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Fouling of Polymeric Hollow Fiber Heat Exchanger by Wastewater

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Warm wastewater can be used as a source of heat for heat pumps in buildings such as gyms, swimming pools, and laundries. Unfortunately, heat exchangers installed in a sewage channel are negatively affected by fouling because deposits on the heat exchange surface create additional resistance to heat transfer and decrease the efficiency of the system. Heat exchangers consisting of polypropylene hollow fibers were prepared and tested to transfer heat from two types of wastewater: from a shower and from laundry.
It was found that these devices have high thermal performance (with an overall heat transfer coefficient of up to 2,020 W/m^2 K) while working in clean conditions. Fouling tests showed that fouling strongly depends on the type of wastewater. During the experiment with shower wastewater the observed fouling was low because it was associated with the accumulation of a small amount of solid particles (particulate fouling). No significant decrease of overall heat transfer coefficient was observed during the two-week test in this case. The experiment with laundry wastewater showed that fouling was more extensive because it was associated with both types of fouling: particulate fouling and biofouling. The overall heat transfer coefficient was decreased by two times (from 1747 W/m^2 K to 863 W/m^2 K) during the 35-day experiment.

1. Introduction

Wastewater (sewage) is a source of energy which can be used for heating buildings and tap water with heat pumps. The technology is simple and proven. According to Schmidt (2006) over 500 wastewater heat pumps are in operation world-wide. However, heat exchangers installed in sewage channels are negatively affected by fouling. Fouling in sewage is complex and consists of two basic types: particulate fouling and biofouling. Particulate fouling is the growth of deposits on a surface associated with the adhesion of solid particles. Biofouling is the growth of a layer of micro-organisms (bacteria, algae and fungi) or macro-organisms (mussels, barnacles, hydroids) (Bott, 1995). Crystallization and corrosion is considered as insignificant and non-affecting.

The growth of deposits on heat exchange surface creates additional resistance to heat transfer and decreases the efficiency of the system. Fouling is considered as a main disadvantage and challenge of waste water heat pump application (Hepbasli, 2014). A few articles concerning waste water applications of plastic heat exchangers are published but they show that plastic heat exchangers are more advantageous than metal for such conditions (Chen, 2006). Comparison of several plastics (polyethylene, polypropylene (PP) and fluoroplastics) showed that PTFE is very proper choice due to its mechanical properties, chemical stability and low adhesion (Chen, 2011).

Nevertheless cheaper materials such as PP are suitable also. The low-cost and light heat exchanger from polypropylene (PP) hollow fibers was prepared and tested under fouling conditions in wastewater. A previous study showed that small-diameter fibers have a superior overall heat transfer coefficient (Astrouski, 2013), smooth surface and low surface energy, causing chemical inertness and low adhesion (Mark, 1999). Polymer fibers are also flexible enough to move in a flow. According to Wicaksana (2006), bubbling is commonly used to control the fouling of submerged hollow fibre membranes. In the same manner, injecting pressurized air can increase liquid velocity, causing the movement of fibers and deposit removal.

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2. Experimental section

2.1 Experimental equipment

Our experimental set-up (see Figure 1) consisted of wastewater and cooling circuits that are connected by the test section. The wastewater was heated by an electric heater in a tank and then was cooled with tap water when it passed through the test section. The fouling process was monitored by measuring the reduction of the overall heat transfer coefficient.

The test section consists of the hollow fiber heat transfer bundle placed into a transparent Plexiglas shell (100 mm in diameter). The wastewater flows through the shell while the coolant (tap water) flows through the lumen path of the bundle. The shell is under atmospheric pressure and the wastewater flows though it aided by gravity, then a circulating pump (Calpeda NCE EL) lifts the wastewater up and it flows down through the shell). The level in the shell is adjusted by siphon piping and the shell flow rate is controlled by a three-way valve installed upstream. This flow regime is similar to the flow in unpressurized sewage systems. The wastewater returned from the shell is reheated in a tank with three heaters with a total capacity of 6 kW to a temperature of 27-31 °C. The wastewater flow rate is measured with a float-type Parker LoFlow 802414 flowmeter (3-22 l/min range). The cold tap water was pumped through the fiber bundle by a centrifugal pump (Pumpa PKM80-1). The flow rate of tap water is adjusted by means of a globe valve and measured by a Parker LoFlow 802413 flowmeter (2-10 L/min range). The flowmeters were calibrated by measuring the time required to collect a certain volume of liquid. The tap water temperature was not controlled and was in the range 10-12 °C depending on flow rate. An inline filter (50 µm particle size) was installed upstream from the fiber bundle to protect the lumen path of fibers from fouling. All temperature measurements were made with Omega PT100 (1/3 DIN Class B precision) sensors and recorded by an Omega Daqpro-5300 datalogger with an accuracy of ± 0.1 °C and frequency 0.1 Hz.

The fiber bundle (see Figure 1) is built from PP fibres whose ends were collected in plastic fittings and moulded by epoxy resin. The fibers were twisted with different curvatures (50-100 mm) to ensure a good distribution of fibres in volume. The bundle was pressurized by water up to a 4-bar gauge pressure to ensure an absence of leaks. Moreover, coloured water (with dye added) was used to determine fibers through which water could flow. Bundles parameters were as follows: fiber number $N = 470$, effective heat transfer length $L = 650$ mm, outer and inner fiber diameters are $D_{out} = 0.7$ mm, $D_{in} = 0.6$ mm and overall heat transfer area based on internal fibre surface $A_{in} = 0.58$ m^2.

2.2 Test procedure

At the beginning of the experiment, a clean heat transfer coefficient was defined with clean water. All experimental runs started with a new, clean heat transfer bundle. Then, tests with wastewater were conducted. The overall heat transfer coefficient (OHTC) was measured once per several days to estimate fouling evolution. Wastewater circulated in the fouling circuit during the entire experiment although tap water and the heater were switched on during HTC measurement only. At the end of each experiment, the fouled heat transfer bundle was removed and inspected for the presence of deposits.

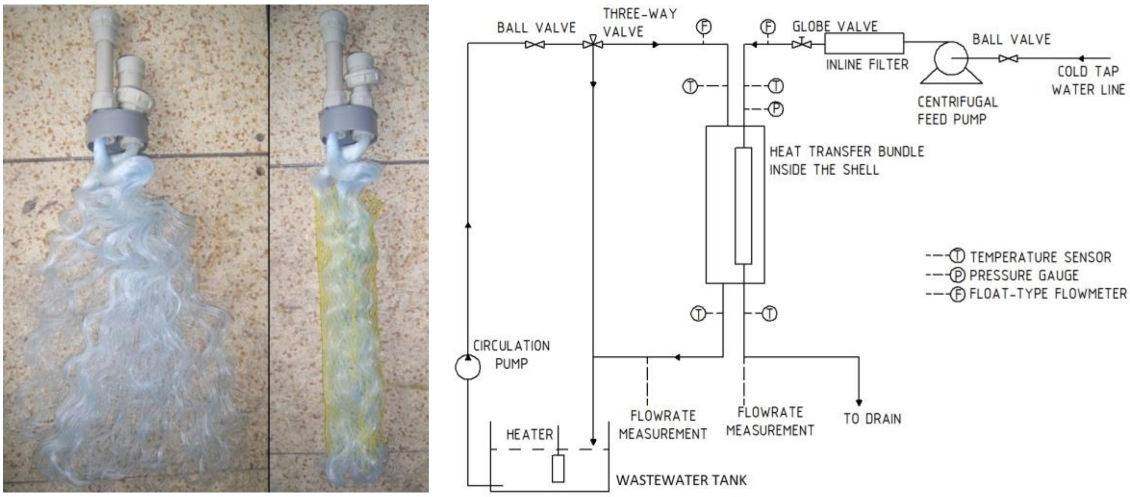

Figure 1: The heat transfer bundle before placement in the heat exchanger shell and the experimental set-up diagram (right)

2.3 Wastewater specification

Two types of wastewater were studied as fouling medium: from shower and laundry wastewater. The following parameters were chosen as significant (see Table 1):

- The chemical oxygen demand (COD) test is commonly used to indirectly measure the amount of organic compounds in water. Most applications of COD determine the amount of organic pollutants found in surface water or wastewater, making COD a useful measure of water quality. It is expressed in milligrams per liter (mg/l), which indicates the mass of oxygen consumed per liter of solution.
- The biochemical oxygen demand (BOD) is the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic material present in a given water sample at a certain temperature over a specific time period. This is not a precise quantitative test, although it is widely used as an indication of the organic quality of water. The BOD value was expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20 °C and is often used as a robust surrogate of the degree of organic pollution of water.
- pH is a measure of the acidity of an aqueous solution.
- Electrical conductivity (specific conductance) measures a material's ability to conduct electricity.
- Turbidity is the cloudiness or haziness of a fluid caused by individual particles (total suspended or dissolved solids) that are generally invisible to the naked eye. Turbidity is measured with a nephelometer and expressed in Nephelometric Turbidity Units (NTU).
- P_{ov} and N_{ov} are the overall amounts of dissolved phosphorus and nitrogen, respectively. Nitrogen and phosphorus in the water cause algae to grow faster.
- Escherichia coli (E. coli) are anaerobic, rod-shaped bacteria that are commonly found in the lower intestine of warm-blooded organisms.
- Coliform bacteria are a commonly used bacterial indicator of the sanitary quality of water. While coliforms themselves are not normally causes of serious illness, they are easy to culture and their presence is used to indicate that other pathogenic organisms of fecal origin may be present.

Table 1: Wastewater properties

Parameter	Unit	Shower wastewater	Laundry wastewater
COD	mg/L	248	242
BOD	mg/L	51.1	136
pH	-	8.12	7.9
Electrical conductivity	µS/cm	897	781
Turbidity	NTU	36	29
P_{ov}	mg/L	1.1	1.1
N_{ov}	mg/L	0.28	4.4
E. coli	KTJ/100 mL	0	68
Coliform bacteria	KTJ/100 mL	50	299

2.4 Reduction data

The thermal performance of a heat exchanger can be expressed through the overall heat transfer coefficient (OHTC):

$$U_{ov} = \frac{q}{A \Delta T_{lm}} \tag{1}$$

where q is the exchanger heat transfer rate (W), A is the heat transfer surface area of the heat exchanger (m^2) and ΔT_{lm} – is the logarithmic mean temperature difference (K). Fouling causes a decrease in OHTC and can be expressed as fouling thermal resistance R_f (Bott, 1995). It is given by

$$R_f = \frac{1}{U_f} - \frac{1}{U_0} \tag{2}$$

where U_f and U_0 are heat transfer coefficients for clean and fouled conditions.

During fouling, the deposit thickness generally reaches a constant asymptotic value R_{fa} (Bott, 1995). If the fouling layer thermal conductivity and density are constant, the time evolution of the fouling thermal resistance can be expressed through the asymptotic value R_{fa} and fouling process time constant t_c as:

$$R_f(t) = R_{fa}\left(1 - e^{-t/t_c}\right) \tag{3}$$

3. Results and discussion

3.1 Shower wastewater

The clean OHTC obtained with pure water (1,640 W/m^2 K) was higher than that obtained with shower wastewater (1,427 W/m^2 K). This can be explained by the different thermophysical properties and difference in flow regime. It should also be noted that shower wastewater has detergents and produces foam and bubbles inside of the shell. In fact, the shell-side flow is two-phase and consists of a water-air mixture. It seems reasonable that this mixture has a lower thermal conductivity causing a decrease of heat transfer.

Table 2 presents the experimental results obtained during 2-week tests. It includes the measurement date, mass flow rates of cooling water and wastewater (m_{12}, m_{34}), inlet and outlet temperatures of both streams (T_1, T_2, T_3, T_4), heat transfer rate Q (calculated based on cooling water data), log-mean temperature difference LMTD, overall HTC U_{ov} and fouling thermal resistance R_f. During two weeks no significant reduction of overall HTC was observed (HTC values were similar to reference value). The small oscillation of HTC is related to the oscillation of flow rate and temperatures during measurements. Few solid particles were observed on the fibers surface at the end of the experiment (see Figure 2). The bio-fouling presence was small so what fouling did occur was particulate fouling. The low rate of biological growth is confirmed by the bacteria level and BOD of shower wastewater. Adhesion forces between particles and the fiber surface were not strong so deposit could be removed relatively easily. This result agrees with Astrouski (2013) which stated that particulate fouling is not strong on polypropylene fibre surface.

Table 2: Shower wastewater fouling experimental data

date	m_{12} kg/s	T_1 ˚C	T_2 ˚C	m_{34} kg/s	T_3 ˚C	T_4 ˚C	Q W	LMTD ˚C	U_{ov} W/m^2 K	R_f (m^2 K)/W
Day 1	0.121	12.2	25.8	0.262	30.6	25.6	6,882	8.4	1,427	0
Day 2	0.120	12.0	24.3	0.251	28.4	24.2	6,157	7.4	1,440	$-6.203\cdot10^{-06}$
Day 5	0.120	12.4	25.7	0.252	29.8	26.8	6,658	8.2	1,410	$8.242\cdot10^{-06}$
Day 8	0.120	12.3	24.9	0.255	29.6	24.5	6,300	7.9	1,391	$1.779\cdot10^{-05}$
Day 11	0.120	12.5	25.2	0.256	29.8	25.5	6,357	8.1	1,365	$3.146\cdot10^{-05}$
Day 13	0.121	11.5	24.2	0.255	28.4	24.1	6,411	7.7	1,456	$-1.415\cdot10^{-05}$

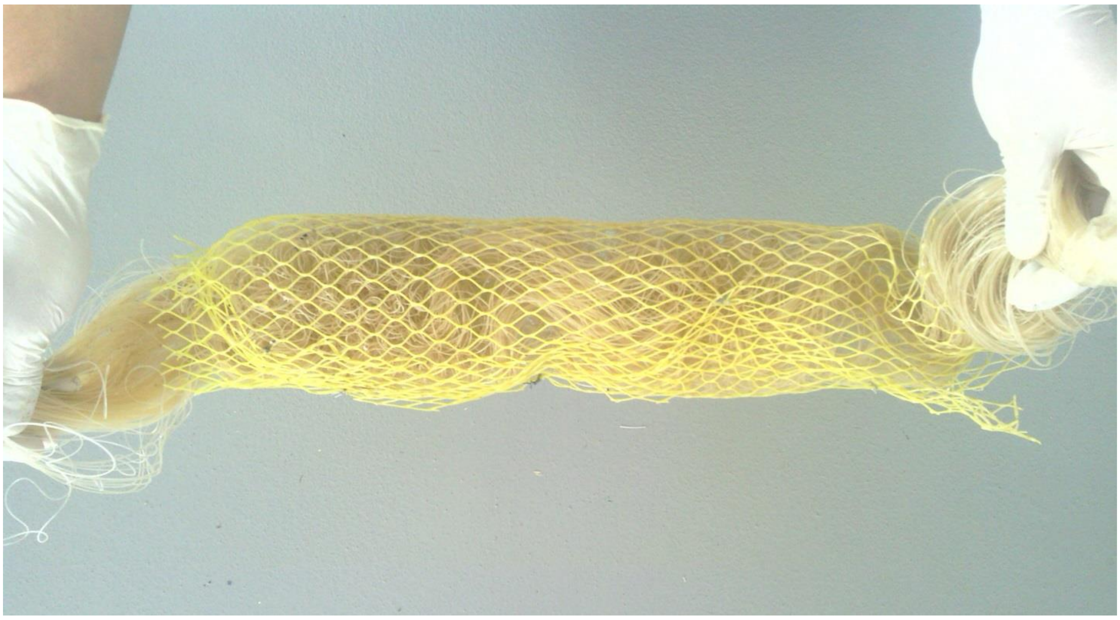

Figure 2: Heat exchange bundle after 2-week experiment with shower wastewater. There is no significant fouling found on the surface, a few solid particles were observed on the fiber surface

3.2 Fouling by laundry wastewater

The experiment with laundry wastewater was conducted over 35 days. The clean OHTC obtained with pure water (2,026 W/m^2 K) was higher than that obtained with laundry wastewater (1,747 W/m^2 K). This discrepancy can be explained the same way as in the case of shower wastewater.

Fouling by laundry wastewater was much more intense than with shower wastewater. The heat exchange bundle was removed from the shell at the end of experiment (see Figure 3). It had collected a great deal of viscous and sticky deposits consisting of biofilm and solid particles. The presence of bio-fouling was also confirmed by wastewater analysis: a high BOD and bacteria level.

The experimental results are presented in Table 3. HTC decreased approximately twice during the 35-day experiment. The values of fouling thermal resistance were, by Equation 2, based on OHTC. These data were fitted to a curve corresponding to Eq. (3). Figure 4 shows the evolution of OHTC and fouling thermal resistance. It can be concluded that fouling achieved about an asymptotic (maximum) value during the 35 days. The value of asymptotic fouling resistance R_{fa} is about 5 times higher that R_{fa} found by Chen, 2011. The discrepancy can be explained by different experimental conditions: wastewater properties, type of heat transfer surface, flow velocity, etc.

Table 3: Laundry wastewater fouling experimental data

date	m_{12} kg/s	T_1 ˚C	T_2 ˚C	m_{34} kg/s	T_3 ˚C	T_4 ˚C	Q W	LMTD ˚C	U_{ov} W/m^2 K	R_f (m^2 K)/W
Day 1	0.132	11.3	23.3	0.267	27.3	21.4	6,626	6.6	1,747	0
Day 2	0.132	11.0	22.7	0.267	27.3	22.6	6,478	7.6	1,486	0.000100
Day 5	0.132	11.2	22.8	0.267	28.1	23.4	6,380	8.3	1,307	0.000197
Day 7	0.130	10.7	22.1	0.267	26.9	22.6	6,133	7.8	1,248	0.000227
Day 9	0.133	10.8	22.1	0.267	27.2	23.3	6,298	8.3	1,150	0.000297
Day 12	0.132	10.7	21.7	0.267	29.3	25.4	6,090	10.8	983	0.000445
Day 14	0.130	10.6	21.5	0.267	29.1	24.5	5,917	10.4	972	0.000458
Day 16	0.130	10.4	21.0	0.267	29.2	24.9	5,769	11.1	940	0.000491
Day 19	0.132	10.4	21.7	0.267	30.0	26.6	6,256	11.8	920	0.000515
Day 30	0.131	10.1	22.3	0.267	31.2	27.5	6,657	12.7	912	0.000524
Day 35	0.124	10.1	22.5	0.267	31.8	27.6	6,447	13.0	863	0.000586

Figure 3: Heat exchange bundle after 5-week experiment with laundry wastewater. There is a great deal of viscous and sticky deposits consisting of biofilm and solid particles on the fiber surface

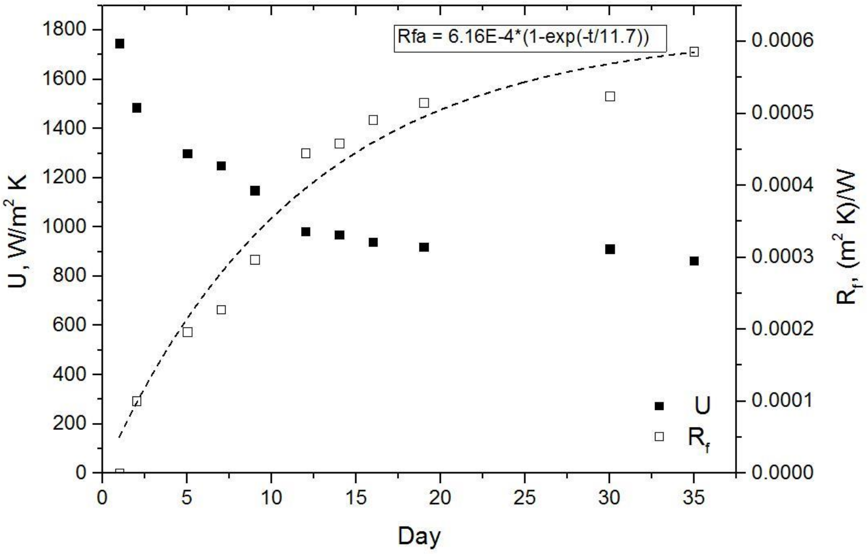

Figure 4: Fouling evolution in time: overall heat transfer coefficient (black squares) and fouling thermal resistance (white squares) during 35-day experiment

4. Conclusions

The fouling of a heat exchanger from polypropylene hollow fibers by two types of wastewater (from shower and from laundry) was studied. It was found that these heat exchangers have high thermal performance (overall heat transfer coefficient up to 2,020 W/m^2 K) and can transfer significant amounts of heat (up to 6.5 kW) when in clean conditions. However, the efficiency is worse when wastewater is used. Fouling tests showed that fouling strongly depends on the type of wastewater. An experiment with shower wastewater showed that fouling was low because it was associated with the accumulation of solid particles (particulate fouling). No significant decrease of overall heat transfer coefficient was observed during two-week tests in this case. An experiment with laundry wastewater showed that fouling was more intense because it was associated with both particulate fouling and bio-fouling. The fouling thermal resistance achieved about 95 % of its asymptotic value (6.16 m^2 K/W) and OHTC decreased approximately twice (from 1,747 W/m^2 K to 863 W/m^2 K) during the 35-day experiment. Thus it can be recommended to start investigations of waste water fouling with study of the water biological activity.

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