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Failures and fouling analysis in heat exchangers

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1. Introduction

A heat exchanger (HE) is a device built for efficient heat transfer from one fluid to another, whether the fluids are separated by a solid wall so that they never mix, or the fluids are directly contacted [1]. The heavy turbulence and counterflow principle enable efficient heat transfer. HE are widely used in refrigeration, air conditioning, space heating (SH), for domestic hot water (DHW), power production, and chemical processing (Fig. 1). Some examples are intercoolers, pre-heaters, boilers and condensers in power plants [2]. A typical HE is the shell and tube heat exchanger which consists of a series of finned tubes, through which one of the fluids runs. The second fluid runs over the finned tubes to be heated or cooled. During HE operation, high temperature and high-pressure water or steam are flowing at high velocity inside tubes or plate systems. In tubes of HE, local wall thinning may result from erosion/corrosion. Therefore, it is important to evaluate the strength and ductility for wall-thinned tubes, assess the risk of failures to maintain the integrity of the secondary tubing systems. Another type of HE is the plate heat exchanger, which can be done with brazed (Fig. 2) or gasket plates. It directs flow through baffles so that the fluids are separated by plates with very large surface area [3]. This plate type arrangement can be more efficient than the shell and tube.

The beginning of using first heat exchangers for SH and DHW in district heating substations is early 1980s (1990s in Lithuania). A pioneer is this matter was Swedish company Alfa Laval. A survey of Lithuanian district heating revealed that in 2005 approximately 95% of all heat exchangers were brazed plate type. Although the HE are usually designed for a normal life of more than 10 years, their actual service life, however varies from 2-3 to 6-8 years, depending on the service conditions and of course on the quality of heat transfer media. The type of scale differs from industry to industry, depending on the mineral content of the available water.

Despite the enormous costs associated with failure and fouling, only very limited research has been done on this subject. Reliable knowledge of fouling economics is important when evaluating the cost efficiency of various mitigation strategies. The total failure and fouling related cost can be broken dawn into three main areas:

- capital expenditure, which includes excess surface area (10-50%, with the average about 35%), costs for stronger foundations, previsions for extra space, increased installation costs;
- extra fuel costs, which arise if fouling leads to extra fuel burning in furnaces or boilers or if more secondary energy such as electricity or process steam is needed to overcome the effects of fouling;
- production losses during planned and unplanned plant shutdowns due to failure and fouling.

This paper presents the results of an investigation the failure of steels tubes or plates in heat exchangers used in district heating and industry.

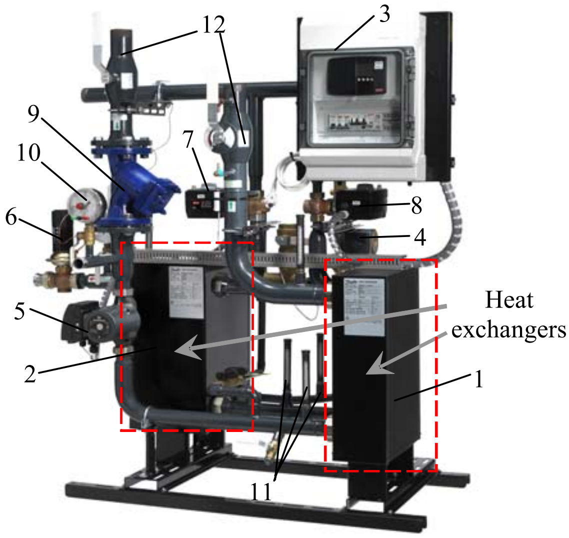


Fig. 1 Brazed plate type heat exchangers for domestic hot water and space heating in district heating substation: *1* - heat exchanger for SH; *2* - heat exchanger for DHW; *3* - control unit; *4* - circulating pump for DHW; *5* - pump for SH; *6* - difference pressure regulator; *7* - valve with actuator for SH; *8* - valve with actuator for DHW; *9* - flanged filter; *10* - manometer; *11* - thermometers; *12* - ball valves

The material of the tubes and plates has suffered corrosion, localized overheating, probably as a result of local heat flux impingement phenomenon, caused by heat water steaming. The aim of this paper is to identify which are the major factors that contribute to water main failures. In this paper, we explain the impact of fouling and corrosion on heat transfer and pressure drop in HE. The studies included microstructural examinations of cracked and uncracked tubes, fracture surface investigations and estimation of creep rupture strength, etc.

2. Background

There is a high degree of uncertainty associated with all the factors contributing to HE element's failure and fouling, and especially corrosion rates because of large spatial and temporal variability [2]. This requires a detailed uncertainly analysis to quantify the probability of HE failures at a given time in order to plan maintenance and repair strategies [4]. Reduced efficiency of the HE due to fouling, represents an increase in fuel consumption with repercussions not only in cost but also in the conservation of the energy resources. This study was performed to evaluate the fracture behavior, failure and fouling mode and allowable limit of carbon steel straight tubes with damage and local wall thinning. Maximum moment of tubes was evaluated using σ_f, R_m and σ_{adm}, where σ_f is the flow stress, R_m is the ultimate tensile strength and σ_{adm} is admissible stress.

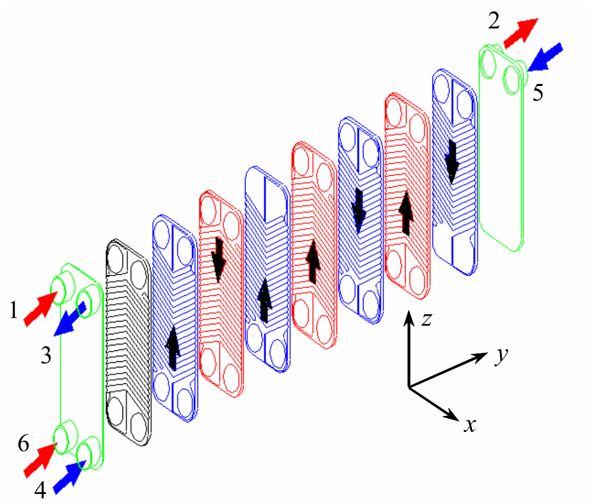


Fig. 2 Two-pass plate heat exchanger. Flow channels connected both in parallel and in series: *1* - heating water flow inlet, e.g. district heating; *2* - heating water flow outlet, e.g. district heating; *3* - heated water outlet, e.g. domestic hot water; *4* - DHW circulation flow inlet; *5* - heated water inlet, e.g. domestic cold water; *6* - water returning from the heating heat exchanger of district heating, a so-called after cooling feed

Regardless of the tube material, the most effective way to ensure that tubes achieve their full life expectancy and heat transfer efficiency is to keep them clean each time the tube deposits, sedimentation and bio-fouling are removed, the surfaces are returned almost to bare metal, providing the most effective heat transfer and the tube itself with a new life cycle [5].

Fig. 3 Defects on brazed plate type HE due to pressure influence of heat transfer media after two years of exploitation

Very negative occurrences are hydraulic shocks of heat transfer media which are closely related with exploitation of all system. Frequent hydraulic shocks may deform plates of HE (Fig. 3), which causes leakage of the media.

According to the current standard, the main criterion for the tube-line estimation is the condition of static strength. Stresses in a pipe wall σ should not exceed the admissible value σ_{adm} for the pipe material

$$\sigma \le \sigma_{adm} \tag{1}$$

For the HE tube-lines, the value of circular tensile stresses σ_y caused by the water service pressure p ($\sigma_y = pR/t$, where $D = 2R$ is the internal diameter of a tube, t is a wall thickness), and the value of σ_{adm} is established from the ultimate strength of the material and safety criteria, which is chosen with respect to the type and service conditions of the tube line. Criterion (1) is the basic one in design calculations and, particularly, in selecting the material of tubes and their dimensions. Its applications for the tube-lines that have been operating for a long time require some additional data, in order to take into consideration the temporal variation of the calculation parameters as compared with their original values. Firstly, the degradation of material can cause the decrease of the strength characteristics of material, that is, a corresponding decrease of σ_{adm} value. The degradation level can be established by laboratory testing or can be approximately evaluated by correlation dependences of the material characteristics and its hardness [6]. For a cylindrical tube under biaxial stress state caused by inner pressure p we can write

$$E\varepsilon_y = \sigma_y - \nu(\sigma_z + \sigma_t) = p\frac{R}{t}\left(1 - \frac{\nu}{2}\right) = 0.85p\frac{R}{t} \tag{2}$$

$$E\varepsilon_z = \sigma_z - \nu(\sigma_z + \sigma_t) = p\frac{R}{t}\left(\frac{1}{2} - \nu\right) = 0.2p\frac{R}{t} \tag{3}$$

$$E\varepsilon_t = \sigma_t - \nu(\sigma_y + \sigma_z) = -\frac{3\nu}{2}p\frac{R}{t} = -0.45p\frac{R}{t} \tag{4}$$

where $\sigma_z = pR/2t$ is axial stress and $\sigma_t = 0$, e.g. radial stress is negligible compared to the circular and axial stresses.

The equivalent strain can be obtained from

$$E\varepsilon_{eq} = \sigma_{eq} = \frac{\sqrt{3}}{2}\sigma_t\frac{pR}{t} \tag{5}$$

giving

$$\varepsilon_{eq}\Big/\varepsilon_y = \frac{\sqrt{3}}{2(1 - \nu/2)} = \frac{\sqrt{3}}{2 - \nu} \tag{6}$$

where ε_{eq} and σ_{eq} are equivalent strain and stress, respectively.

Anyhow, as it is seen from the basic three-dimensional relations, the difference between equivalent and tensile strain is less than 2%. Slightly stronger influence is due to the remote tensile stress which is determined from the tensile and axial strain gauges. The difference produced by bi-axial stress state is less than 7.5 % in this case.

Scibetta et al. [6], summarizing a wealth of existing data, showed that for ductile metals the hardness H and yield stress σ_y could be related by the simple relationship $H = C\sigma_y$, where $C \approx 2.8$ is a constant.

Fig. 4 shows a cross-section of a HE tube consisting of various forms of iron oxide and other corrosion products. The mechanism described in connection with corrosion at the bottom of a crack in an iron oxide layer continues till the pit is filled with porous iron compounds. The presence of tubercles generally increases the roughness to fluid flow. Large tubercles may break loose from the surface as a result of shear stress, and become lodged in downstream equipment such as heat exchanger header boxes.

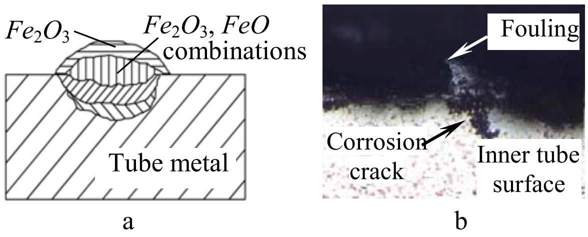


Fig. 4 Cross-section of heat exchanger tube: a – schematic cross-section of a HE tube; b – transverse section of a tube with inner crater on the surface

Table 1

Features of some typical exchangers types

No	Type	Materials of construction	Ease of cleaning against fouling	Notes
1	Shell and tube	Most materials	Tubes relatively easy to clean, shell more difficult	Widely used
2	Gasket plate	Stainless steel (usually)	Easy to clean	Compact
3	Spiral	Most materials	Easy access to whole channel length	Compact: useful for … and fouling conditions
4	Brazed plate	Stainless steel, titanium	Only chemical cleaning possible	Highly compact

The principal types of fouling encountered in process HE include [2]:

- particular fouling
- corrosion fouling
- biological fouling
- crystallization fouling
- chemical reaction fouling
- freezing fouling.

In most cases, it is unlikely that fouling is exclusively due to a single mechanism, and in many situations one mechanism will be dominant.

3. Characterization of failure and fouling mechanisms

3.1. Failure mechanisms

The failure mechanisms generally encountered are fatigue, corrosion fatigue, stress corrosion cracking (SCC) and ductile fracture [8]. Corrosion represents mechanical deterioration of construction materials of HE surfaces under the aggressive influence of flowing fluids and environment in contact. In addition to corrosion, other mechanically induced phenomena are important for HE design and operation, such as getting (corrosion occurs at contact areas between metals under load subjected to vibration and slip). Fouling and corrosion represent HE operation – induced effects and should be considered for both the design of a new HE and operation of an existing exchanger.

The loss of plate thickness due to corrosion can be relatively uniform or localized. The rate of wall loss has been the subject of debate, where it has been assumed to be constant or otherwise. The rate of corrosion in uncoated HE plates is generally high at early age. There is evidence to suggest that corrosion is a self-inhibiting process, whereby as corrosion proceeds, the protective properties of its products (generally iron oxides) improve, thus reducing the corrosion rate over time. Consequently, prediction of pit depth, say in the first 5-10 years of HE life, should be considered highly uncertain. The most used model for surface corrosion indicates $d = kt^n$, where d = depth of corrosion pit (mm), k = constant (~2), n = constant (~0.3), t = exposure time (years). Table 1 lists some of the features of common HE and may be used as a preliminary guide in HE selection.

There are two limiting parameters that affect the sizing of HE. They are the required heat transfer surface area and the pressure drop. The capacity of a HE is directly proportional to the mass or volume flow and temperature difference. Therefore, with small design temperature differences, such as the 60 – 80°C of radiator circuits, a relatively greater flow rate will be required in order to achieve the desired capacity. In this case, the pressure drop becomes the limiting design parameter. It is well known that the grain boundary cavitation is one of the detrimental processes for the degradation of austenitic stainless steels that reduce the creep-fatigue life at high temperatures [9].

Beyond a general simple description, stainless steels may be collected in five families, which differ from each other for the basic microstructure and the specific characteristics. For example, grade AISI 430 steel belongs to the family of ferritic stainless steel, while grade AISI 304 steel belongs to the family of austenitic stainless steel. It is worth nothing that the austenitic type steel is among the most easy to weld and allows fabrication of elevated toughness welded joints even in the as-welded conditions, without any further treatment.

Although austenitic stainless steel posses excellent resistance to general corrosion, they are susceptible to the localized corrosive attacks.

Before considering the failures, it is useful to consider the metallurgical development, corrosion and mechanical properties of these high-strength austenitic materials. The high levels of molybdenum in particular but also of chromium and nitrogen endow grade 254 SMO steel with extremely good resistance to pitting and crevice corrosion. The addition of cooper provides improved resistance in certain acids. Furthermore, due to its relatively high nickel content in combination with high levels of chromium and molybdenum grade 254 SMO steel possesses good resistance to stress corrosion cracking. Numerous field tests and extensive application experience show that grade 254 SMO steel has a high resistance to crevice corrosion in seawater at ambient and slightly elevated temperatures. Grade 254 SMO steel is anncaled at 1150-1200°C to obtain an austenitic structure. Grade 254 SMO steel has very low carbon content (0.01 %). This means that there is very little risk of carbide precipitation in connection with heating. In the case of the grade AISI 316 steel (Cr 17 %, Ni 10.8 %, Mn 1.3 %) and grade AISI 304 steel (Cr 18.5 %, Ni 8.7 %, Mn 2.0 %) austenitic stainless steels, it is found that grain boundary is considerably serrated with the modified heat treatments to the change of carbide morphology [10]. Within the term stainless steel it is commonly indicated an alloy, including at least 10.5 % of carbon.

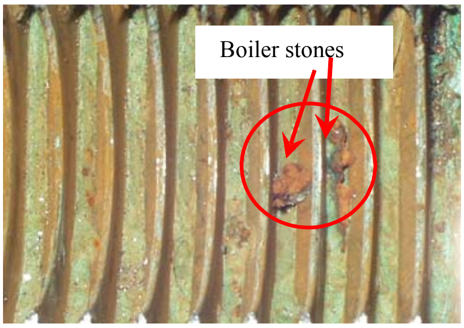


Fig. 5 Damages caused by boiler stones

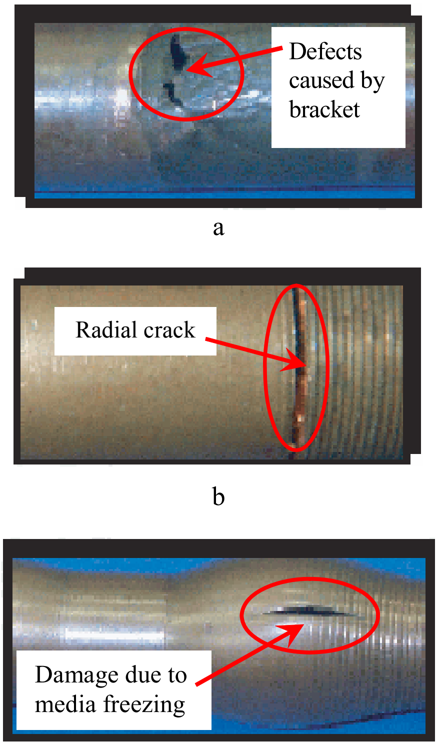
One of the most important chemical values for the HE manufactures is water hardness. It is the main compound which is causing the boiler stones (Fig. 5) which are the most frequent reason of leakage of HE. As an example the standard value of hardness in Europe is between 0.89 – 2.68 mmol/l. When the value exceeds 3.81 mmol/l then the water is qualified as very hard one and must be treated. According to the above mentioned criteria, hard water in Lithuania has place in Šiauliai, Joniškis, Jonava district heating systems.

In low-carbon steels the formation of stress corrosion failure has two phases:

- the surface layer gets damaged and a new protective layer cannot form because of the presence of corrosive medium;
- under the combined action of the corrosive medium and tensile stress, the surface crack becomes deeper, grows and develops into fracture. The protective layer may get damaged in consequence of external effects (e.g. scratches, cutting, etc.), but it can also take place under combined effect of plastic deformation and corrosive environment.

The heat transfer media has high influence on the durability of HE not only from biological fouling point of view but also from exploitation conditions.

Very often failures occur not only in heat exchangers but also in the connecting pipes due to unsuitable working conditions (Fig. 6). The pipes to be connected must be mounted so that the strain caused by thermal expansion, for instance, does not harm the heat exchanger. The pipes must be equipped with brackets to prevent any torsional stress concentration at the HE’s pipe connections.



a

b

c

Fig. 6 Examples of damaged connecting pipes of heat exchanger: a – defects caused by bracket inadequacy; b – damage due to corrosion and incorrect fixation; c – damage due to media freezing

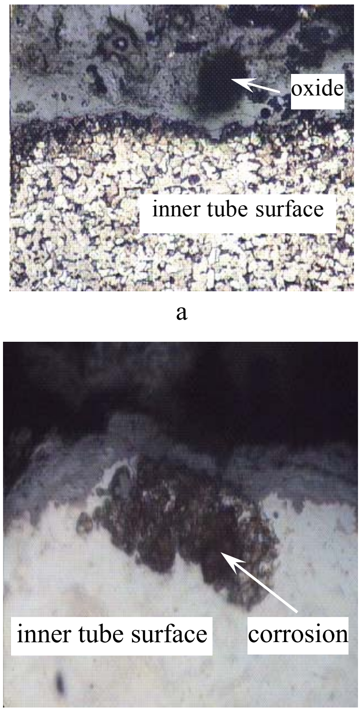
3.2. Fouling mechanisms

When hard water is heated (or cooled) in heat transfer equipment, scaling occurs. When scale deposits on a HE surface, it is traditionally called “fouling” [2]. Once fouling occurs in a HE, scale is removed by using acid chemicals, which shorten the life of heat exchanger plates or tubes. Fouling is an accumulation of undesirable material (deposits) on HE surfaces [11].

Undesirable material may be crystal, sediments, polymers, cooking products, inorganic salts, biological growth, corrosion products, and so on. This process influences heat transfer and flow conditions in a HE. However, most manifestations of these various phenomena lead to similar consequences. In general, fouling results in the reduction of thermal performance, an increase in pressure drop, may promote corrosion (Fig. 7), and may result in eventual failures of some HE.

HE dimensioning in some cases considers the fouling factor. The fouling factor use means that it is possible to guarantee a better heat exchanger operation when the media or water is dirty. The fouling factor use with dimensioning gives more heat transfer surface. Practically this is equal to over-surfacing.

Fouling is usually classified into six categories depending on the key physical or chemical process essential to the particular fouling mechanism. The categories are crystallization, particulate, chemical, corrosion, biological and solidification [4]. Crystallization fouling accounts for over 30% of fouling problems encountered. Crystallization fouling, or scaling, occurs when inverse solubility salts that are originally dissolved in the process fluid, deposit on heat transfer surfaces.



a

b

Fig. 7 Cross-sections of connecting pipes of heat exchangers for DHW after two years of exploitation (x150)

Precipitates were found on the internal material surfaces of the carbon steel connecting tubes near the tube beginning. The precipitates were in two forms, namely: broken mud and granular (Fig. 7, a). In addition to the precipitates, localized shallow corrosion attack was observed on the surface of the material (Fig. 7, b).

As the water is untreated, calcium and other chemicals are dissolved and precipitation fouling occurs at least on the surface of the heating elements of the electrical heater and on the heat transfer surfaces in the HE. So, some customers have to change the HE and/or the circulation heater after only a few months of operation. In this case, a preventive maintenance can be carried out, and the lifetime of the equipment increases. Periodic cleaning results in additional costs arising from the loss of production and additional maintenance activities. It is not surprising that fouling related costs constitute a significant portion of the industry's running costs [12].

4. Material and experiments

The chemical composition and mechanical characteristics of the HE materials are given in Table 2. Mechanical properties such as Brinell, Vickers hardness, tensile strength and impact toughness were tested on the ТШ-2 and microhardness testers, 50 kN multi-functional hydraulic servo machine and CIEM-30D testing machine, respectively. The diameter of the tensile specimens was 5 mm. The size of the impact toughness specimens was 10x10x55 mm. Three specimens were tested in each experiment and an average of the experimental data was taken as the result. The tube specimens were sectioned perpendicular to the axis, polished and etched by amount of flux. The thickness was measured on the unfailed tube as well as on the failed tubes using micrometer. A thin layer of scaling was noticed in the inner side of both the cracked tubes. On the inner surface a thick, hard and sticky deposit noticed and the tubes were found to be distorted and changed their dimensions.

For HE stainless steel is always used. Grade 254 SMO steel has a very good resistance to uniform corrosion in environments containing halides and to stress corrosion cracking. Also this material has very high resistance to pitting and crevice corrosion.

Table 2

Typical properties for HE steels

Parameter		Unit	AISI 304	AISI 316
C_{max}	%	0.03	0.03	0.01
Mn_{max}	%	2.0	1.3	1.0
Cr	%	18.5	17.0	20.0
Ni	%	8.7	10.8	18.0
Mo	%	-	2.2	6.1
R_m	MPa	520	550	650
$R_{p0.2}$	MPa	190	210	300
A_5	%	45	45	35
KCV	J/cm^2	100	100	120
Hardness	HB	215	215	260

The corrosion resistance of stainless steels is a result of passive layer of oxidized chromium contained in the steel [10]. The formation and stability of this layer mainly depends on the chromium content, but these qualities can be increased by the presence of molybdenum and nitrogen in the stainless steel; the environment of use also affects the corrosion resistance. Stainless steels are susceptible to both various forms of local corrosion damage, wear and general corrosion. It has been observed experimentally that resistance to pitting corrosion follows the index which can be derived from chemical composition of stainless steel. The *PRE* (Pitting Resistance Equivalent) index can be calculated as follows:

$$PRE = \%Cr + 3.3\%Mo + 16\%N$$

The higher is the index value, the better corrosion resistance. Table 3 presents the *PRE* values of various stainless steel grades in HE.

Tables 2 and 3 show chemical analysis and mechanical properties for some steels used for HE. The microstructure is controlled by heat treatment in order to achieve the best compromise between strength, ductility and toughness. 9% nickel steels have even higher yield and tensile strength and are the ideal materials for large boilers.

Table 3

Pitting resistance equivalent (PRE) values for examined steels

Steel designation :	PRE	AISI	Material standard EN
X5 Cr Ni 18-10	18.5	304	1.4136
X2 Cr Ni Mo 17-12-2	24.0	316	1.4004
X1 Ni Cr Mo Cu N 25-20-7	42.0	904L	1.4325

Addition of nitrogen as in grade AISI 304 or grade AISI 316 steels increases yield and tensile strength and material thickness may be reduced in vessels. Because of the high cost the use of stainless steels is restricted and is mainly used when there is need also for high corrosion resistance. Strong chlorine or salt-based waters are very aggressive to stainless steel (AISI 316). Such mediums are usually e.g. seawater and swimming pool water. Chlorine concentration under 100mg/l grade AISI 316 steel is suitable. If the chlorine concentration is 100-400 mg/l, only the grade SMO 254 steel is available.

5. Results and discussion

Stress corrosion cracking (SCC) may occur if a material is subjected to tensile stress while in contact with a corrosive medium, usually resulting in the formation of cracks. Tensile stress may be caused by fabrication processes such as welding and bending. Typically, HE with their possible plates thickness (<1.5 mm) are subjected to possible damaging temperature gradients and transients due to cyclic operation during start-up and shut down (Fig. 5). These types of load cause large strain ranges in the wall. Whenever bad chemical conditions are present, corrosion might occur, especially during stand-still periods, when oxygen and water are present. This happens in plates and severe pitting might be the result.

Water used for HE should meet all national (domestic) standards. Some of water features are more important than other from HE maintenance point of view. Those agents (if are above allowed levels) are dangerous for HE. It means that the chemical process can cause some damage to the HE plates (both materials AISI 304 and AISI 316) and also can interfere with the brazing material (cooper). There are two main things which may help to avoid problems in operating HE. One of them is to create a better chemical treatment of the water so that hardness will satisfy European norms. It is possible to decrease hardness of the water by installing the magnetizers. Second thing which is very important when there is a danger of HE stone creating is to ensure proper maintenance. All the time the pressure drop on the HE should be examined and if it is rising it means that the resistance is caused by the HE stone created inside. At that point the HE should be cleaned with the compound recommended by the manufacturer.

Fig. 8 shows how the yield stress of carbon steel changes with temperature. It is to be noted how the yield stress fall rapidly once the metal temperature has reached about 350°C. However, such a high temperature arises only in some technological processes where the use of heat exchangers is very rare.

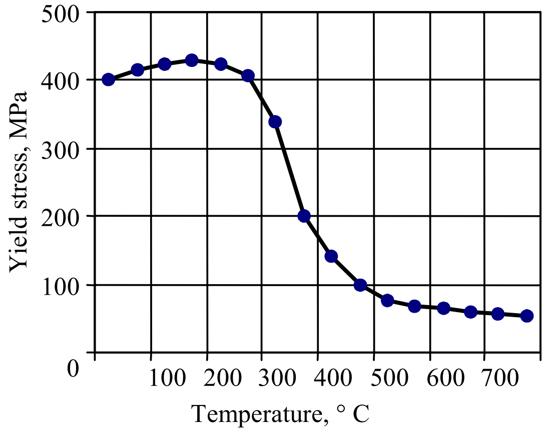


Fig. 8 The variation of yield stress of carbon steel with temperature

Table 4

Vickers's hardness values of tube material

No	Material	Vickers hardness HV, MPa
1	Typical stainless steel	1420
2	Titanium	1450
3	Brass	840
4	Cupro nickel (90/10)	750
5	Cupro nickel (70/30	950

If the fouling problem only becomes apparent after a period of operation it is possible to retrofit on-line cleaning equipment. An alternative to on-line cleaning is to stop operations and to clean the HE either chemically or by mechanical means.

Visual inspection of one of the HE revealed that the tube-sheets contained deep grooves, while the oval tubes suffered corrosion in the form of metal thinning, removed metal pieces and occasional formation of blisters and was sagged at various locations.

There is a wide variety of different materials of construction for the fabrication of corrosion resistant HE (Table 4).

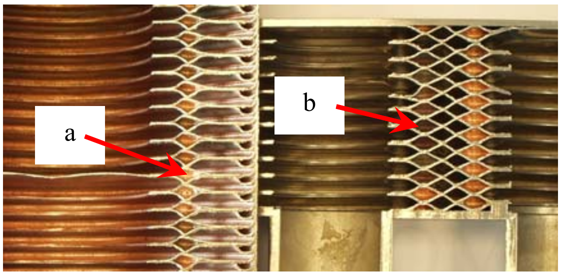


Fig. 9 Plate type heat exchangers with present defects: a – copper only in channels that did not have contact with aggressive liquid; b – because of very aggressive liquid influence the copper has been rinsed

As you can see on the attached pictures (Fig. 9) the heat exchanger is totally "silver". No cooper is left between the plates. In this case pressure inside the heat exchanger begins to separate the plates' one from another what can cause a leakage.

For liquid systems associated with shell and tube HE, tubes are often made of various copper base alloys, principally admiralty brass, aluminium brass, cupro nickel (70/30) and aluminium bronze together with stainless steels, monel and other high quality corrosion resistant alloys. Mild steel tubes are also used for low cost applications. In certain operating conditions the use of "duplex" or bimetal materials may be required.

The principal types of evaluated temperature failures are creep and stress rupture, low-cycle or high-cycle thermal fatigue, and combinations of these failure types. Identifying features of low-cycle thermal fatigue failures are multiple initiation sites that join randomly to form the main crack, transverse fractures and transgranular fracture.

All of the tubes with inner fouling showed a significant enhancement in the hardness of the layers (Fig. 10). Maximum hardness values were found at the distance of 0.1-0.2 mm from tube's surface. The reason for the enhanced hardness was studied by Bott [2]. Bott

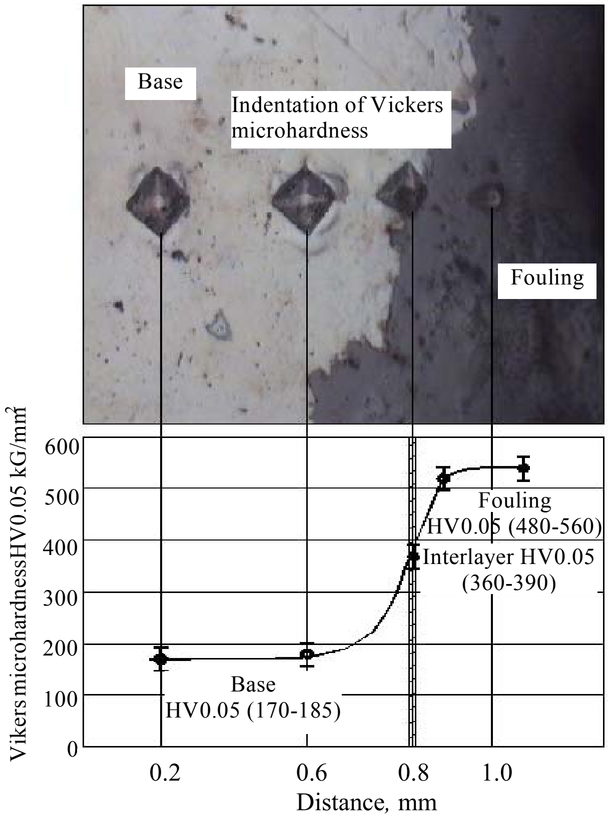


Fig. 10 Distribution of Vickers hardness indents and hardness values in cross-section of the pipe

showed that the coherency strain only plays a minor role in the hardening of these alloyed super-lattice layers. Zettler et al. [5] concluded that a difference in elastic modulus between two layer materials is required for the increase in hardness for the fouling. It is very critical to control the inner thickness of the individual layers in this multiplayer film and by so doing to control the thickness of the super-lattice period.

However, cracks with similar characteristics, but distinguished by intergranular fracture are caused by creep or stress-rupture phenomena [13]. The present investigation disclosed both multiple initiation sites and transverse fractures. This indicates that the likely failure cause of the cracking heater tube could be attributed to either creep or thermal fatigue. However, intergranular fracture increases the possibility of creep damage as the main cause of failure. Creep is time dependent strain occurring under stress and may terminate in fracture by stress rupture (creep rupture). The main variables determining the rate of deformation under creep conditions are temperature, time, and stress. In general, the used cracking heater material is mainly carbide precipitation strengthening alloy.

To minimize such failure in future, periodic inspection to monitor crack formation will be scheduled. Nondestructive tests including dye penetration test for surface cracking and radiographic test for internal crack will be implemented.

5. Conclusions

1. On the inner wall side, the fracture was found to be initiating from some pits, and hard, non-brittle region which caused layer wise separation and chipping off of the material.

2. The degradation in microstructure is reflected by the formation of continuous chains of brittle hard phase along the grain boundaries of microstructure. This effect is more pronounced on the inner wall side of the tubes.

3. Fouling starts at areas that are subjected to minimum shearing forces, rear at the end of the tubes and then spreads to the circumference due to particle transport to the already deposited particles.

4. The investigation has indicated that the fouling attributed to the formation of thick scale of magnetite with mud on the inner surface of the tube wall.

5. The failure in HE tubes could be avoided by: (a) limiting the temperature; (b) minimizing the impurities and harmful chemical species of the heat transfer media to reduce the chemical attack on the inner side; (c) removal of contaminants in the water to minimize carburisation and scaling on the plates and tube walls.

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ŠILUMOKAIČIŲ PAŽEIDIMŲ IR DEFEKTŲ ANALIZĖ

Rezumė

Straipsnyje pateikiama šilumokaičių pažeidimų ir defektų analizė, apimanti tiek laboratorinius tyrimus, tiek eksploatuojamų plokštelinių šilumokaičių darbo sąlygų nagrinėjimą siekiant nustatyti defektų atsiradimo priežastis.

Nagrinėjamas šilumos perdavimo procesas įvertinant realias šilumokaičių darbo sąlygas. Straipsnyje pateikta dažniausiai pasitaikančių šilumokaičių jungiamųjų vamzdžių defektų, taip pat pačių šilumokaičių korozijos dėl šilumnešio terpės poveikio pavyzdžių.

Atlikta šilumokaičių plokštelėms naudojamų medžiagų analizė. Išnagrinėti šilumokaičių pažeidimai dėl netinkamo montavimo, eksploatavimo sąlygų nesilaikymo, korozijos poveikio. Panaudojus teorinius duomenis, palyginti vidutiniai įtempiai ir vidutinės deformacijos, gauti matuojant kietumą įspaudimu. Rezultatai gerai sutapo esant mažesnei nei 12% vidutinei deformacijai. Eksperimentiniam tyrimui taikytas įspaudimo metodas, nes deformacijų ir suirimo atsiradimas kontakte patvirtina naudotus supaprastintus tyrimus. Įspaudimo metu gautų įtempių ir deformacijų matavimai pažeistose šilumokaičių vamzdžių ar šilumos mainų plokštelių vietose gali būti naudojami jų stiprumo savybėms nustatyti įvertinant šilumokaičių patikimumą bei ilgaamžiškumą.

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FAILURES AND FOULING ANALYSIS IN HEAT EXCHANGERS

Summary

In this paper the analysis of failures and fouling in heat exchangers has been presented. The approach combines laboratory scale experiments with industrial observations to study the thermal and fouling characteristics of plate type heat exchangers.

The process of heat transfer under real operation conditions is investigated. The paper presents examples of defects in connecting pipes, corrosion inside heat exchangers due to influence of heat transfer media.

Materials for heat transfer plates of heat exchangers were analysed. Damages of heat exchangers due to wrong installation and exploitation conditions and corrosion have been investigated. The Vicker's indentation method has been employed in the experimental verifications of this analysis, because the resultant deformation/fracture geometry appears to confirm the main simplifying assumption of the analysis. Analyzing an interface between inner tube surface and fouling it was determined that fouling has hardness of 100 Vicker's points higher than that of the tube analyzed. Measurements of indentation stress-strain responses on defected tubes and heat transfer plates may be used to determine strength properties during evaluation reliability and durability of heat exchangers.

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АНАЛИЗ ПОВРЕЖДЕНИЙ И ДЕФЕКТОВ В ТЕПЛООБМЕННИКАХ

Резюме

В статье представлен анализ возникновения дефектов и повреждений в теплообменниках. Анализ включает лабораторные исследования и исследование рабочих условий эксплуатируемых пластинчатых теплообменников при определении причин появления дефектов.

Процесс передачи тепла рассмотрен с учетом реальных рабочих условий теплообменников. В статье приведены примеры наиболее часто появляющихся дефектов в соединительных трубопроводах теплообменников, случаи коррозии в самих теплообменниках из-за воздействия среды теплоносителя.

Проведен анализ материалов, используемых в изготовлении пластин теплообменников. Исследованы повреждения из-за неправильного монтажа, нарушения условий при эксплуатации, воздействия коррозии. При экспериментах использован метод индентирования по Виккерсу, так как появление в контакте деформаций/разрыва подтверждает использование упрощенных исследований. Исследования прослойки между внутренней поверхностью трубы и дефектом показали, что твердость по Виккерсу в самом дефекте на 100 единиц больше твердости исследуемой трубы. Измерения напряжений-деформаций в местах поврежденных труб и пластин теплоносителя может быть использовано для расчета их прочностных свойств Sпри определении надежности и долговечности.

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