

Scale Deposition in Tubular Heat Exchanger of Phosphoric Acid Concentration Process

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Abstract— Scale deposition is one of the most important and serious problems in which heat transfer equipment generally applies. This phenomenon is considered to be a major technical problem in the treatment industries because deposits on the heat transfer surfaces create a barrier to heat transfer, increase pressure drop and promote corrosion of the tube material. These effects greatly reduce the performance of the heat transfer equipment. Progress is constrained by a lack of quantitative knowledge about the dynamic effects of deposition on heat exchanger transfer.

The topic of this work is an experimental determination of the thermal fouling resistance in tubular heat exchangers of phosphoric acid installed in a concentration process. The measurements of the inlet and outlet temperatures and the mass flows of the two fluids, allows us to determine the overall heat transfer coefficient. The determination of this coefficient in both clean and dirty surfaces makes it possible to calculate the fouling resistance. The results of the heat exchanger studies have shown that the resistance to fouling increases over time, showing an exponential evolution in agreement with the model proposed by Kern and Seaton, with the existence of fluctuations due to the instability of the flow rate and temperatures. Poor equipment cleaning of heat transfer resulted in the absence of the induction period and, thus, resulted high values of fouling resistance and fouling deposition for a relatively short period of time.

Keywords—Fouling, Scale Deposition, Heat Exchanger, Fouling Resistance, Phosphoric Acid Concentration Unit.

I. INTRODUCTION

The most severe and complex problem faced by various industries is the accumulation, on the heat transfer surfaces, of organic compounds or various particles dissolved or present as a suspension in the fluid [1],[2]. This phenomenon which called fouling affects the device functioning by reducing their thermal efficiency and by engendering a considerable pressure loss. This causes a significant economic loss due to the pumping and the frequent cleaning of facilities [3], [4]. Fouling in heat transfer systems is often inevitable and reduces energy efficiency and the functionality of the facility. Mitigation of fouling, and effective cleaning strategies, require both understanding of the mechanisms involved in deposition and cleaning [5].

Numerous heat transfer systems are subject to fouling, reduces the efficiency of heat transfer and limiting productivity [6]. Phosphoric acid fouling in heat exchangers in the concentration process is a persistent operational problem that compromises energy recovery in these systems. Progress is impeded by the lack of quantitative knowledge of the dynamic effects of fouling on heat transfer exchanger [7]. Typically the phosphoric acid flows through the tube side while the steam flows through the shell side of the heat exchangers [8].

There are a wide variety of deposit problems and facility types susceptible to fouling. In this study, we present a description of the deposit phenomenon for its modeling [9]. Tools to understand fouling should be developed so as to provide quantified information for the validation of the fouling models. Several studies have been devoted to the parameters influencing the fouling deposit by scaling. For instance, number of studies have shown that the fouling rate rise by the reduction in the fluid temperature [10].

They are explained by the fact that the velocity and temperature constant, the increase of the thermal transfer involves rise of fouling rates. Others have gone to the increase of fouling rates with the fluid temperature [11], [12]. Radhakrishman et al. [8] developed a predictive model using statistical methods allows the prediction of the fouling rate and the efficiency decrease of the heat exchanger. Mohanty and Singru [6] used the C-factor for fouling monitoring in shell and tube heat exchanger. Ishiyama et al. [13] address in their work the problem of the inlet temperature monitoring in the event of a disaster using hot flow, within a PHT fouling mitigation strategy based on heat exchanger cleaning. Wang et al. [14], in their results of heat transfer experiments, show that the shell-side heat transfer coefficient of the improved heat exchanger raised by 18.2–25.5 %, the overall heat transfer coefficient increased by 15.6–19.7 %, and the energy efficiency increased by 12.9–14.1 %. Sanaye and Hajabdollahi [15] used a first thermal model which is the ϵ -NTU method which is applicable to optimal conception of tubular heat exchanger.

Most engineering calculations in heat transfer use the experimental heat transfer coefficients [16]. Heat exchanger

fouling used in concentration process is a barrier to their development.

In this study, we will examine the fouling phenomenon of the heat exchanger tubes for the preheat circuit of phosphoric acid in the concentration process. The heat exchangers which are used for the heating of the phosphoric acid are exposed to the fouling problem at the tube side of heat exchangers. Within this framework, an experimental determination of the thermal fouling resistance, by measuring the inlet and outlet temperatures and mass flows of the two fluids, allowed to determine the overall heat transfer coefficient. Determining the overall heat transfer coefficient for the heat exchanger with clean and fouled surfaces, the fouling resistance was calculated for the heat exchanger studied.

II. PROCESS DESCRIPTION

The study was done on the level of heat exchanger of the concentration phosphoric acid process. The mixture of phosphoric acid (the dilute and the circulating phosphoric acid) leaves the basket filter; the centrifugal pump drives it back towards the heat exchanger, which is the tube-and shell type [17].

The phosphoric acid crosses the heat exchanger where it is heated from 70 °C to about 80 °C using the steam flow which undergoes a condensation at the heat exchanger at a temperature of 120 °C. The superheated mixture of phosphoric acid passes them by the boiler where a quantity of water evaporates and the concentrated acid is produced by overflowing in a piping system inside the boiler. The remaining quantity of phosphoric acid is recycled. The condenser also ensures incurring uncondensable gases outgoing of the boiler by the effect of sea water created as water falls (Fig. 1).

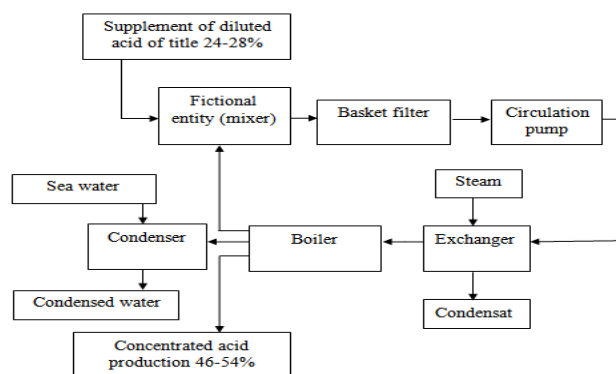


Fig. 1 Simplified Diagram of the Phosphoric Acid Concentration Process

Our experimental study is based on the following hypotheses.

1. The flow of two fluids (Phosphoric acid and steam) is at counter-current.
2. Values of the thermo-physical properties of the fluids were considered constant.
3. The thermal losses were neglected.

4. The inlet and outlet temperatures of the two fluids are determined at the ends of the heat exchanger.

5. Pump suction and discharge pressure measurements are performed at the ends of the circulation pump.

III. CALCULATION METHOD

The method that we used to monitor the fouling evolution consists of carrying out a heat balance at the boundaries of the heat exchanger through the measurements of inlet and outlet temperatures (Fig. 2), pump suction and discharge pressure and acid density. The latter were taken every 2 h throughout all the day.

This method, although indirect, allow to detect the necessary moment to shut down the installation for cleaning. In the present study, the temporal evolution of the fouling resistance of the phosphoric acid was studied.

The calculation of the fouling resistance was carried out using the following relation:

$$R_f(t) = \left(\frac{1}{U_s}\right) - \left(\frac{1}{U_p}\right)$$

The overall heat transfer coefficient at the dirty state was given in the time course, via the expression:

$$U_s = U(t) = \frac{\dot{m}_{ac,cir} * C_{p_{ac}} * (t_{out,ac} - t_{in,ac})}{A * F * \Delta T_{lm}}$$

This relation is drawn from the evaluation of energy on the heat exchanger assuming the isolated system and the physical properties of the two fluids remain constant along the exchanger.

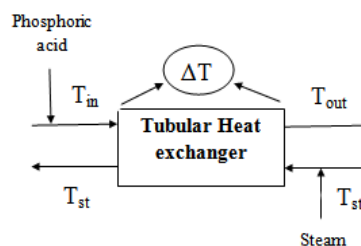


Fig. 2 The Measurement Method at the Boundaries of the Heat Exchanger

In the phosphoric acid concentration process, the operating conditions at the boundary of the heat exchanger are unstable, it is necessary to disclose the heat exchanger coefficients in proper conditions U_p corresponding to the new operating conditions. Assuming that the cleaning between operational runs is perfect and that the heat exchangers are totally free of fouling at the outset of a new cycle. The initial value of the overall heat transfer coefficient at the beginning of every cycle is considered as the value of the overall heat transfer coefficient in the clean state.

$$U_p = U(t=0) = \frac{\dot{m}_{ac,cir} * C_{p_{ac}} * (t_{out,ac} - t_{in,ac})}{A * F * \Delta T_{lm}}$$

IV. RESULTS AND DISCUSSION

TEMPORAL EVOLUTION OF FOULING RESISTANCE

The evolution of the fouling resistance in the phosphoric acid concentration process of the heat exchanger was followed for a study period quoted previously. All the results of the fouling resistance are presented in the curve form on Fig. 3.

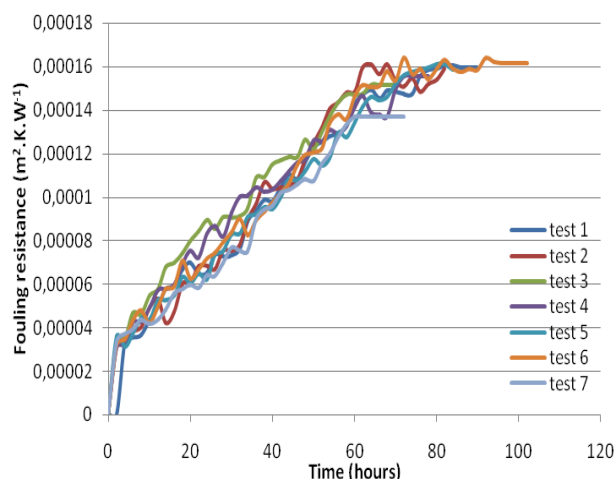


Fig. 3 Variation of the fouling resistance as a function of time.

From the values of these resistances, which are the higher than zero, the heat exchanger contains in his surface fouling. The curves presented show that the temporal evolution of the fouling resistance, appears to follow an asymptotic evolution, which conforms to the model of Kern and Seaton [18], with the lack of the induction period. This is explained by the fact that there are a time offset between the last cleaning, which corresponds to $t = 0$, and the beginning of this experiments. As it appears clearly as the fouling resistance increases with time until reaching a maximum value, ranging from $6.99 \cdot 10^{-5}$ to $1.65 \cdot 10^{-4} \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$. As can be seen from Fig. 3, the time required to reach a fouling deposit is 70 h for the tubular heat exchanger. As of that moment, the asymptotic zone begins and the fouling thickness does not vary any more overtime.

At that time, it is necessary to stop the heat exchanger for an emergency cleaning.

The fluctuations observed on these curves are caused by the variation of flow rate, which, acting on the shear stress on the wall, causes re-entrainment of deposit particles or their deposition depending on the flow rate sent.

So, it is necessary to know the operational parameters which promote the formation of fouling in the concentration process, such as:

- The decrease of the phosphoric acid flow rates, whence the decrease the fluid speed (phosphoric acid);
- The good quality of the phosphoric acid: a very low content of impurity;
- The washing water of the heat exchanger is well treated and does not pose the tartar and corrosion problem.

TEMPORAL EVOLUTION OF VOLUME FLOW RATES

Fig. 4 and 5 shows a temporal evolution of the volume flow rates at the tube side (phosphoric acid) and the shell side (steam) in heat exchanger. The values for the flow rates are picked up directly from the concentration process. We therefore note, according to these Figures, that the volume flow rates of phosphoric acid is higher than the volume flow rates of steam, elsewhere, the flow rates of the two fluids decreases in the time. As shown previously according to Fig. 3, which represent the increase of the fouling resistance as a function of time in the heat exchanger, we have noticed that this increase caused the decrease of the volume flow rates of fluids (tube side and shell side), as of Fig. 4 and 5.

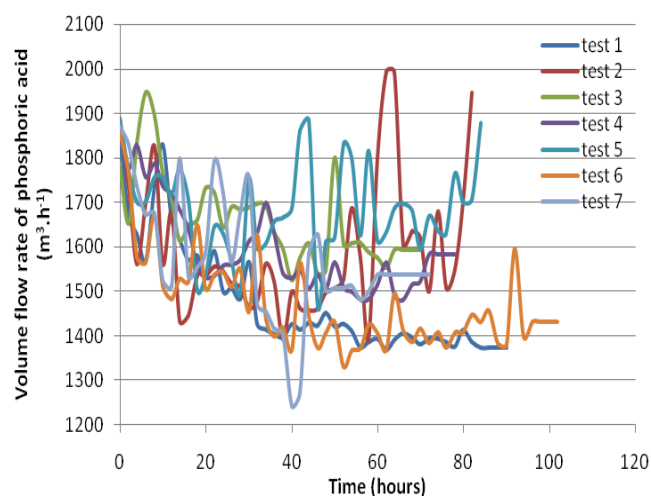


Fig. 4 Variation of volume flow rates of phosphoric acid as a function of time.

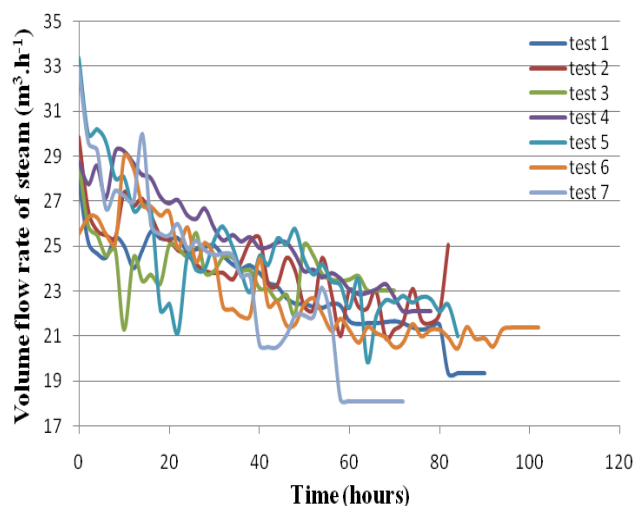


Fig. 5 Variation of volume flow rates of steam as a function of time.

TEMPORAL EVOLUTION OF THE DIFFERENCE PHOSPHORIC ACID TEMPERATURE

The fluid temperature also has a complex effect on the fouling resistance. Various behaviors, among which the increase, decrease and the absence of variation of the

resistance to fouling with the increase of the temperature of the fluid have been reported so far.

The variation in the temperature difference of the phosphoric acid solutions is illustrated on Fig.6.

As expected, the resistance to fouling depends on the temperature of the fluid. When the temperature difference of the fluid on the tube side decreases, the resistance to fouling due to crystallization increases. The temperature range at $t = 0$ is between $[8.6-11.1^{\circ}\text{C}]$, while at the end of the operating cycles, it is of the order of $[7-9.3^{\circ}\text{C}]$, for the tubular heat exchanger.

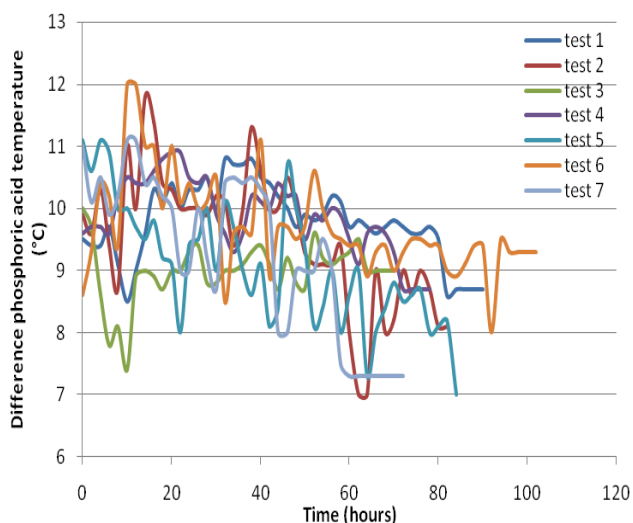


Fig. 6 Variation of temperature difference of phosphoric acid as a function of time.

TEMPORAL EVOLUTION OF THE STEAM TEMPERATURE

The variation of the temperature of the hot fluid with time is illustrated on Fig.7. As expected, the resistance to fouling depends on the temperature of the heat transfer surface. As the temperature of the heat transfer surface increases, the reaction rate increases with the approach of the Arrhenius relationship and this effect is more pronounced at a higher surface temperature. As a result, the resistance to fouling due to crystallization increases. The temperature range at $t = 0$ is between $[110-116^{\circ}\text{C}]$ while at the end of the operating cycles, it is of the order of $[110-122^{\circ}\text{C}]$ for the stainless steel tubular exchanger.

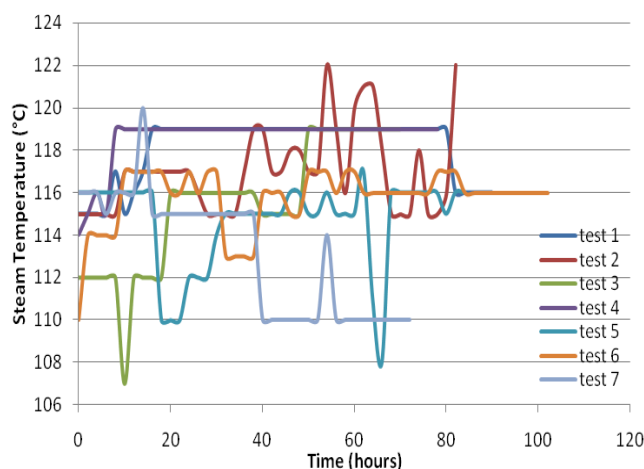


Fig. 7 Variation of steam temperature as a function of time.

TEMPORAL EVOLUTION OF THE PHOSPHORIC ACID DENSITY

The density of the fluid plays a minor role in the fouling behavior. Therefore, the density of the fluid is considered as an independent variable for the calculation of the resistance to fouling.

The effect of the density of the solution on the fouling resistance is shown on Fig.8. The results show that the density has an effect on fouling rates. This figure shows that the increase of the fouling resistance leads to instability of the density.

The important factor for fouling of crystallization is the degree of super-saturation of the species forming the deposit, rather than the density. Therefore, the extent of super-saturation will generally determine the rate of the crystallization or deposition process.

Super-saturation leads to nucleation and consequently to crystal growth. Whatever the mechanism of fouling, the effect of the density is strong and it is more pronounced under controlled reaction conditions.

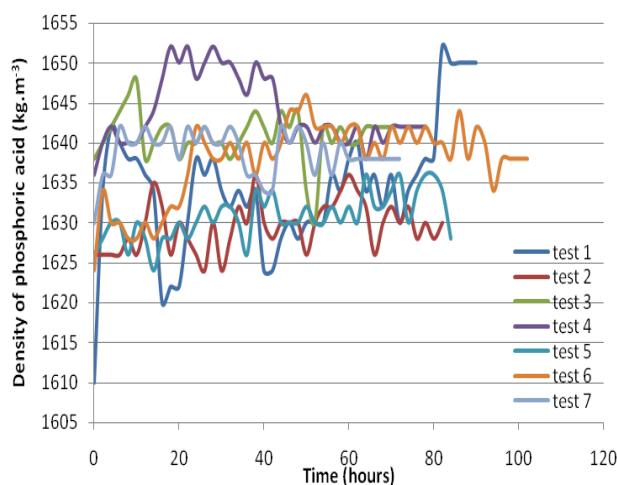


Fig. 8 Variation of phosphoric acid density as a function of time.

V. CONCLUSIONS

The monitoring of heat exchangers allows to fully knowing the fouling evolution under specific conditions of the process. The deposit formation is a thermal resistance that causes significant economic and ecological penalties [19].

The objective of this work was the study of the heat exchanger fouling phenomenon in the concentration process. The study focused on the temporal evolution of the fouling resistance, the volume flow rates, the temperature difference of phosphoric acid, the steam temperature and the effect of the phosphoric acid density.

Results indicated that the fouling resistance follows an exponential evolution in conformity with the model of Kern and Seaton with the absence of the induction period, which is explained by a poor cleaning, or a deviation between the present study and the beginning of the functioning of the heat exchanger after the last stop.

In the concentration process, the phosphoric acid flow rates is not maintained constant, they decrease as a function of time, this is explained by the important production demand as well as the problems which appear when the unit function.

Concerning the influence of parameters on the fouling resistance, we found an analogy between our experimental results and the theoretical prediction. Indeed, the increase of the fouling resistance causes the decreases of volume flow rates of both the phosphoric acid and the steam, the decrease of temperature difference of phosphoric acid and the increase of steam temperature and phosphoric acid density.

The instability of the operating conditions (flow rates, input and output fluids temperatures, density...) is favorable factors for the deposits formation in the heat exchanger.

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NOMENCLATURE

A	Area, m ²
C _p	Specific heat capacity, J.Kg ⁻¹ .K ⁻¹
F	Correction Factor (=1 for a steam condenser)
\dot{m}	Mass flow rate, kg.s ⁻¹
Q	Thermal power, W
R _f	Fouling resistance, m ² .K.W ⁻¹
T	Temperature, K
t	Time, h
U	Global heat transfer coefficient, W.m ⁻² .K ⁻¹
\dot{V}	Volume flow rate, m ³ .h ⁻¹
Greek letters	
Δ	Difference of greatness between two points

Subscripts

ac	Acid
cir	Circulation
in	Input
ml	Logarithmic average
0	Clean
out	Output
s	dirty state
st	Steam
p	proper state