ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0010.3164

THE ASSESSMENT OF SURFACE LAYERS TEXTURE OF THE FOULING GATHERED ON THE HEAT TRANSFER SURFACES WITHIN REGENERATIVE FEEDWATER HEAT EXCHANGERS

Tomasz Hajduk

Gdynia Maritime University, Faculty of Marine Engineering
Morska Street 83, 81-225 Gdynia, Poland
tel.: +48586901549, fax: +48586901399, e-mail: t.hajduk@wm.am.gdynia.pl

Abstract

The fouling presence on the heat transfer surfaces, both on the waterside and the steam side of the steam power plants heat recovery exchangers usually leads to the loss of their heat transfer capacities. This loss appears owing to the high value of heat resistance of fouling. Furthermore, these deposits are most often formed with irregularities in the surface layers. These textures are usually characterized by a varied, often stochastic and difficult to define, geometric structures. The most common measure of their inequalities is the roughness parameter describing the surface geometry. The fouling surface layer texture can, on one hand, cause enhancement of the heat transfer process, but on the other hand, it may contribute to an additional increase in thermal degradation of the heat exchanger. Many experimental studies have shown that the greater the unevenness of the heat transfer surface on the waterside of a given heat transfer device, the smaller increase in the thermal resistance of the impurities over time, thereby increasing the amount of heat transferred. It should be emphasized, however, that the rise in roughness results in an increase in the heat transfer coefficient, while simultaneously intensifying the flow resistance of the working medium. Taking into account the heat transfer surface by steam side, the increase in the roughness promotes the formation of a thicker condensate layer, thus impairing the condensate drainage organization. It can be explained by the fact that deposits settle in a sort of quasi-rib effect, although with undefined ribbed grid, it may lead to the overflow of inter-finned passages. The article shows the previously mentioned phenomena and also presents the descriptive quantities for the fouling surface layer texture, based on the results of the author's own experimental research.

Keywords: *steam power plants, heat recovery devices, fouling, surface layer texture*

1. Introduction

The deposits gathered on the heat exchanger diaphragms in the steam power plants are created by a combination of the following five basic mechanisms: a) crystallisation of undissolved salts during the flow of a working medium, b) sedimentation of particulate suspensions present in the working medium, c) chemical reactions, most often the process of polymerisation of high molecular weight particles, d) corrosion arising from electrochemical processes, e) proliferation of microorganisms and macroorganisms, causing also microbial corrosion [4, 11].

Additionally, these deposits are most often formed in irregular grids with varied geometrical structures of the surface layer [9, 10, 12]. It is interesting to note that the irregularity of the external heat transfer surface created by the accumulating deposits, on one hand may enhance the heat transfer process, and on the other, it may lead to the increase in thermal degradation process of a given heat exchanger [4, 6, 8].

As an example, Brahim et al. [3] have investigated the influence of the shape of the geometric structure of the sediment surface gathered on the cooling waterside of the heat transfer device on the course of time characteristics for the fouling thermal resistances. These studies have shown that greater unevenness of the internal heat transfer surface of the heat exchanger (waterside) presents results in lower increase in the heat resistance of deposits over time but on the other hand, the increase in roughness is simultaneously correlated positively with the increase in the cooling water flow resistances.

Hobler [8] states that the increase in the roughness of the heat transfer surface on steam side favours the formation of a thicker condensate layer, thus worsening the so-called run-off conditions during the condensation process. This phenomenon can be explained by the fact that the deposited fouling on the vapour side, in a sense, forms quasi-fins with undefined ribbing density. It can lead to the phenomenon known in the literature as the flooding of the inter-finned passages. This phenomenon occurs due to the surface tension forces, when the width of the ribbed channel is much smaller than the capillary constant of the water vapour. This has a detrimental effect on the operation of a single tube, because the bottom layer of the condensate roughly equal to the height of the ribs constitutes additional heat transfer resistance [5, 21].

The size of the surface roughness and the surface tension value are also important, as confirmed by Beatty and Katz studies dealing with the effect of the fins height ratio to the fineness of the ribs as well as the surface tension on the organization of the condensate-flow during the water vapour condensation process. These studies supported the thesis that condensate drainage is most effective when the values of surface tension and rib-to-rib pitch are the lowest [21].

The effect of deposit presence for a single pipe wall is often taken into account by correction factors directly related to the calculated convective coefficient α_v (steam side). Especially, when it is difficult to distinguish the influence of thermal resistance of the deposit layer from the influence of surface roughness. According to Kutateładze, the convective coefficient α_v should be corrected with the coefficient ε, whose value depends on the type of material and the condition of the surface of the pipe as well. However, this relation has been described solely in a descriptive manner. For example, for a steel tube coated with thin deposit layer, this factor equals 0.67, but the author does not reveal how thick the deposit layer is or what geometrical irregularity of its surface is [8, 13].

Förster and Bohnet research carried in order to characterize the influence of the heat transfer surface roughness on the course of time characteristics for deposit thermal resistances has shown that larger irregularities of this surface result in a significant increase in deposits thermal resistances over time. For instance, in the early stages of salts dissolution in water, during the so-called induction period τ_{ind}, the deposits are gathered in the form of flakes, tightly adhering to the surface of the tubes. They are in the form of micro-ribbed shapes, which, on the one hand, extend a heat transfer surface of a given heat exchanger but on the other act as a turbulizer, which breaks off the laminar boundary layer, resulting in heat transfer process enhancement [6]. Hence, some authors also name the induction period of fouling as the period of heat transfer intensification [17, 20]. Amjad's study on the sedimentation process for calcium sulphate proved that the sediments induction period increases with the increase in the cooling water flow rate while the elongation of the τ_{ind} period results in lower increase in overall heat resistances of a heat exchanger [14].

Concluding, the influence of fouling presence on heat transfer surfaces within a heat exchanger on the steam condensing process is ambiguous in interpretation and difficult to describe due to its complexity as well as due to overlapping of many phenomena at the same time. Evidence of this is often contradictory to the results of many experimenters, e.g. the above-mentioned research result of the influence of fouling layer roughness both on the water and steam side on the water vapour condensation process.

2. The texture of surface layers deposits

The actual surface of a given solid constitutes a boundary between itself and the surroundings. It is an integral and outer part of the surface layer. The surface layer is an outer part of a material and it exhibits the altered physical or chemical characteristics in comparison to the core material. The surface layer formed under certain technological conditions is the so-called technological surface layer, while the surface layer, which has been formed under operating conditions, is the so-called operating surface layer established due to tribological process. The outer surface texture is determined by surface geometry structure [18]. It is conventionally assumed that surface texture also known as surface topography, is the nature of a surface defined by the four characteristics, i.e. lay (class I irregularity which shows the direction of the predominant surface pattern ordinarily determined by the production method used), waviness (a measure of surface irregularities with a spacing greater than that of the surface roughness, class II irregularity), surface roughness (is a measure of the finely spaced surface irregularities, class III irregularity) and micro-roughness (class IV irregularity dedicated to nanometrology) [2, 15, 16]. In the author's own studies, it was assumed that the surface texture of deposits is similar to the outer heat transfer surface (steam side) of the tested tubes of steam power plants heat recovery exchangers.

2.1. Parameters describing the profile features of fouling surface layer

The measure of fouling surface layer unevenness can be characterized by a set of parameters whose values, among other things, depend on the properties of the constituent material and on the conditions under which it was formed [7]. The assessment of the geometrical structure of the surface of the sediments was based on the theory valid for the evaluation of the surface microgeometry for description of the co-operating machine components. Metrology issues, in total, are extremely extensive. Among others, shaping of the surface layer geometry and its influence on the utility properties of machines is a very complex problem that goes far beyond the scope of the research undertaken by the author of this article [1, 2, 15, 16, 18, 19]. Therefore, the study was limited to the application of some basic parameters in the evaluation of surface layer geometry for the unevenness of class III surface layer i.e. surface roughness.

The profile roughness parameters are defined on a single measuring length and results are typically calculated as average values from five sampling lengths. Each of the roughness parameters is calculated using a formula for describing the surface layer. Many of them are closely related to the parameters found in statistics for characterizing population samples. The following roughness parameters were used in the studies [16, 22]:

1. *The arithmetic mean deviation of the R profile*, *Ra* – is the arithmetic average value of the absolute values of the ordinate deviations Yi about the centre line within the measuring length of the profile R. It is the most widely used one-dimensional roughness parameter:

$$Ra = \frac{1}{N}\sum_{i=1}^{N}|Yi|, \tag{1}$$

2. *The average square deviation of the R profile*, *Rq* – the mean square of the ordinates deviations Yi of the profile R.:

$$Rq = \sqrt{\frac{1}{N}\sum_{i=1}^{N} Yi^2}, \tag{2}$$

3. *The maximum span of the R profile, Rz* – an average distance between the highest peak and lowest valley measured in each profile from *n* sampling length *Rzi*:

$$Rz = \frac{1}{n}\sum_{i=1}^{n} Rzi, \tag{3}$$

4. *The mean peak width of the R profile, Rsm* – horizontal parameter describing the width characteristics of a profile, expressing the average width value of the profile elements Xs in the sampling length, thus horizontal and vertical thresholds are stipulated for this evaluation:

$$Rsm = \frac{1}{m}\sum_{i=1}^{m} Xsi, \tag{4}$$

5. *The outer heat transfer surface texture parameter K* – measures the surface irregularity of heat transfer surface by measuring the fouling surface layer and is defined as follows:

$$K = (Rz \cdot Rsm)^{-1}. \tag{5}$$

Förster and Bohnet [6] have confirmed in their studies that the texture parameter K has a significant effect on the value of the fouling induction period τ_{ind}, giving the following empirical positive correlation between the τ_{ind} (measured in hours) and texture parameter K:

$$\tau_{ind} = 70.8 \times K + 12.8, R^2 = 0.871, K \in (0 - 0.8) \wedge \tau_{ind} \geq 12.8\ h, \quad (6)$$

3. Research methodology

Each measurement of the examined fouling surface roughness was preceded by a visual assessment of the research sample, which determined the direction of measurement and selected the measurement section for the measurement length. Measurements of surface microgeometry for tested tube samples were performed on their cylindrical surfaces in the longitudinal direction to the sample axis. Subsequently, for each sample, measurements were carried out for three relevant measuring sections. These sections as line segments were selected from two cross sections of the research material. They were formed by the intersection of the cylindrical surface of the tested tube with the plane determined by the following three central angles: $\varepsilon\gamma_1 = 0°$, $\varepsilon\gamma_2 = 120°$ and $\varepsilon\gamma_3 = 240°$ (Fig. 1). For each tested tube, the arithmetic mean values of the measured roughness parameters in the given planes were taken into account for further analysis.

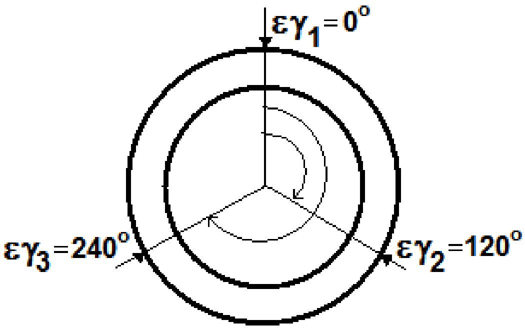

Fig. 1. The planes measuring the roughness of the research samples, according to [author's own concept]

3.1. Test-bench

Roughness measurements were performed by means of the contact-stylus method, using two-dimensional surface recording in the test-bench, which is located in the Centre of Hydrodynamics – Laboratory of Cavitation Department of The Szewalski Institute of Fluid-Flow Machinery of Polish Academy of Sciences. This test-stand comprises of two main parts: a roughness surface analyser – the Mitutoyo profilograph Surface Roughness Tester SJ-301 type, (Fig. 2) and a computer software for acquisition and processing data, i.e. Mitutoyo software ver. 3.20 [23].

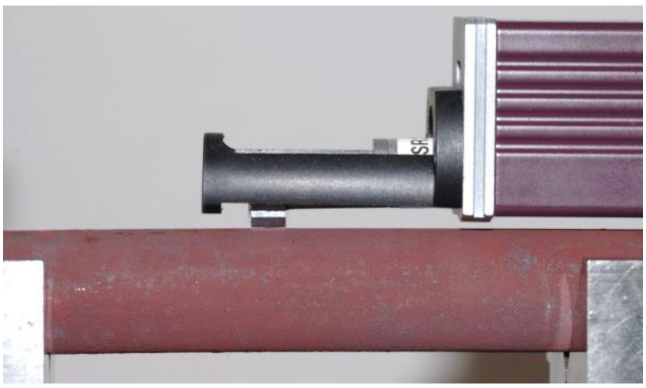

Fig. 2. The Mitutoyo profilograph Surface Roughness Tester SJ-301 type, according to [author's own archives]

In order to describe microgeometry of the tested deposit surface layer, the following setups for roughness measurement were selected in Mitutoyo software: measured profile – R, amplitude transmissive filter – GAUSS, sampling length, lr = 0.8 mm, measuring length, ln = 4.0 mm (multiplicity n = 5), start and finish length $\lambda_c/2 = 0.4$ mm, where λ_c is the filter cut-off length equals to lr. Roughness measurements were carried out on tube samples where one FS#00 was free of deposit as a reference sample, while the other two samples designated by FS#07 and FS#12 were derived from the steam power plant heat recovery exchangers.

3.2. Research results

After reaching stability state within each measurement series, an electronic test protocol was prepared by Mitutoyo software data acquisition system. Tab. 1 shows measured roughness parameters and their mean values (mv).

Tab. 1. Measured roughness parameters and average values (mv) of the tested samples in the planes determined by relevant central angles $\varepsilon\gamma1$, $\varepsilon\gamma2$, $\varepsilon\gamma3$, "n.d." – not determined, according to [author's own research]

Roughness parameter	Research sample											
	FS#00				FS#07				FS#12			
	mv	$\varepsilon\gamma_1$	$\varepsilon\gamma_2$	$\varepsilon\gamma_3$	mv	$\varepsilon\gamma_1$	$\varepsilon\gamma_2$	$\varepsilon\gamma_3$	mv	$\varepsilon\gamma_1$	$\varepsilon\gamma_2$	$\varepsilon\gamma_3$
Ra [μm]	0.96	0.53	1.14	1.21	7.07	4.45	11.78	4.98	6.22	4.24	8.57	5.84
Rz [μm]	6.62	4.47	7.52	7.88	37.17	23.10	54.95	33.47	34.81	23.31	49.02	32.09
Rq [μm]	1.33	0.73	1.59	1.69	8.85	5.60	14.17	6.79	7.78	5.27	10.55	7.52
Rsm [μm]	161	161	n.d.	n.d.	330	279	382	n.d.	255	200	368	198

The roughness of the deposit surface layer (steam side) for tested tubes is the measure of the outer heat transfer surface irregularity for these tubes and it was determined by using the texture parameter K (dependence 5). The values of parameter *K* were presented in Tab. 2. Also, considering the correlation (6), the hypothetical deposit induction period τ_{ind} for the deposit-free tube (sample FS#00) was estimated at the level of 19 hours.

Tab. 2. The texture parameter K values for samples FS#00, FS#07 and FS#12, according to [author's own study]

Texture parameter	Research material		
	FS#00	FS#07	FS#12
$K\times10^{10}$ [m^{-2}]	0.094	0.008	0.013

4. Conclusions

The purpose of the experimental research was to evaluate the surface layer of deposits gathered on the heat recovery exchangers (steam side) within steam power plants. Studies have shown that the deposit-free tube was characterized by the smallest vertical surface irregularity, i.e. the Ra and Rz values of the sample FS#00 were smaller, than those for the fouled tubes (FS#07 and FS#12). Furthermore, the results of the study also confirmed the greater variation of the surface layer structure for the fouled tubes FS#07 and FS#12, because K texture parameter of these tubes was smaller than K deposit-free tube, respectively about 12 and 7 times.

When comparing the K parameter with fouled pipes FS#07 and FS#12, it was found that pipe FS#07 (the lowest K value) was featured by about 60% greater irregularity in the surface layer geometry than pipe FS#12. During operating, such a state of deposits may result in a significant collapse in condensate drainage output from a single pipe due to flooding of the inter-finned passages, while at the same time constituting an additional heat resistance which ultimately leads to the thermal degradation of a given heat recovery device.

References

[1] Adamczak, S., *Ocena chropowatości i falistości powierzchni, Zasady i warunki przeprowadzania pomiarów,* Mechanik, Nr 3, s. 180-183, 2006.

[2] Adamczak, S., *Ocena chropowatości i falistości powierzchni, Informacje podstawowe,* Mechanik, Nr 5-6, s. 492-495, 2005.

[3] Brahim, F., Augustin, W., Bohnet, M., *Numerical simulation of the fouling structured heat transfer surfaces*, ECI Conference on Heat Exchanger Fouling and Cleaning, Fundamentals and Applications, pp. 121-129, Santa Fe 2003.

[4] Butrymowicz, D., Hajduk, T., *Zagadnienia degradacji termicznej wymienników ciepła*, Technika chłodnicza i klimatyzacyjna, Rok XIII, Nr 3(121), s. 111-117, 2006.

[5] Butrymowicz, D., Trela, M., *Intensyfikacja wnikania ciepła w poziomych skraplaczach płaszczowo-rurowych*, Technika chłodnicza i klimatyzacyjna, Rok VI, Nr 3(43), s. 92-99, 1999.

[6] Förster, M., Bohnet, M., *Modification of the interface crystal/heat transfer surface to reduce heat exchanger fouling,* (ed.) Müller-Steinhagen, H., Heat Exchanger Fouling, Fundamental Approaches & Technical Solutions, pp. 27-34, Essen 2002.

[7] Hajduk, T., *Identification of fouling deposited on the heat transfer surfaces of the steam power plants heat exchangers*, Journal of KONES Powertrain and Transport, Vol. 23, No. 4, pp. 135-142, 2016.

[8] Hobler, T., *Ruch ciepła i wymienniki,* WNT, Warszawa 1986.

[9] Karabelas, A. J., *Scale formation in tubular heat exchangers – research priorites*, Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, pp. 73-81, Piza 2001.

[10] Kazi, S. N., Duffy, G. G., Chen, X. D., *A study of fouling and fouling mitigation on smooth and roughened metal surfaces and a polymeric material,* (ed.) Müller-Steinhagen, H., Heat Exchanger Fouling, Fundamental Approaches & Technical Solutions, pp. 65-72, Essen 2002.

[11] Knudsen, J. G., *Fouling in Heat Exchangers, Overview and Summary*, (ed.) Hewitt, G.F., Handbook of heat exchanger design, Begell House Inc., pp. 3.17.1.1-7.5, New York 1992.

[12] Kukulka, D. J., Devgun, M., *Fouling surface finish evaluation*, Applied Thermal Engineering, Vol. 27, pp. 1165-1172, 2007.

[13] Michiejew, M., *Zasady wymiany ciepła*, PWN, Warszawa 1953.

[14] Mwaba, M. G., Rindt, C. C. M., Vorstman, M. A. G., van Steenhoven A. A., *Calcium sulfate deposition on a heated plate and removal characteristics,* (ed.) Müller-Steinhagen, H., Heat Exchanger Fouling, Fundamental Approaches & Technical Solutions, pp. 57-63, Essen 2002.

[15] Nowicki, B., *Chropowatość i falistość powierzchni*, WNT, Warszawa 1991.

[16] Panicz, A., *Chropowatość powierzchni – co nowego?*, PAK, Nr 5, s. 39-41, 2000.

[17] Perrakis, M., Andritsos, N., *$CaCO_3$ scaling under constant heat flux,* (ed.) Bott, T., Understanding Heat Exchanger Fouling and Its Mitigation, pp. 185-192, New York 1999.

[18] Santorski, J. K., *Podnoszenie tribologicznych właściwości materiałów przez obróbkę cieplną i powierzchniową*, Instytut Mechaniki Precyzyjnej, Warszawa 2003.

[19] Stefański, W., *Wpływ zwiększenia chropowatości i zmniejszenia średnicy rur na opory hydrauliczne*, Instal, Nr 9, s. 66-74, 2006.

[20] Xu, Z. M., Wang, J. G., Chen, F., *A new predictive model for particulate fouling,* (ed.) Bott, T., Understanding Heat Exchanger Fouling and Its Mitigation, pp. 185-192, New York 1999.

[21] Webb, R L., *The Use of Enhanced Surface Geometries in Condensers: An Overview*, (eds) Marto, P. J., Nunn, R .H., Power Condenser Heat Transfer Technology, pp. 353-366, 1981.

[22] DIN-EN ISO 4288, *GPS – Surface texture: Profile method. Rules and procedures for assessment of surface texture*, 1998.

[23] *Program komputerowy Mitutoyo*, wytwórca Mitutoyo, wersja 3.20.