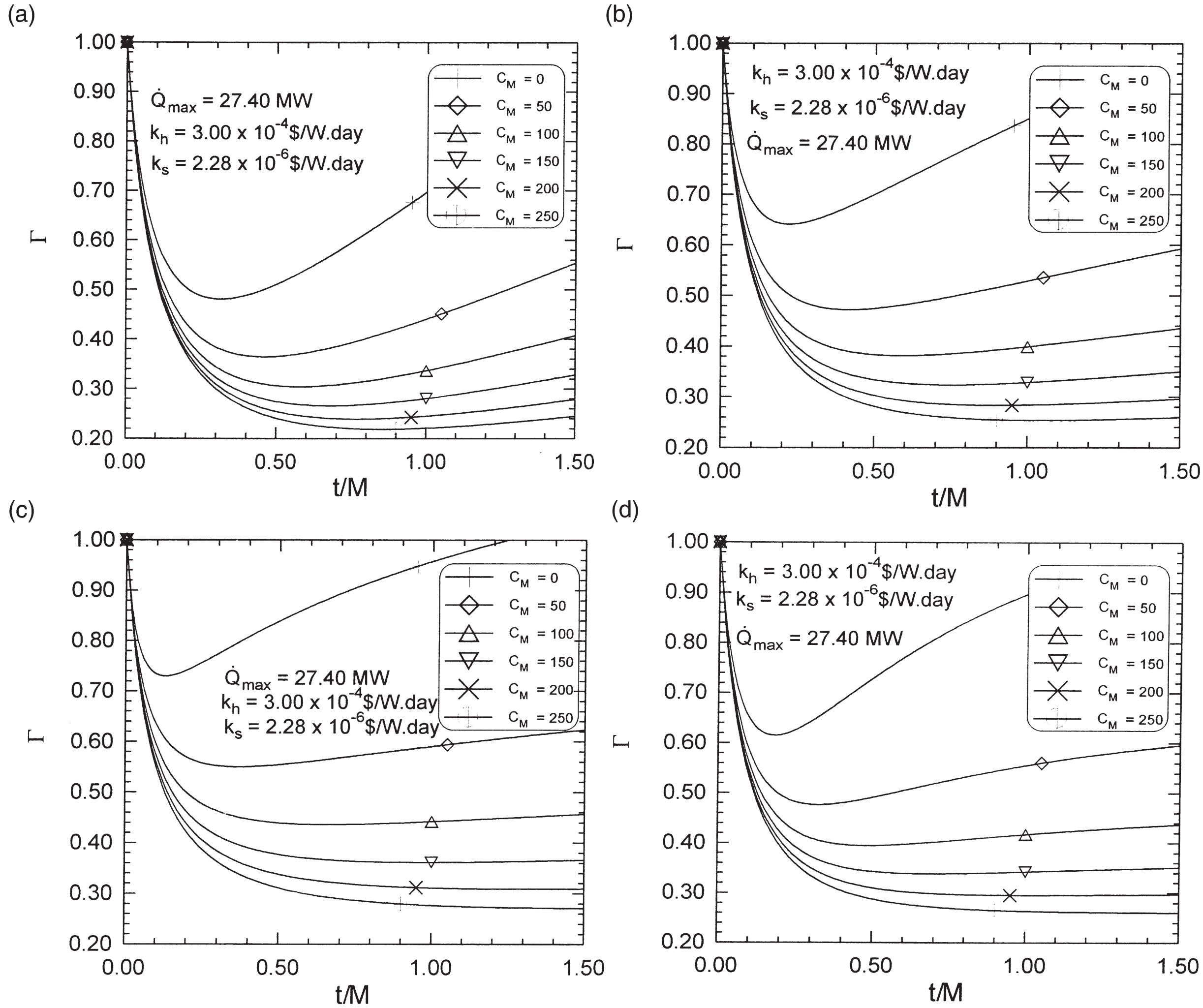

Fig. 4. The effect of miscellaneous cost C_M on the total dimensionless cost for a deterministic case p=0.50 (a) linear; (b) power-law with exponent n=0.50 ; (c) falling rate; and (d) exponential fouling growth models.

For example, in the case of linear fouling model [refer to Fig. 6(a)] the constant (A=A_1/M^2) varies from 0.069 to 0.042 when p changes from 0.01 to 0.50, respectively. We found that the above representation is valid, particularly when the variations in the heat exchanger effectiveness are not significant with time. This is typical of many heat exchangers operating in power and process industries. Using this alternative representation of the first term in the cost model and for given M, we can write the cost function of Eq. (9) as

$$\Gamma(t,p;\sqrt{\alpha})=\gamma_1 At^2/T_0+\gamma_2 t/T_0+\gamma_3 t_{\mathrm{down}}/T_0 \tag{11}$$

or in terms of the cycle and down time, we get

$$\Gamma=A\gamma_1(T_0-2t_{\mathrm{down}}+t_{\mathrm{down}}^2/T_0)+\gamma_2(1-t_{\mathrm{down}}/T_0)+\gamma_3(t_{\mathrm{down}}/T_0). \tag{12}$$

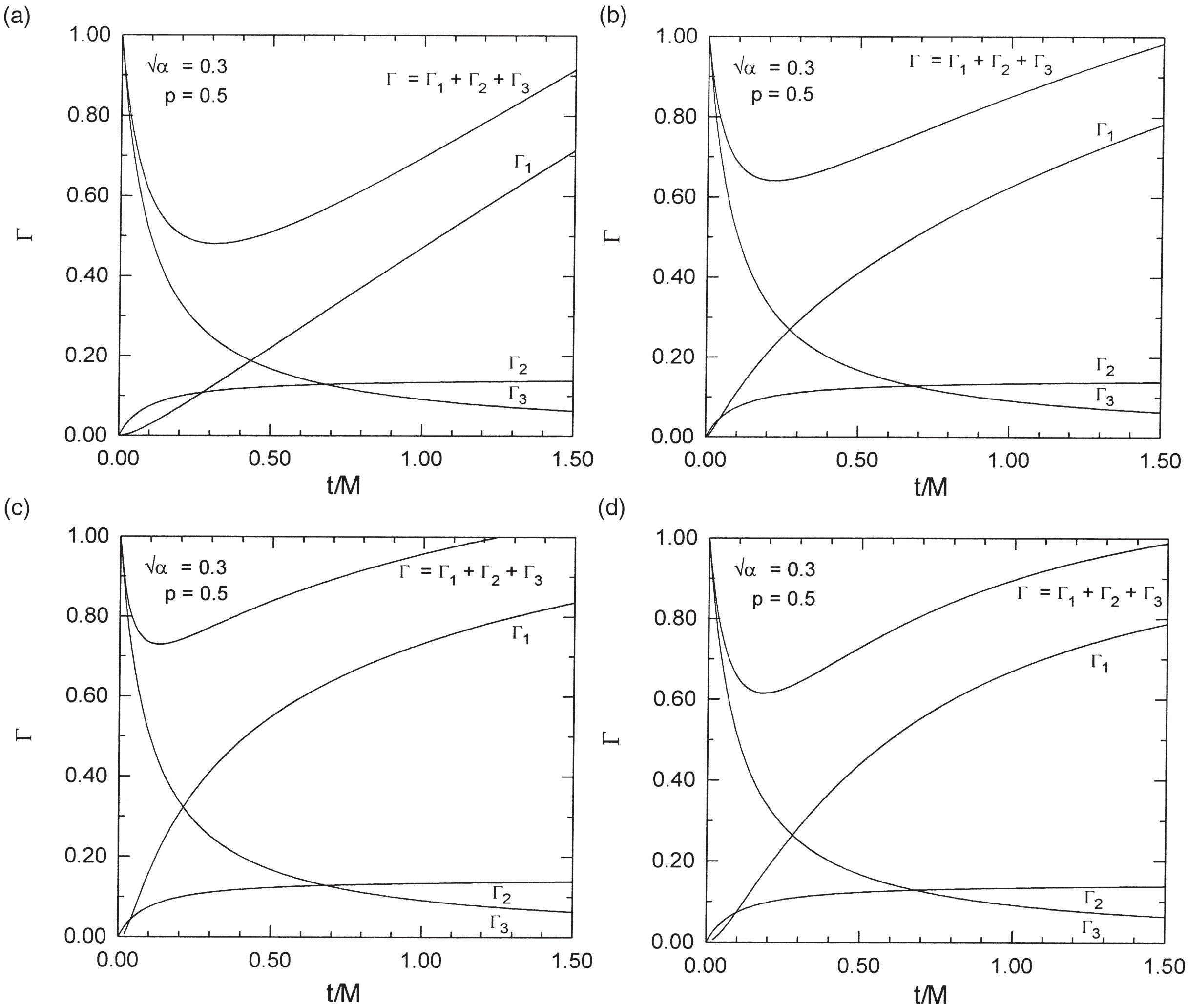

Fig. 5. The effect of various cost elements (Γ_1, Γ_2, Γ_3) to the total dimensionless cost ($\Gamma=\Gamma_1+\Gamma_2+\Gamma_3$) for a deterministic case p=0.50 (a) linear; (b) power-law with exponent n=0.50 ; (c) falling rate; and (d) exponential fouling growth models.

To find the optimum total cost, we differentiate Eq. (12) with respect to the cycle time and equate it to zero. This gives

$$T_0^*=t^*+t_{down}=\left(t_{down}^2-\frac{\gamma_2 t_{\rm down}}{\gamma_1 A}+\frac{\gamma_3 t_{\rm down}}{\gamma_1 A}\right)^{1/2}. \tag{13}$$

Since in our analysis γ_3=1.00 and is always fixed, therefore the sensitivity analysis of optimum cycle time to dimensionless cost variables γ_1 and γ_2 can be assessed by differentiating T_0^* with respect to γ_1 and γ_2, respectively, to give

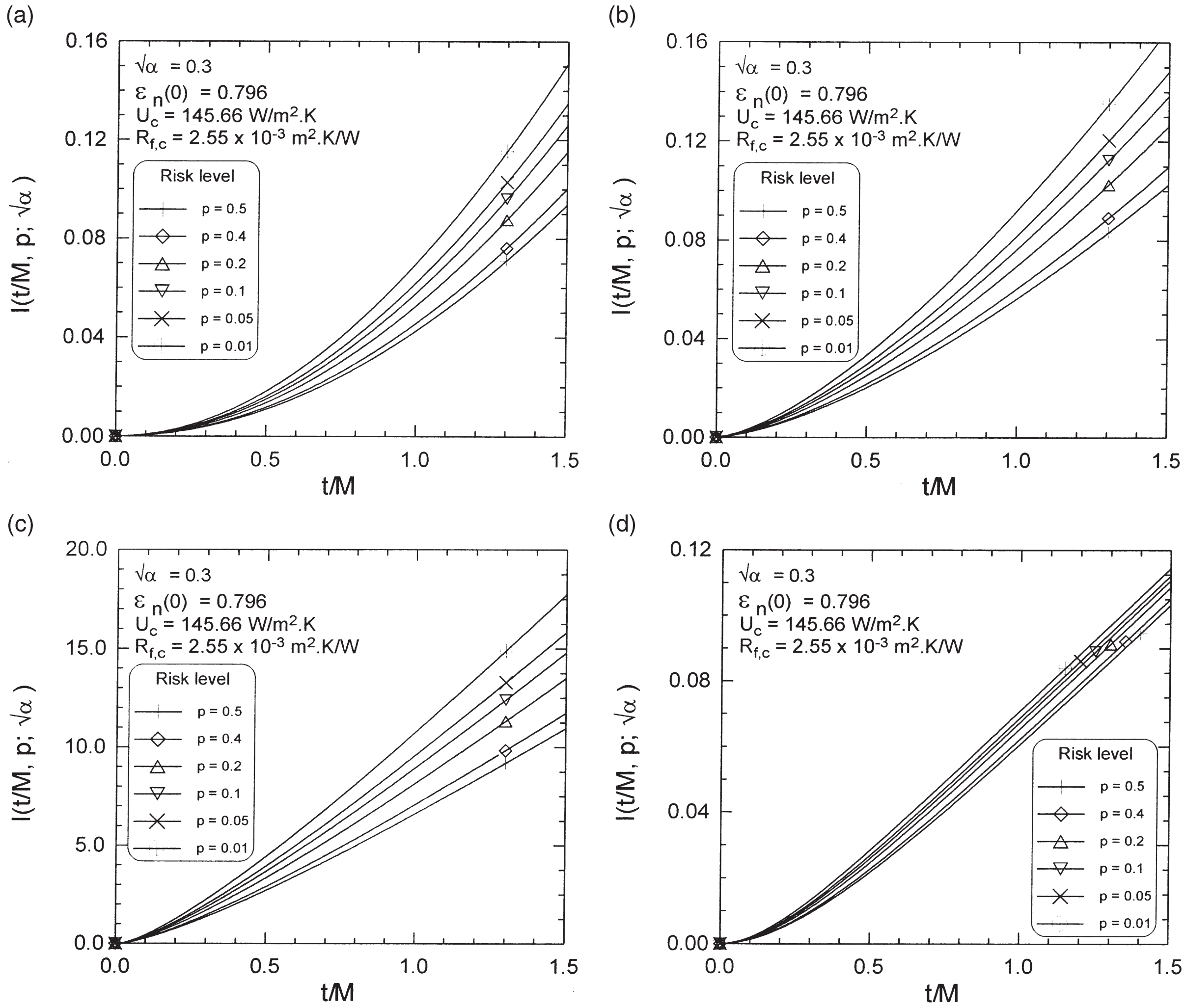

Fig. 6. The representation of the effectiveness degradation function $I(t,p{:}\sqrt{\alpha})$ as a function of reduced time t/M with different values of risk level p and scatter parameter $\sqrt{\alpha}$=0.30 (a) linear; (b) power-law with exponent n=0.50 ; (c) falling rate; and (d) exponential fouling growth models.

$$\frac{\partial T_0^*}{\partial \gamma_1}=\frac{t_{\text{down}}}{2A}\left(\frac{\gamma_2}{\gamma_1^2}-\frac{\gamma_3}{\gamma_1^2}\right)\left(t_{\text{down}}^2-\frac{\gamma_2 t_{\text{down}}}{\gamma_1 A}+\frac{\gamma_3 t_{\text{down}}}{\gamma_1 A}\right)^{-1/2}, \tag{14}$$

$$\frac{\partial T_0^*}{\partial \gamma_2}=-\frac{t_{\text{down}}}{2A\gamma_1}\left(t_{\text{down}}^2-\frac{\gamma_2 t_{\text{down}}}{\gamma_1 A}+\frac{\gamma_3 t_{\text{down}}}{\gamma_1 A}\right)^{-1/2}. \tag{15}$$

The above equations are plotted in Fig. 7 for the case of a linear fouling model with the values of γ_1 and γ_2 correspond to values that are given in Table 1 expect C_M=200. As expected, the figure shows that the optimum cycle time T_0^* is quite sensitive to the dimensionless cost parameter

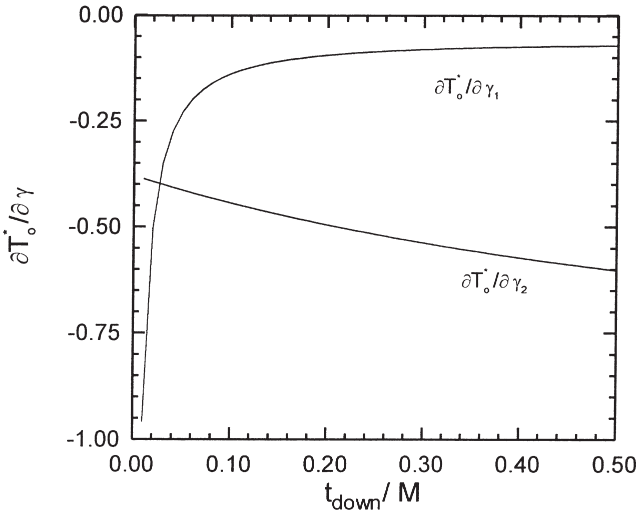

Fig. 7. The sensitivity of dimensionless cycle time $T_0=t+t_{down}$ with respect to the cost parameters γ_1 and γ_2 as function of reduced downtime t_{down}/M for a linear model; the parameters are same as those given in Table 1.

due to extra fuel consumption, γ_1 only up to the reduced downtime t_{down}/M=0.10. while the effect of γ_2 is negligible in this range.

Referring to Eq. (13) and simplifying in terms of dimensional quantities (by using the values of γ_1, γ_2 and γ_3), we get

$$T_0^*=t^*+t_{down}=([\dot{Q}_{max}(k_H+k_S)At^2_{down}-C_{AF}'t_{down}+(C_Lt_{down}+C_M)]/A\dot{Q}_{max}(k_H+k_S))^{1/2}. \quad (16)$$

It is important to note that the closed form solution for the optimum cycle time (refer to Eq. (13) or Eq. (16)) can help us to easily identify the role of various cost elements in shifting the optimum planned maintenance interval. For example, the following conditions are necessary to have an optimal solution, i.e.

$$([\dot{Q}_{max}(k_H+k_S)At^2_{down}-C_{AF}'t_{down}+(C_Lt_{down}+C_M)]/[A\dot{Q}_{max}(k_H+k_S)])^{1/2}>t_{down}, \quad (17)$$

and

$$[\dot{Q}_{max}(k_H+k_S)At^2_{down}+(C_Lt_{down}+C_M)]>C_{AF}'t_{down}. \quad (18)$$

It can be seen from the above equations that for a given value of C_L and C_M, as $A\dot{Q}_{max}(k_H+k_S)$ increases t^* decreases. To increase the value of t^* for a fixed value of C_L and C_M we must decrease the cost parameter $A\dot{Q}_{max}(k_H+k_S)$ either by decreasing $\dot{Q}_{max}$ or (k_H+k_S) , or both, or decreasing value of A which corresponds to improved thermal performance of the exchanger with time. This may be achieved either by a better design or by more effective on-line fouling mitigation techniques.

For heat exchanger applications, when the down time is very small compared to the cycle time, i.e. $T_0^*\approx t^*$. Substituting t_{down}=0 in Eq. (16) and differentiating with respect to the appropriate variables, we get

$$\frac{\partial T_0^*}{\partial C_M}=\frac{1}{2}\sqrt{\frac{1}{AC_M\dot{Q}_{max}(k_H+k_S)}}, \tag{19}$$

$$\frac{\partial T_0^*}{\partial A}=-\frac{1}{2A}\sqrt{\frac{1}{A\dot{Q}_{max}(k_H+k_S)}}, \tag{20}$$

$$\frac{\partial T_0^*}{\partial (k_H+k_S)}=-\frac{1}{2(k_H+k_S)}\sqrt{\frac{C_M}{A\dot{Q}_{max}(k_H+k_S)}}, \tag{21}$$

$$\frac{\partial T_0^*}{\partial \dot{Q}_{max}}=-\frac{1}{2\dot{Q}_{max}}\sqrt{\frac{C_M}{A\dot{Q}_{max}(k_H+k_S)}}. \tag{22}$$

These equations provide us an idea about the role of each parameter in shifting the optimal median time for planned maintenance. Sample results for the case of the linear fouling model are presented in Fig. 8, indicating again that there is a strong influence of the parameter A which is controlling the performance degradation of the heat exchanger. Although the numerical results will be different for other fouling models, the trends and influence of various cost parameters are similar to the case discussed above.

6. Concluding remarks

A comprehensive thermoeconomic study of heat exchangers cleaning cycles is presented in a probabilistic manner by introducing the risk level p and scatter parameter $\sqrt{\alpha}$ in the algebraic expression of the total cost function. It is demonstrated that decreasing the risk level from p=0.5 increases the total costs of operating and maintaining the heat exchanger. The difference in the dimensionless total cost with reduced time t/M is quite visible in the vicinity of the optimal solution for all cases of the fouling models. We also demonstrated the influence of downtime t_{down} and miscellaneous cost C_M on the optimum total cost. It is found that for large values of C_M the optimum cost occurs very close to the time corresponding to the critical level of fouling $R_{f,c}$. For all cases, the numerical solutions are presented for a specific heat exchanger, which can be appropriately modified for other heat exchangers whose performance degrades due to fouling. In addition, the dimensionless cost associated with additional fuel cost is simplified in terms of a simple algebraic expression. This simplified expression has helped us to obtain the closed-form solution for an optimum cycle time in terms of important cost parameters of the heat exchanger, in addition we have used the solution to demonstrate the sensitivity of various important parameters on the cost-based-optimum time for cleaning the exchangers.

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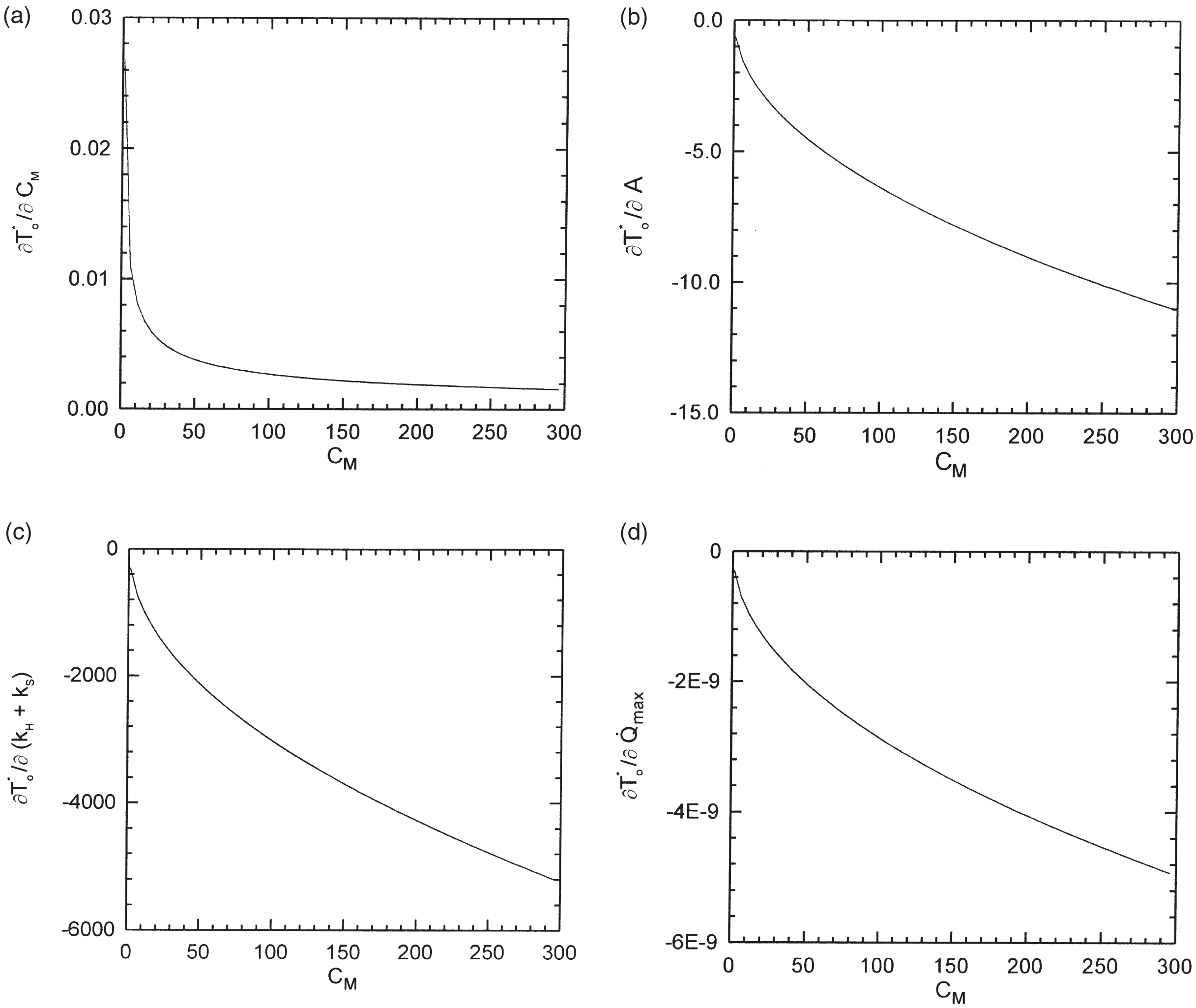

Fig. 8. The sensitivity of dimensionless cycle time $T_0 \approx t$ with respect to different thermal-cost parameters C_M, A, (k_H+k_S) and Q_{max} as function of miscellaneous cost C_M for a linear model: the parameters are same as those given in Table 1.

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