EVALUATION OF OLIGOMER FOULING RESISTANCE IN A PLATE HEAT EXCHANGER FOR HEAT RECOVERY FROM POLYESTER DYEING WASTEWATER

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ABSTRACT

The aim of this work is a preliminary investigation of the possible correlation between the fouling resistance and the operating conditions of a Plate Heat Exchanger (PHE) operating on a real wastewater from the textile industry. Existing literature approaches are mainly devoted to the treatment of liquid streams from the food industry and are not reliable for predicting the behaviour of a PHE with dyeing wastewater. In particular, when liquids from polyester dyeing are involved, the presence of many oligomer compounds strongly affects the fouling phenomenon.

A PHE has been installed in a polyester dyeing mill where exhaust dyeing liquors contain noticeable amounts of oligomers and both the overall heat transfer coefficient and fouling resistance were measured for different operating times and liquid flow rates. The results suggest a linear relationship between the fouling resistance and both time and liquid flow rate.

The evaluation of the deposit mass on the surface of each plate was also performed and demonstrated that the contribution of the cold stream to total fouling was negligible. The fouling resistance can therefore be correlated to the total mass of deposit measured on the hot-side of the PHE.

Keywords: plate heat exchangers; fouling; wastewater; thermal recovery.

INTRODUCTION

Plate heat exchangers (PHE) are preferentially used when a large heat transfer area or high heat transfer coefficient are required. They offer additional advantages in terms of compactness and easy removal of fibrous deposits, as in the case of wet textile operations; internal inspection is also easier with respect to the more common shell-and-tube exchangers.

Fouling is a complex phenomenon caused by the undesired accumulation of deposits on the internal surfaces of the heat exchanger, where the fluids are flowing. This results in a considerable reduction in the heat transfer efficiency. More details on the different fouling mechanisms can be found in the literature (Epstein, 1988; Grandgeorge et al. 1998; Hesselgreaves, 2002).

The efficiency loss of the heat exchangers due to fouling has very significant economic and technical implications: costly overdesign and frequent cleaning are empirical approaches to keep the system working. For this reason, determining the time-evolution of the fouling coefficient allows scheduling maintenance and cleaning procedures, thus minimizing out-of-service events and optimising heat recovery from hot fluids.

The scientific literature reports several examples describing PHE fouling, mainly in the dairy industry (Delplace et al. 1997; Visser and Jeurnink, 1997), since this type of exchanger is widely used in this industrial field. In contrast, data on PHE performance related to dyeing wastewater are lacking. The correct design and usage of a PHE intended for heat recovery from a hot textile water stream appears to be quite difficult, since the phenomena connected to fouling in the dairy industry are very different from those encountered in textile processing.

The aim of this work is to investigate the possible correlation between the fouling coefficient in a PHE, which operates on a real textile wastewater stream, and the operating time of the unit. It is a preliminary work mainly intended to set up an experimental procedure to correctly evaluate the fouling coefficient and to monitor its trend with time. For this purpose a pilot PHE unit has been installed in a polyester dyeing mill where exhaust dyeing liquors contain noticeable amounts of oligomers, which are the main ingredients responsible for heat exchanger fouling in this specific textile branch. Polyester dyeing, in fact, usually requires high process temperatures (approximately 130° C) since the glass transition temperature of the polymer is high (in excess of 80 °C). As a consequence, oligomers are released from the polyester fibres. Wastewater streams, then, contain large amounts of oligomers as well as residual dyes, many dyeing auxiliaries and fiber fines. All these components contribute to fouling and the loss of heat transfer efficiency when the stream is introduced into a heat exchanger. In particular, oligomer compounds are initially dissolved in water due to the high dyeing temperature and, due to cooling, precipitate as fine particles, progressively forming paste deposits adhering to the downstream equipment surfaces. This is a typical problem encountered in the textile industry, since oligomer deposits not only affect the heat transfer coefficient of heat exchangers but

also the quality of the final dyed product. This phenomenon also requires discharge of the dyeing equipment under pressure at about 130° C to avoid oligomer precipitation.

EXPERIMENTAL METHODS

A PHE pilot plant (Gea Ecoflex PWT Varitherm VT 20 type) was installed and operated at a polyester yarn dyeing plant in parallel with a similar industrial size unit. The experimental equipment had 17 plates with chevron angles of 60° and 30°, an individual plate surface area of 0.26 m^2 and a nominal plate separation distance of 3.2 mm. The gasket system was composed of NBR packings to drive the fluids through the required paths inside the plate exchanger. Two channels per four passes generated a flow similar to a countercurrent heat exchanger (Figure 1). The design flow rate was 2 m^3/h for both streams. The hot stream was taken directly from the wastewater current at the outlet of the dyeing section of the polyester mill; the cold stream was cold freshwater. The two flow rates were regulated through two control valves and two rotameters.
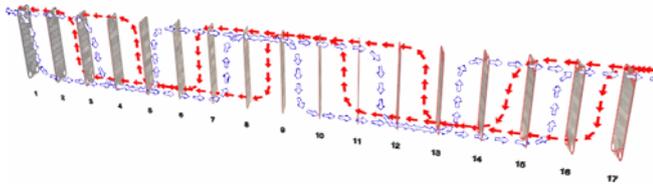

Fig. 1 Flow paths inside the PHE. Solid arrows indicate wastewater as hot fluid; empty arrows indicate clean water as cold fluid.

The total volumetric throughput was also monitored over time by two water meters and used as a monitoring coordinate. During all experiments reported in this work, both streams were kept at the same flow rate. Figure 2 shows the schematic of the pilot equipment where the hydraulic circuit components and the PHE can be seen.
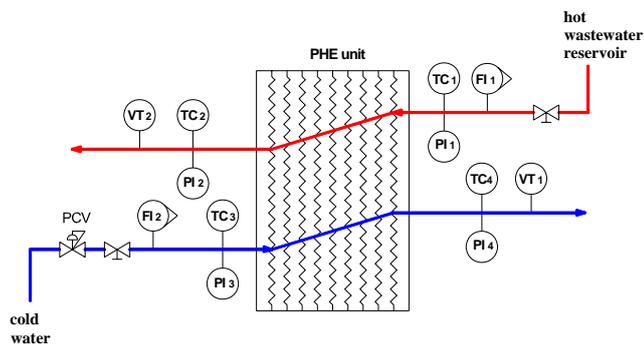

Fig. 2 Schematic of the experimental apparatus.

The fluid temperatures were measured by means of K type thermocouples positioned at the inlets and the outlets of the PHE. Temperature data profiles were recorded by a smart card interfaced to a PC. Temperature values were logged at time intervals of 10 seconds. Figure 3 reports, as an example, the temperature profiles recorded during a typical test run.
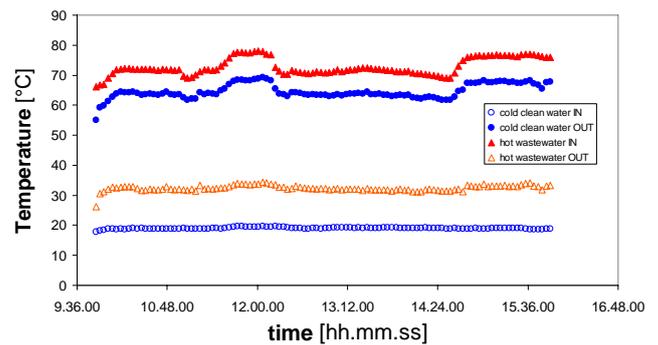

Fig. 3 Temperature profiles monitored during a one-day test (flow rate = 1.5 m^3/h).

Each experimental run lasted several hundreds of hours. At the end of each run, the PHE was cleaned by counter-washing with solutions of caustic soda at 80°C. Each test was extended over time to measure a significant reduction in the heat transfer coefficient; the corresponding wastewater volume that flowed through the exchanger was between 1000 and 1500 m^3. By maintaining the operating conditions constant over long periods, the flow rate was set in different experiments at 2.0, 1.5 and 1.0 m^3/h.

The overall heat transfer coefficient U = U(t) was calculated by knowing the inlet and outlet temperatures, writing the heat balances and the transfer equation according to:

$$UA = q/\Delta T_{lm} \tag{1}$$

The overall heat transfer coefficient U is given by:

$$U = 1/[(1/h_c + 1/h_h) + s/k + 1/h_f] \tag{2}$$

where h_c and h_h are the cold- and hot-side heat transfer coefficients; s and k represent the plate thickness and thermal conductivity, and h_f is the fouling coefficient. For a thin metallic plate characterized by a high thermal conductivity, Eq. (2) can be simplified to:

$$U = 1/[(1/h_c + 1/h_h) + 1/h_f] \tag{3}$$

The overall heat transfer coefficient, multiplied by the exchange area A, was then calculated and presented in Figure 4, which shows the data obtained from the temperature profiles reported in Figure 3. The less than 6% average difference between the two independently calculated data sets can be ascribed to fluctuations of the cold water flows from the mains.
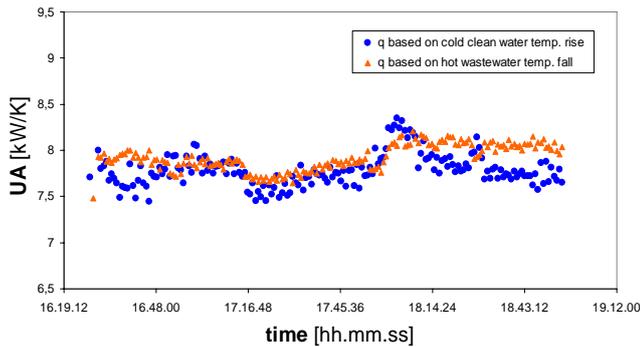
Fig. 4 Evaluation of the overall heat transfer coefficient from the temperature profiles monitored during a one-day test as reported in Figure 3 (flow rate = 1.5 m³/h).

As shown in the following section, monitoring the overall heat transfer coefficient for long periods of time resulted in a considerable decrease of U due to fouling. The fouling thermal resistance, $R_f(t)$, was then calculated according to:

$$R_f(t) = 1/h_f = 1 / U(t) - 1 / U_0 \qquad (4)$$

where U_0 corresponds to the clean surface conditions at the initial time.

RESULTS AND DISCUSSION

Figure 5 reports the overall heat transfer coefficient, multiplied by the exchange area A, plotted against the actual time of fluid flow through the PHE during the trial. The figure reports the data at three flow rates. It can be noted that higher flow rates yield higher heat transfer coefficients.
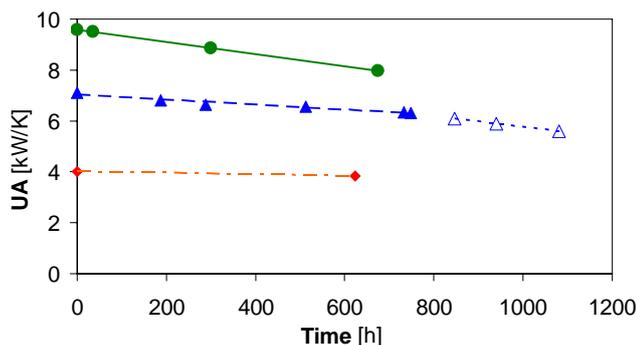

Fig. 5 Overall heat transfer coefficient *vs* time: --●-- flow rate = 2 m³/h; --▲-- flow rate = 1.5 m³/h initial run; --△-- flow rate = 1.5 m³/h continuation of the run; --◆-- flow rate = 1 m³/h.

The fouling thermal resistance $R_f(t)$ was calculated according to Eq. (4) and $R_f(t)/A$ is plotted versus time in Figure 6. It is clear that for the investigated operating conditions the fouling resistance increases linearly with time.

Figure 7 shows that the fouling rate, and therefore the value of R_f after a fixed operating time, increases linearly

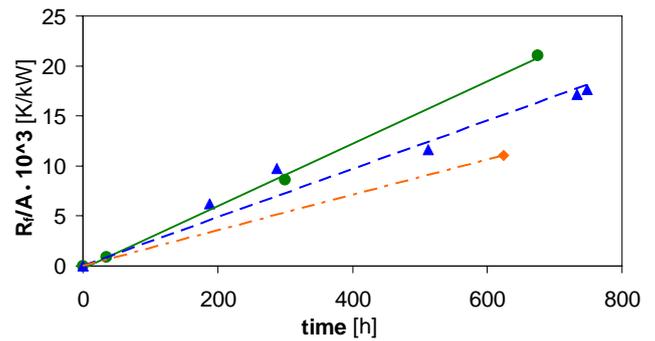with flow rate over the range of flow rate tested.

Fig. 6 Fouling resistance *vs* time: --●-- flow rate = 2 m³/h; --▲-- flow rate = 1.5 m³/h ; --◆-- flow rate = 1 m³/h.
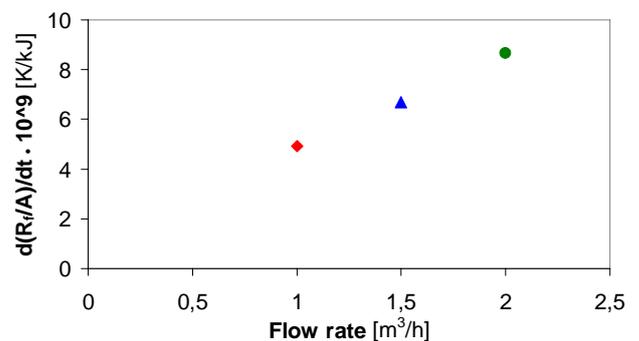

Fig. 7 Fouling kinetics at various operating conditions.

The increase of fouling rate with wastewater flow rate can be attributed to mass transfer control of the fouling process (Epstein, 1988), the wastewater velocity never exceeding 0.30 m/s (Re ≤ 3200) for deposits that are gluey, sticky, adhesive and pasty. These preliminary results thus indicate that a linear relationship between the fouling resistance and both time and liquid flow rate could be found. Further experiments at different liquid flow rates are required to develop a comprehensive mathematical correlation.

Additional data are also required to establish a direct correlation between the mass of deposit and the fouling resistance. A procedure was tested on the experimental apparatus here presented.

At the end of each run, the plate heat exchanger was completely dismantled in order to quantify the mass of deposit on each plate. First, each plate surface in contact with the cold stream was cleaned with a proper sulphuric acid solution; the cleaning solution was then collected for subsequent COD determination. Chemical Oxygen Demand (COD) is a redox method (reduction of potassium dichromate, to oxidize the organics, i.e. the oligomers in this case) that is conventionally assumed to be a direct stoichiometric measure of the deposit (or oligomers) concentration in the cleaning solution. Second, the plate surface in contact with the hot stream was immersed in hot water while a brush removed the dirt. The cleaning liquid was again collected and the COD determination was carried out.

The results showed that the COD values measured for the cold-side surfaces were orders of magnitude lower than those found for the hot-side ones. This indicates that the contribution of the cold stream to total fouling is negligible.

From the COD values and the total mass of cleaning liquid employed at each plate, the total mass of deposit for each surface can be evaluated. Figure 8 reports the mass of deposit profile for the hot-side channels in the PHE, obtained after the experiment at 1.5 m^3/h. Similar trends were observed for the other two flow rates. Each point is the value on one of the two hot surfaces of each channel. The linear trend is approximately linear due to the fact that the hot liquid enters the channel between plate # 16 and 17 and exits from that between plate # 2 and 3 (Figure 1). Fouling occurs mainly in the first channels crossed by the hot fluid since it is dirtier. The only exception to this trend is given by the values measured in the first hot channel (between plate # 16 and 17), where the stream was not cooled enough and there was insufficient cooling time, to achieve significant precipitation of oligomer compounds. The sum of the deposit masses measured in each hot channel can also be evaluated (approximately 50.7 g), representing the total mass of deposit responsible for fouling.
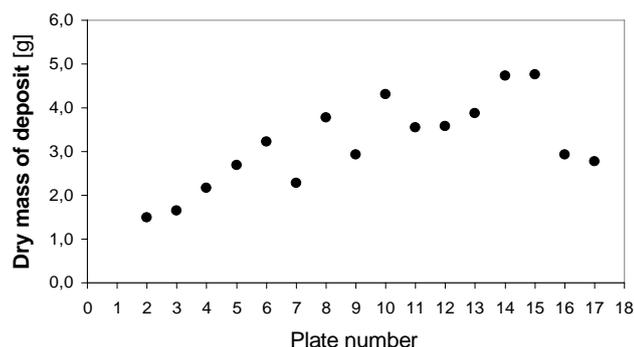

Fig. 8 Profile of deposit mass removed from the hot-side of each plate in the PHE, flow rate = 1.5 m^3/h.

CONCLUSIONS

An experimental apparatus has been set up and preliminary experiments have been conducted to quantify the fouling resistance in a PHE that operates on a real textile wastewater stream.

1. The results obtained suggest a positive linear relationship between the fouling coefficient and both time and liquid flow rate.
2. The increase of R_f with flow rate suggests mass transfer, rather then shear stress, control of the fouling rate.
3. The evaluation of the mass of deposit on the surface of each plate demonstrated that the contribution of the cold stream to total fouling was negligible. The fouling resistance can then be correlated to the total mass of deposit measured on the hot-side of the PHE.
4. Oligomer fouling was shown to be a strong positive function of temperature.

5. The results demonstrated that the experimental procedure allows credible measurement of both the fouling resistance and the mass of deposit at different liquid flow rates.
6. Additional data are required to propose a comprehensive mathematical correlation useful to predict the time-evolution of the fouling resistance and the mass of deposit for different sizes of the heat exchanger.

ACKNOWLEDGEMENTS

NOMENCLATURE

A	heat transfer surface area, m^2	
h_c	heat transfer coefficient, W /m^2 K	
h_f	fouling coefficient, W / m^2 K	
h_h	heat transfer coefficient, W / m^2 K	
k	thermal conductivity, W / m K	
q	heat flow rate, J / h	
$R_f(t)$	fouling thermal resistance, $1/h_f$, m^2 K / W	
S	plate thickness, m	
t	time, h	
U(t)	overall heat transfer coefficient, W / m^2 K	
U_0	clean overall heat transfer coefficient, W / m^2 K	
ΔT_{lm}	logarithmic mean temperature difference, K	

Subscript

c	cold side
f	fouling
h	hot side
0	initial condition at t = 0

REFERENCES

Epstein, N., 1988, General thermal fouling models, in *Fouling Sci. and Tech.*, edited by L. F. Melo, T. R. Bott and C. A. Bernardo, Kluwer Academic Publishers, pp. 15-30.

Grandgeorge, S., C. Jallut and B. Thonon, 1998, Particulate fouling of corrugated plate heat exchangers. Global kinetic and equilibrium studies, *Chem. Eng. Sci.*, Vol. 53 (17), pp. 3051-3071 .

Hesselgreaves, J.E., 2002, An approach to fouling allowances in the design of compact heat exchanger, *Appl. Thermal Eng.*, Vol. 22, pp. 755-762.

Delplace, F., J.C.Leuliet and D.Levieux, 1997, A reaction engineering approach to the analysis of fouling by whey proteins of a six-channel-per-pass plate heat exchanger, *J. Food Eng.*, Vol. 34, pp. 91-108.

Visser J. and Th. J. M. Jeurnink, 1997, Fouling of heat exchangers in the dairy industry , *Exp. Thermal and Fluid Sci.*, Vol. 14, pp. 407-424.