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Experimental study of fouling in plate heat exchangers in district heating systems

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Abstract

Fouling in plate heat exchangers is a significant process in the heating industry. This paper presents related experimental research on 2 plate heat exchangers, which are components of the district heating system in Cracow. The primary issue of this research was an analysis of operating conditions such as volume flow rate, temperature of fluids, heat transfer coefficients and thermal resistance of scale deposits in the process of domestic hot water production. As a result fouling thermal resistance over time was determined.

Keywords: fouling, plate heat exchangers, thermal resistance

1. Introduction

Fouling in plate heat exchangers (PHE) is a major problem in heating systems. Plate heat exchangers form a fundamental part of central district heating systems. In every heat substation there are one or more plate heat exchangers, which are primarily responsible for heating and domestic hot water production. In time the hot water that flows through the heat exchanger precipitates a sizeable amount of deposition.

As borne out in many previous research studies, fouling on heat exchanger surfaces has a negative effect on the heat transfer, reducing heat flow rates between hot and cold fluids [1]. Due to a lack of theoretical methodology for predicting scale deposition, the causes of fouling may be viewed as complex. At the present time the most commonly used method for predicting the impact of fouling in heat exchangers is observation of changes in heat transfer during operating time [2]. As a result it is possible to schedule temporary shutdowns for cleaning purposes.

Fouling depends on many parameters, for example: type of heat exchanger and its geometry, type of fluids, temperature of fluids, fluid velocities and pressure, among other factors. The last few decades have seen several studies on the fouling process. Significant investigations were carried out by Kern and Seaton [3] as they propose a theoretical asymptotic model of fouling thermal resistance. Merhab et al. [4] monitored fouling using low-frequency acoustic waves. Lei et al. [5] analyzed the impact of surface roughness of plates in heat exchangers on calcium carbonate fouling. Experimental studies have also shown that surface fouling is a function of the difference between the deposition rate and the removal rate [6].

Further research has identified a significant relationship between wall temperature and flow velocity. On the one hand the maximization of fluid velocity [7] and simultaneous minimization of wall temperature [8] result in a decrease in surface fouling. On the other hand it is important to point out that there is a rapid increase in pressure loss with higher fluid velocity [9].

As a result of fouling in heat exchangers a significant decrease in effectiveness can be observed. In order to keep the heat transfer rate at an acceptable level the inlet temperature of hot fluid or fluid velocity has to be raised. When effectiveness reduces, operating costs increase.

2. Fouling phenomena

Previous studies have shown that there are seven mechanisms by which heat exchanger surfaces become

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fouled [6]:

1. crystallization,
2. particulate deposition,
3. biological growth,
4. chemical reaction,
5. corrosion,
6. freezing,
7. mixed fouling.

Current research proposes that the most important causes relevant to this study are crystallization, particulate fouling and biological growth. The fluid used in the heat exchanger is hot water. This means that one particular problem might be scale deposition during heat exchanger operation. Biological growth should also be considered when PHE are used for domestic hot water production. Furthermore, the water supply may include microorganisms which can grow in such conditions.

3. Plate heat exchangers

The objective of this research was to determine and compare the thermal resistance in plate heat exchangers installed in a district heating. The measurements were conducted on two different plate heat exchangers ownwed by the municipal company supplying heat (MPEC) in Cracow. In both variants the heat exchangers are used for domestic hot water production.

The first PHE, having a power (heat flow rate) of 270 kW and 40 plates, is located in the southern part of the city. The second, having a power of 585 kW and 158 plates, is located in the northern part of the city1.

Table 1: Characteristic of PHE

	PHE 1	PHE 2
Heat transfer surface, m^2/plate	0.11	0.099
Number of plates	40	158
Number of plates	0.160	0.260
Plate material	Stainless steel	
Temp. max, °C	230	180
Temp. min, °C	–195	10

4. Mathematical formulation of the problem

Fouling resistance on plate surfaces is primarily determined through one of two methods. Both are based on monitoring a few parameters during operating time. The on-line methods enable permanent observation of changes in thermal resistance during operation.

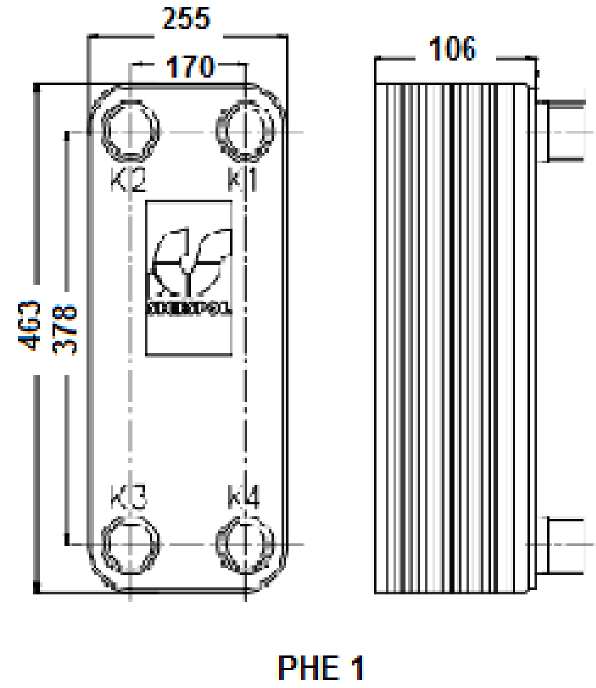

Figure 1: Plate heat exchanger 1 dimensions

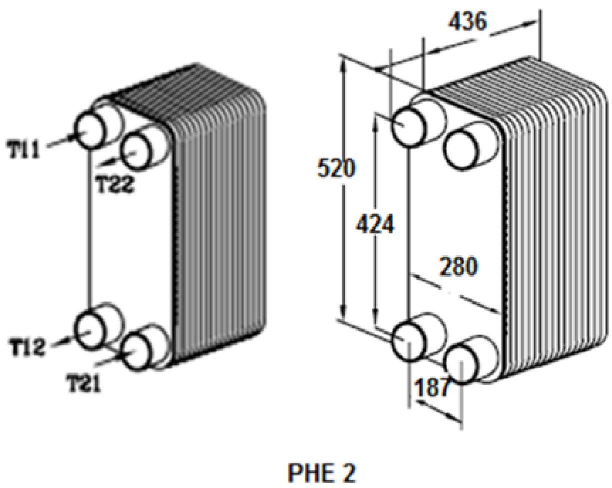

Figure 2: Plate heat exchanger 2 dimensions

These methods require the measurement of the following parameters:

- V_h—volumetric flow rate of hot fluid, m^3/h
- V_c—volumetric flow rate of cold fluid, m^3/h
- $T_{h,in}$ —inlet temperature of hot fluid

- $T_{h,out}$—outlet temperature of hot fluid
- $T_{c,in}$—inlet temperature of cold fluid
- $T_{c,out}$—outlet temperature of cold fluid

4.1. Method I—The log mean temperature difference

The total rate of heat transfer between two fluids can be expressed in three different ways:

- Hot fluid

$$\dot{Q}_h = \dot{m}_h c_h (T_{h,in} - T_{h,out}) \quad (1)$$

- Cold fluid

$$\dot{Q}_c = \dot{m}_c c_c (T_{c,out} - T_{c,in}) \quad (2)$$

- Based on heat exchanger surface and heat transfer coefficient

$$\mathring{Q} = kA\Delta T_m \quad (3)$$

where $\dot{m}_h$—mass flow rate of hot fluid, kg/h; $\dot{m}_c$—mass flow rate of cold fluid, kg/h; $T_{h,in}$—inlet temperature of hot fluid, ^{o}C; $T_{h,out}$—outlet temperature of hot fluid, ^{o}C; $T_{c,in}$—inlet temperature of cold fluid, ^{o}C; $T_{c,out}$—outlet temperature of cold fluid, ^{o}C; k—overall heat transfer coefficient, W/m^2/K; A—heat exchange surface, m^2; ΔT_m—the log mean temperature difference, K.
The overall heat transfer coefficient is defined as

$$\frac{1}{k} = \frac{1}{\alpha_h} + \frac{\delta_{z,h}}{\lambda_{z,h}} + \frac{\delta_{met}}{\lambda_{met}} + \frac{\delta_{z,c}}{\lambda_{z,c}} + \frac{1}{\alpha_c} \quad (4)$$

where a_h—hot stream heat transfer coefficient, W/m^2/K; a_c—cold stream heat transfer coefficient, W/m^2/K; $\delta_{z,h}$—thickness of deposition on hot fluid side, m; δ_{met}—thickness of plate, m; $\delta_{z,c}$—thickness of deposition on cold fluid side, m; $\lambda_{z,h}$—thermal conductivity of deposition on hot fluid side, W/m/K; λ_{met}—thermal conductivity of plate, W/m/K; $\lambda_{z,c}$—thermal conductivity of deposition on cold fluid side, W/m/K.
Transformation of equation 3k gives

$$k = \frac{Q}{A\Delta T_m} \quad (5)$$

Mean rate of heat transfer is defined as

$$\dot{Q}_m = \frac{\dot{Q}_h + \dot{Q}_c}{2} \quad (6)$$

The thermal resistance is given by

$$r_0 = \frac{\delta_{z,h}}{\lambda_{z,h}} + \frac{\delta_{z,c}}{\lambda_{z,c}} \quad (7)$$

The thermal resistance is determined from the equation 4 to give

$$r_0 = \frac{1}{k} - \frac{1}{\alpha_h} - \frac{\delta_{met}}{\lambda_{met}} - \frac{1}{\alpha_c} \quad (8)$$

The coefficients$\alpha_h$and $\alpha_c$are determined from the appropriate empirical correlations. The change of thermal resistance over time is estimated using equation8.

4.2. Least squares method

The determination of fouling resistance is also possible with the least squares method, but this paper does not deal with it.

5. Results and discussion

The study was carried out during a one year period, starting in May 2013 and finishing in June 2014. The measurements enable the operation of two different heat exchangers to be compared. Many parameters have been compared, including: volume flow rate(3), temperatures of fluids (34), heat transfer coefficients (56). The thermal resistance determined from equation 8 is depicted in8.
Every figure consists of two lines for each heat exchanger. The blue line presents the operation conditions of PHE 1 and the orange line the operation conditions of PHE 2.
The values of heat transfer coefficients of hot and cold fluid have been determined from the empirical equations for flat plate in laminar flow:

$$Nu = 0,332 Re^{1/2} Pr^{1/3} \quad (9)$$

$$\alpha_h = \frac{Nu\lambda}{1} \quad (10)$$

$$\alpha_c = \frac{\alpha_h}{2^{0,64}} \quad (11)$$

It should be noted that PHE 2 has a higher velocity flow rate of hot fluid and also a higher inlet temperature of hot fluid. Significant is the change in velocity flow rate for PHE 2 after about 60 days and a similar decrease in outlet temperature of hot fluid. This change results from the power of PHE 2, which is on the level of 585 kW and is used solely at a level of 50%.

Figs 6 and 7 show that the heat transfer coefficient on both sides of cold and hot fluid is almost two times higher for PHE 1. From Figs 3 and 4 it was observed that PHE 2 has a higher volume flow rate and a higher inlet temperature of hot fluid, which can lead to a higher heat transfer coefficient. The explanation for this difference is in the

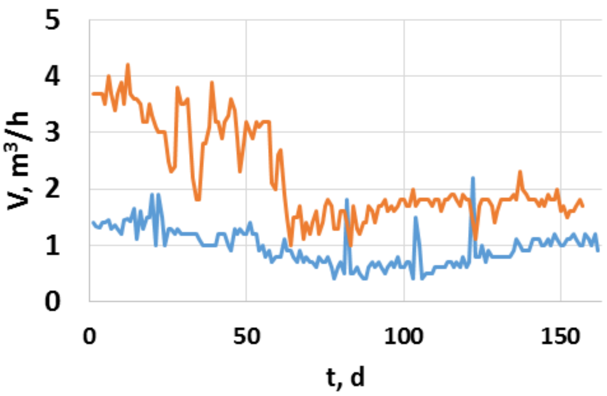

Figure 3: Volume flow rate for PHE 1 and PHE 2

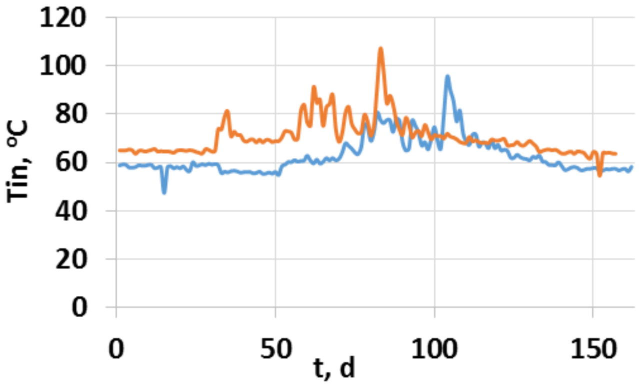

Figure 4: Inlet temperature of hot fluid

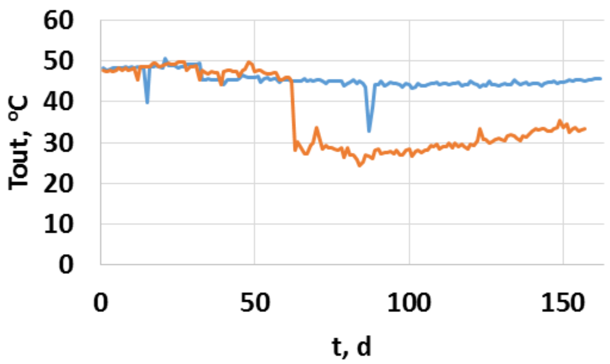

Figure 5: Outlet temperature of hot fluid

number of plates. Even if PHE 2 has a velocity flow rate at an average level of 2.24 m^3/h and PHE 1 0.96 m^3/h, PHE 2 has four times more plates (158) than PHE 1 (40), thus the average fluid velocity is significantly lower in PHE 2 (2).

It should be noticed that the Reynolds number is very low in both heat exchangers, as is the Nusselt number, which guarantees that the flow is laminar2.

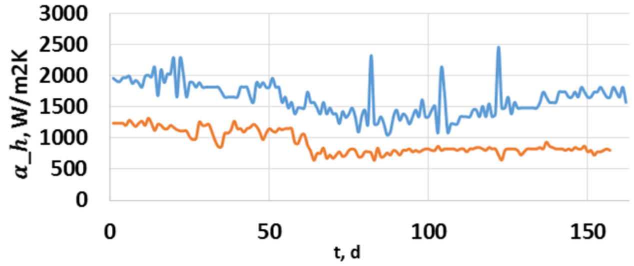

Figure 6: Hot stream heat transfer coefficient for PHE 1 and PHE2

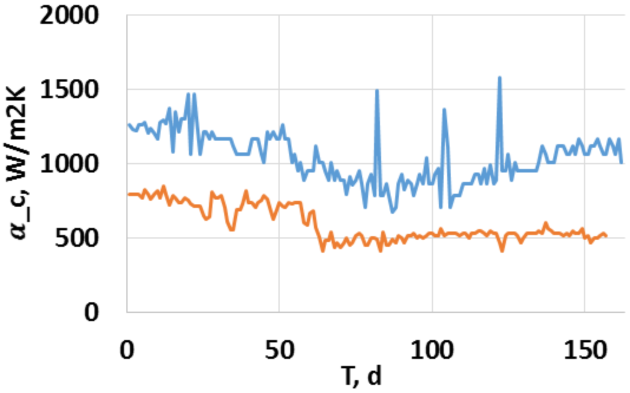

Figure 7: Cold stream heat transfer coefficient for PHE 1 and PHE 2

Table 2: Calculated parameters for PHE 1 and PHE 2

PHE	w, m/s	Re	Nu	Rzn, m ^{2}K/W
PHE1	0.038	199	6.97	0.00285
PHE2	0.016	113	5.10	0.00407

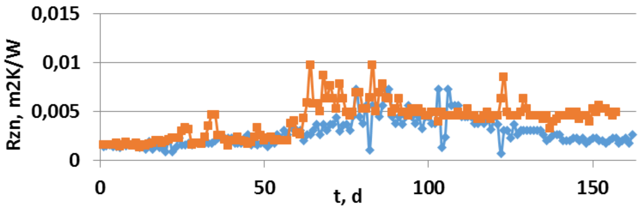

Figure 8: Fouling thermal resistance for PHE 1 and PHE 2

Calculation of the Nusselt number enables fouling thermal resistance to be determined8. For PHE 1 (blue line) the increase from the level about 0.0014 to 0.0026 m^{2}K/W is not thus as significant as it is for PHE 2 (orange line), where it increases from about 0.0016 to 0.0049 m^{2}K/W.

6. Conclusions

This paper provides an experimental investigation of fouling thermal resistance in plate heat exchangers which form part of Cracow's district heating system. The primary issue of this research was an analysis of operating condition such as volume flow rate, temperature of fluids, heat transfer coefficients and thermal resistance in the process of domestic hot water production. The following conclusions can be drawn on the basis of the measurements and calculations presented in the paper:

- a steady increase in thermal resistance can be observed in the conducted research
- the average thermal resistance for PHE 1 and PHE 2 is 0.00285 and 0.00407 m^2K/W respectively,
- increasing fluid velocity will raised the heat transfer rate of a fouled heat exchanger, but this could only be a temporary solution.

The conducted analysis and further studies make it possible to observe changes in fouling thermal resistance over time and to schedule temporary shutdowns for cleaning purposes to optimize the efficiency of heat substations.

Acknowledgements

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