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RESEARCHARTICLE

OPTIMIZATION OF THE OPERATING TIME OF A HEAT EXCHANGER: THERMO-ECONOMIC CRITERION

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ABSTRACT

Fouling of heat exchangers is one of the most common problems in the industry. This phenomenon considerably reduces the heat exchange coefficients over time and therefore decreases the performance of the exchanger, hence the need for periodic cleaning. In this study, we propose an optimization of the operating time of a heat exchanger subjected to fouling before stopping the installation for cleaning. The model we develop for a concentric two-pipe heat exchanger with a laminar flow regime is based on a thermo-economic criterion. This criterion takes into account, on the one hand, the thermal aspect of the transfer and, on the other hand, the costs generated by the shutdown of the installation, those related to the cleaning of the exchanger, as well as those related to energy losses caused by the malfunction of the exchanger due to its fouling. Various dimensionless parameters were introduced into the model in order to evaluate the parametric sensitivity of the operating time t_1. The results show a strong influence of the parameters on the operating time.

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INTRODUCTION

Heat exchangers are important equipment in any energy management policy in the industry. Indeed, the heat treatment of the heat exchangers rests in the majority of the cases on the exchanged power which diminishes as a function of the time with the appearance of the fouling. Fouling can lower the efficiency of heat transfer, corrode equipment, block tubes, increase pressure drop, interrupt normal production and increase operating costs. These additional costs can be classified into four categories (Kazi, 2012):

- Increase in capital expenditure;
- Energy costs;
- Costs of the maintenance;
- Production loss costs and environmental costs.

Müller Steinhagen estimates that the total cost of all fouled heat exchangers in the United Kingdom is in the order of 2.5 million $ and the equivalent in the USA is 14 million$ (Steinhagen, 1995). According to Van Nostrand, fouling expense only for oil refinery in America was in the order of 10^7dollars every year (Bott, 1995).It is therefore necessary to limit these thermal and economic losses eliminate this deposit by performing a periodic cleaning of the exchange surfaces. But how often do you do this cleaning work? Ebert and Panchal, cited in (Wilson et *al*., 2005), (Wilson et *al*., 2015) introduced a concept of "fouling threshold", they proposed a model of prediction of the fouling threshold to quantify and eliminate fouling deposition in the treatment of crude oil. The fouling threshold is considered to be the maximum of the wall temperature for a given flow velocity below which significant deposition can not take place. This model has been developed in recent years by several scientists. However, this model does not take into account the fact that the power exchanged must be maximum at the time of shutdown for cleaning.A. Bejan (Bejan et *al*., 1994) has shown in his work that an optimal on / off sequence exists in the operation of thermal machines (motor or receiver). This amounts to saying that an optimal operating time must be determined to clean the equipment while the power exchanged is maximum. In 1998, LR Schaal quoted in (Schaal., 1998) takes over the works of A. Bejan, and proposes a process in which it has optimized an average power exchanged during a complete operating cycle on / off of an exchanger.

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MATERIALS AND METHODS

We choose to study the case of against current concentric two pipe cylindrical geometry exchanger with the turbulent flow regime (Fig. 1). Indeed, this is the case most met in industry. We will limit this study to only one fouling fluid (the internal fluid), this fluid will also be the limiting one. That is the calorific product characterizing it will be the smallest of the two fluids concerned in the heat exchange.

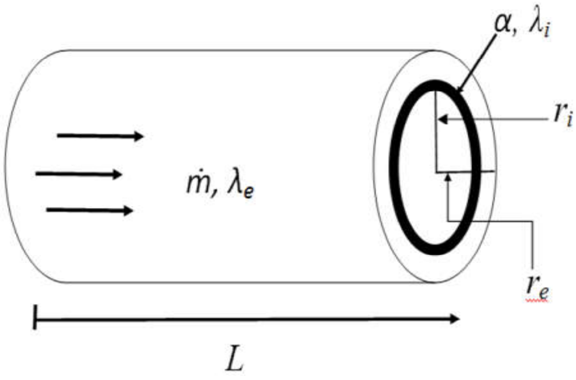

Figure 1. Representation of a tube, component of heat exchanger in cylindrical geometry

Power exchanged: Most heat treatment operations are generally based on the power exchanged. Then we can write the power exchanged in the heat exchanger during the transfer considering the case of constant mass flow operation.

$$\dot{q}(t) = \dot{m} \times Cp \times \Delta Tmax \times \varepsilon(t) = \dot{q}_{max} \times \varepsilon(t) \quad (1)$$

Let us note t_1 the operating time and t_2 the duration of shutdown. The energy exchanged during the complete cycle corresponds to equation (2):

$$ec = \int_0^{t_1+t_2} \dot{q}(t)dt \quad (2)$$

Efficiency of the exchanger: The efficiency of the exchanger is expressed as follows, equation (3):

$$\varepsilon(t) = \frac{1-\exp[-(1+\beta c)\times Nut(t)]}{1-\beta c\, \exp[-(1+\beta c)\times Nut(t)]} \quad (3)$$

Fouling is opposed to the heat transfer by a resistance $R_f(t)$ in the following way:

$$Rf(t) = \frac{ln\left(\frac{r_i}{r_i - \delta(t)}\right)}{2.\pi.\lambda_d.L} \times S_i$$

The evolution deposit is:

$$\delta(t) = r_i \times \left\{1 - \frac{1}{\exp\left(\frac{\lambda d}{r_i} \times Rf(t)\right)}\right\} \quad (5)$$

In the literature, we have noted four fouling kinetics. The asymptotic kinetics model in which the resistance evolves until value is developed by the following expression (Kearn and Seaton, 1959), (Chamra and Webb, 1994):

$$R_f(t) = R_f{}^* \times \left[1 - exp\left(-\frac{t}{\tau e}\right)\right] \quad (6)$$

The kinetics of power, affine, square root and quadratic can be represented by the following equation:

$$R_f(t) = R_f^* \times \left(\frac{t}{\tau e}\right)^n \quad (7)$$

However, in the following calculations, to simplify expressions, we will keep the general form of the kinetic, that is:

$$R_f(t) = R_f^* \times f\left(\frac{t}{\tau e}\right) \quad (8)$$

We can note that the total resistance that opposes the heat exchange between the two fluids is the sum of the conduction and convection resistances.

Evolution of the geometry of the fouled tube: Consider as the reference surface the internal surface of the clean tube.

$$Sio = \pi \times Di_0 \times L \quad (9)$$

The fouled exchange surface will evolve over time as:

$$Si(t) = Sio \times \exp\left(-B \times f\left(\frac{t}{\tau e}\right)\right) \quad (10)$$

Where,

$$B = \frac{\lambda d \times R_f^*}{ri} \quad (11)$$

The cross-section area is

$$Seo = \pi \times ri^2 \quad (12)$$

$$Se(t) = Seo \times \left(\exp\left(-B \times f\left(\frac{t}{\tau e}\right)\right)\right)^2 \quad (13)$$

The tube inside diameter is

$$Di(t) = Dio \times \exp\left(-B \times f\left(\frac{t}{\tau e}\right)\right) \quad (14)$$

Convective exchange coefficient: Then we introduce quantities characterizing the laminar flow in a circular section.

The Prandtl number

$$Pr = \frac{\mu \times Cp}{\lambda} \quad (15)$$

The Reynolds number

$$Re = \frac{\dot{m} \times Di}{\mu \times Se} \quad (16)$$

The Nusselt number for Sieder and Tate

$$Nu(t) = 0,026 \times [Re(t)]^{0,8}[Pr]^{\frac{1}{3}} \times \mu^{*} \quad (17)$$

The heat transfer coefficient

$$hi(t) = \frac{Nu(t) \times \lambda}{Di(t)} \quad (18)$$

$$hi(t) = hi_0 \times [exp(B \times f(t/\tau_e))]^{1,8} \quad (19)$$

So we can express the NTU as follows:

$$NTU(t) = \frac{K(t) \times S_{io}}{(\dot{m} \times C_p)_{min}} \quad (20)$$

$$\frac{1}{Kg(t) \times Sref} = \frac{1}{he \times Se} + \frac{Rcd}{Sref} + \frac{Rf(t)}{Sref} + \frac{1}{hi(t) \times Si} \quad (21)$$

By introducing expressions of surface, the diameter and thickness of the deposit in the function of the fouling kinetic, and by introducing no dimensional parameters noted *Xe, A', A'', L, H,* the NTU is (Schaal and Feidt, 1995)

$$NU_{tu}(t) = \frac{X_e \times L}{L + A' + A'' \times f\left(\frac{t}{\tau_e}\right) + H \times \left[exp\left(B \times f\left(\frac{t}{\tau_e}\right)\right)\right]^{0,8}} \quad (22)$$

Where:

$$Xe = \frac{he \times S_{io}}{(\dot{m}_o \times Cp)min} \quad (23)$$

$$L = \frac{ri}{re} \quad (24)$$

$$H = \frac{he}{hi} \quad (25)$$

$$A' = he \times Rcd \quad (26)$$

$$A'' = he \times R_f^{*} \quad (27)$$

Minimum Power: t_2 corresponding to the shutdown time of the cleaning installation, we define a minimum threshold power below which the heat transfer is no longer effective; this power will therefore correspond to the operating time t_1 (Fig. 2).

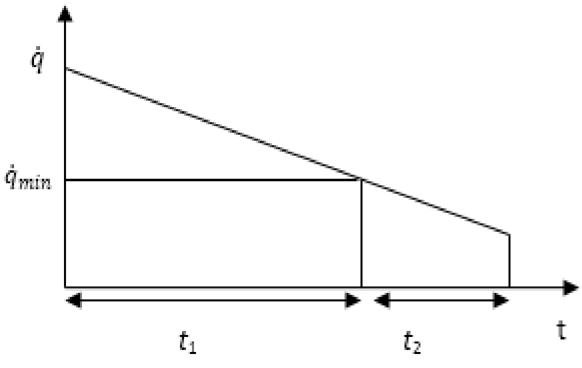

Figure 2. Evolution of the power exchanged as a function of time

We can write $\dot{q}_{min} = \dot{q}(t_1)$ because in t_2 the exchanger is stopped, there is no heat exchange.

$$ec = \int_0^{t_1} \dot{q}_{min}\,dt \quad (28)$$

$$= \dot{q}_{max} \times \int_0^{t_1} \varepsilon(t)dt \quad (29)$$

The conventional approach to be considered for optimization will consist in maximizing the average heat energy exchanged on each on / off sequence of a duration $t_1 + t_2$. However, this approach does not take into account the financial aspect of the problem. In what follows, taking into account the expressions of the heat energy exchanged (Eq. 22) and which is variable over time because of the fouling; we establish a thermo-economic model that takes into account both the thermal aspects and the economic aspects of the problem.

THERMO-ECONOMIC APPROACH

In this approach, we take into account, the number of cycles on / off during a whole year which is given by the following equation (Eq. 30):

$$N_c = \frac{8000}{t_1 + t_2} \quad (30)$$

We express the annual energy exchanged over all these cycles as follows:

$$E = Nc \times \int_0^{t_1 + t_2} \dot{q}(t)dt \quad (31)$$

If we consider that the exchanger is used to recover heat energy from a hot fluid to give it to a cold fluid, and that in the absence of this exchange, we should have used an external energy resource (a fossil energy for example) to heat the cold fluid, we can deduce that the exchange made in this exchanger has avoided a financial expense for the purchase of the external energy resource. In the thermo-economic approach, avoiding an expenditure corresponds to a financial "recipe". Thus this annual recipe linked to the exchanger is written:

$$Re = E.Ce \quad (32)$$

The annual cost (annual payment of a credit) related to the purchase of the exchanger is written:

$$Ci = Chx \times CRF \quad (33)$$

CRF is the Capital Recovery factor expressed by;

$$CRF = \frac{i}{(1-(1+i)^{-n})} \quad (34)$$

Where n is the life of the exchanger and i is the financial discount rate.
We write the annual cost of cleaning as follows:

$$CN = Cn \times Nc \quad (35)$$

Where *Cn* is the unit cost of a cleaning operation.
We express the cost of the stop by:

$$Ca = A \times Nc \times t2 \quad (36)$$

A is the financial cost in euro/second (in terms of operating loss) of a stop.

We deduce the net annual CNA revenue will then be expressed as follows:

$$CNA = F(t1) = E.Ce - Chx.CRF - Cn.Nc - A.Nc.t2 \quad (37)$$

The function F (t_1) (Eq. 37) is the function that should be optimized. It expresses the net annual revenue of the exchanger during the *Nc* on/off cycles carried out in one year. We then look for the maximum of this recipe function that will be realized for an optimal run time before shutdown for cleaning that we will note t_1^*. We have for this optimal duration:

$$\left(\frac{\partial F}{\partial t_1}\right)_{t_1=t_1^*} = 0 \quad (38)$$

The part of the equation most concerned by this approach is the annual energy exchanged, So optimization equation becomes:

$$8000(C_e \times \dot{q}_{max}) \times \left[(t_1 + t_2)\varepsilon(t_1) - \int_0^{t_1} \varepsilon(t)dt\right] + 8000(C_n + At_2) = 0 \quad (39)$$

It's the equation to solve to obtain the operating time on the basis of a thermo-economic optimization criterion finding its optimum can only be done numerically.

SENSIBILITY STUDY

The dimensionless parameters introduced into the model for reasons of generalization will make it possible to evaluate the influence of each of them on the optimal operating time of the heat exchanger. The following table 1 shows all the parameters with their ranges of variation and their central values.

Table 1: Values of the parameters of sensitivity study

Adimensional Parameters	*Range of variation*	*Central value*
X_e	0.5 - 5	2
A'	1.846 10^{-3}-1.841846	0.05
A''	0.0001-80	0.05
L	0.01 - 6	1
H	0.1 - 10	1

The results of the influence of the dimensionless parameters introduced in the model are represented by Figs. 3, 4, 5, 6 and 7.

The evolution of parameter *Xe* (Fig. 3) corresponds to the reduction in the operating time of the exchanger, that is to say that the NTU being linked to thermal efficiency is a factor representative of the exchange capacity of the heat exchanger. exchanger. It can also be seen in the shape of the curve that the economic aspects certainly have an effect on this optimal duration. Because generally the value of the number of transfer unit makes the operation of the exchanger better when it is large (Shall, 1998).The parameter *H* represents the ratio of the surface convective exchange coefficients. His study(Fig. 4) reveals that the more dominant the transfer, the less the fouling is sensitive. Since the parameter *A'* (Fig. 5) corresponds to the conduction resistance, we can therefore translate this pace by the fact that the nature of the material influences the optimal duration t_1.

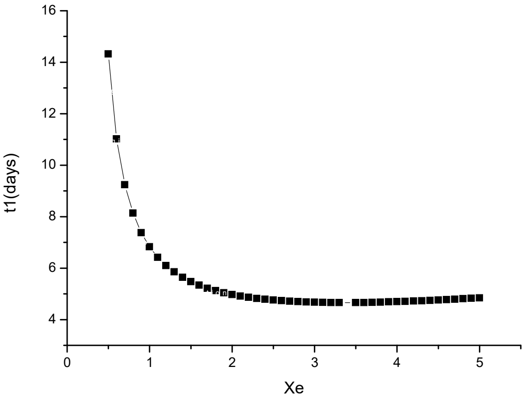

Figure 3. Evolution of the optimal operating time according to X_e

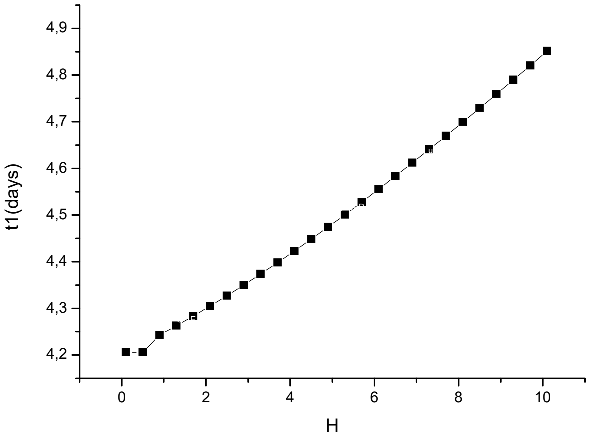

Figure 4. Evolution of the optimal operating time according to *H*

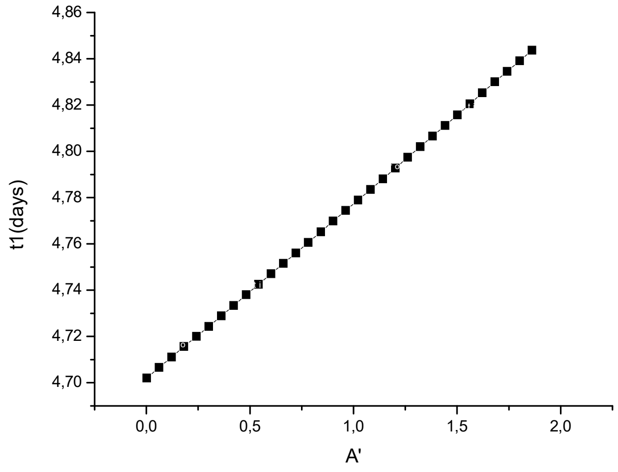

Figure 5. Evolution of the optimal operating time according to *A'*

This means that a high thermal conductivity induces high operating times or the thermal resistance opposed by the material is proportional to an increase in the operating time of the heat exchanger. What is obvious because the nature of the material corresponds to a given thermal conductivity, the latter can in the case where it is low to promote heat transfer or otherwise oppose a high resistance to heat exchange. The evolution of parameter A'' (Fig. 6) seems natural, indeed, this parameter is the product of the asymptotic fouling resistance by a system-specific exchange coefficient. Thus, any increase in this parameter is directly related to an increase in this resistance. In addition, it is obvious that any increase in the asymptotic fouling resistance is the consequence of a greater fouling, therefore an optimal shorter operating time.

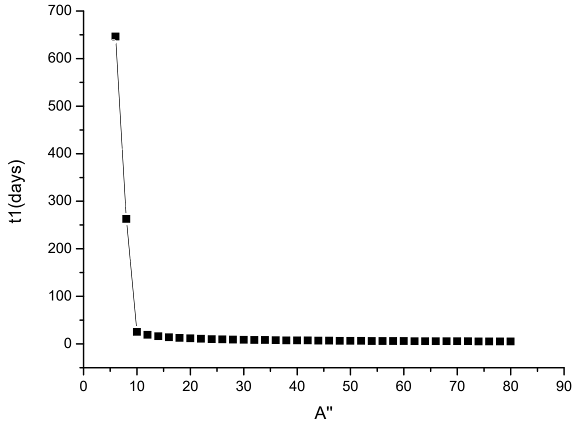

Figure 6. Evolution of the optimal operating time according to *A"*

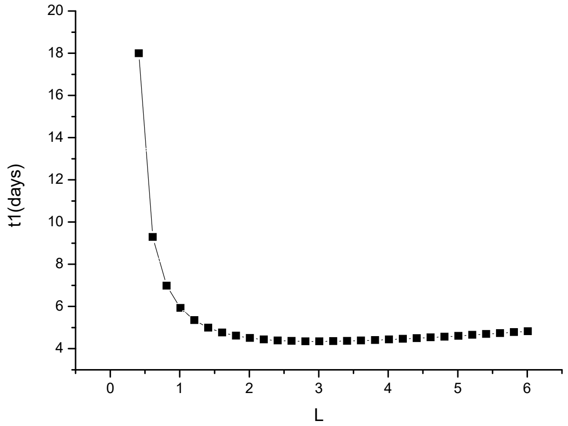

Figure 7. Evolution of the optimal operating time according to *L*

Conclusion

In this paper, we presented a study on the optimization of the operating time of a fouled exchanger which is the minimum allowable power bellow which the transfer is no longer effective. We considered all the on/off cycles of the equipment during a year, on the basis of a thermo-economic optimization criterion. We have therefore taken into account the thermal and economic aspects related to the operation of a bi-tube exchanger. The model we have defined is a case of constant flow operation in an exchanger with against-current and turbulent flow. It is quite possible, by adopting the appropriate expression (Eq.1) to decline in case of operation at constant fluid velocity and in case of constant pumping power. We also performed a parametric sensitivity study to judge the influence of these dimensionless parameters on the operating time. This study showed that these different parameters have a remarkable impact on the optimal operating time.

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