MECHANICAL ONLINE SYSTEM FOR CLEANING HEAT EXCHANGER TUBES BY SPONGE RUBBER BALLS (TAPROGGE-SYSTEM)

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ABSTRACT

Cooling waters used in power stations or industrial plants contain dissolved and unsolved substances which can significantly vary in both quantity and composition. Undesired deposition of these substances on tube surfaces is designated as micro fouling. Normally several fouling mechanisms occur in heat exchanger tubes at the same time and intensify. Fouling impairs the heat transfer in heat exchanger tubes. As a result, the efficiency of heat exchangers and of the overall process decreases. To avoid unplanned outages and take advantage of an additional opportunity of recognizing problems at early stage, online cleaning procedure with sponge rubber balls for prevention and removal of deposits in heat exchanger tubes, like the TAPROGGE-System, is advisable. This paper provides a practical insight into the possibilities and benefits resulting from the operation of online cleaning system furthermore, it will be demonstrated that cleaning balls also promoted the formation of protective layers in tubes.

INTRODUCTION

The commonality of the tube bundle heat exchangers, which are treated in this paper, is that they are operated with cooling water, which is passed through tubes to cool a second fluid. The differences are the geometry, the current conduction and the physical properties of the fluids in tube bundle heat exchangers, but for this consideration basically the tube material and the type and properties of the cooling water.

Usually, three different material types are used as tube material: Copper alloys, such as copper-nickel or brass materials, stainless-steels or titanium, very rarely also aluminium compounds. [6]

Cooling water systems are divided into two categories: Once-through and circuit cooling water systems. The sources of cooling water for once-through cooling systems are, for example, river, brackish or seawater. Circuit cooling systems are divided into open and closed systems and the corresponding source for make-up water, for example, pond, well or seawater [1]. These two aspects alone (kind of cooling water and tube material) may account for almost thirty different fouling problems. [6]

The generic term fouling is divided into macro and micro fouling. Micro fouling comprises bio fouling (e.g. bacteria), sedimentation (e.g. sand) and the precipitate of salts (e.g. lime). Usually micro fouling causes a layer on the tube surface consisting of salts or bacteria. Moreover, it is possible that sediments enter this layer. Macro fouling designates coarse particles, which block or plug system parts, like tubes. It is classified according to its source: biological, like mussels, or industrial sources, like synthetics. Frequently, macro fouling provides optimal conditions for micro fouling, for instance, lower flow rates. [6]



Fig. 1 Examples of bio fouling (a), corrosion products (b), biological macro fouling (c) and lime layer (d).

Examples of the various types of fouling are shown in Fig. 1. Fig. 1a shows so-called tubular worms which encapsulate in the tube. This hard encapsulation provides ideal protection against external influences. Fig. 1b shows an example of corrosion. Nickel dissolves from the coppernickel material due to a poor covering layer formation. The tube surface roughness increases. An example of macro fouling is shown in Fig. 1c. A shell is jammed in the tube inlet and thus blocks the tube. Fig. 1d shows a typical example of micro fouling by scaling. A complete top layer of calcium carbonate is formed. This covering layer is built up in several phases. Two phases can be seen here.

The initiation of or tendency to different fouling mechanisms is determined by the type of cooling water, too. While circuit cooling systems are mainly responsible for micro fouling, like concentration of ingredients, the main problem in once-through cooling systems is, for example, the ingress of macro fouling, like mussels or sand.

Which fouling mechanisms occur in heat exchanger tubes also depends on the tube material and its surface condition. The rougher a material, the better can the deposits adhere and grow. Irrespective of the material, particularly ribbed tubes have this disadvantage.

Due to the natural toxicity of copper, copper-alloyed tubes are rarely affected by bio fouling (macro and micro fouling). However, there is an increased risk of corrosion. In the case of stainless-steels and titanium, the corrosion risk is rather low, but there is an increased problem of bio fouling, both macro and micro fouling.

The online condenser tube cleaning system (CTCS) continuously cleans the heat exchanger tubes during the cooling water operation. A simplified description is shown in Fig. 2. The cleaning balls are fed into the cooling water flow just before entering the tube bundle heat exchanger. Due to the oversize of the cleaning balls against the inner tube diameter, the cleaning balls wipe the deposits over the tube surface, similar to a sponge, and remove them from the tube. Different cleaning ball types (coated or uncoated) or properties (hardness, size or additives) are used in accordance with the type of deposits (hard or soft). After exiting the tube bundle heat exchanger, the cleaning balls are separated from the cooling water flow by means of a strainer section and fed back to the ball injection point via the ball recirculation pump and the ball collector, which also serves to replace the cleaning balls. The CTCS runs fully automatically. [2, 8]



Fig. 2 Sketch of online CTCS by TAPROGGE [8].

The cleaning system can also be extended by a filter system (different versions), which serves for the direct protection of the tube bundle heat exchanger by separating cooling water from macro fouling, a single-stage water extraction (TAPIS[®]), reasonably, for example, for once-through cooling water systems, and an automatic online ball quantity monitoring device (BRM®). [8]

CONDENSER TUBE CLEANING SYSTEM

Deposits which settle on the inner side of the heat exchanger tube or which can block the tubes are continuously introduced with the cooling water or are present in the cooling water due to the conditioning. The deposition of micro fouling in the tubes is promoted by high temperatures, increased concentration in the cooling water and low flow conditions. Based on the entire cooling water system the cooling water temperature is the highest in the heat exchanger, the speed in the tubes is limited to a maximum of 2 m/s in copper-alloyed tubes and 2.5 m/s in stainless-steel or titanium tubes. For this reason, the greatest risk of fouling is in the heat exchanger. Scaling occurs at the hottest point in the heat exchanger that means at the cooling water outlet and at the inlet of the fluid to be cooled. But there is also the possibility to recognize scaling at an early stage.

The continuous and effective cleaning performed by the online CTCS during cooling water operation immediately removes deposits from the tubes and prevents them from settling on the tube surface and growing up. With the help of an online CTCS, the effort of manual cleaning in down times is no longer required.

The cleaning balls clean all tubes according to the Gaussian distribution principle. This also applies to macro fouling which may clog entire plant parts.

Cleaning Ball

The core task of the tube cleaning is taken over by the cleaning ball which is made basically from natural rubber. The cleaning ball must meet various requirements. It must completely remove all deposits and fouling residues, irrespective of their properties (hard, soft, loose or strongly adherent), and the tube material must not be attacked or damaged. An additional special feature is that protective layers must be applied, preserved and protected.

In order to clean the tube on the entire inner surface, a certain pressure must be applied to the surface of the tube material by the cleaning ball. Therefore, the cleaning ball has a certain oversize against the inner tube diameter. The oversize is limited by the predetermined differential pressure, the pressure loss of the cooling water side via the heat exchanger, respectively. The differential pressure is dependent on the number of tubes, the tube length, the tube inner diameter, the general heat exchanger design and the cooling water velocity. [2, 8]

The determination of the release pressure is a precaution. If the cooling water flow is disabled and the cleaning balls are still in the heat exchanger tubes, they must be circulated when the cooling water starts again and must not block the tubes. The release pressure indicates the necessary pressure that must be built up to bring a cleaning ball that has got stuck in the tube back into circulation.

When passing through the tube, the cleaning ball is not only pushed or pulled by the pressure difference but also perfused by the cooling water. This is favoured by the open pore structure of the cleaning balls. As a result, the so-called "jet effect" occurs. The deposits are removed and driven out of the tubes in front of the cleaning ball. [8]

Another important aspect which the cleaning ball must fulfil is the undisturbed recirculation in the CTCS circuit. In addition to the passes through the heat exchanger tubes, the strainer section and the recirculation pump must be observed: The recirculation pump is a special centrifugal pump which is designed for a non-destructive cleaning ball transport. The strainer section ensures the separation of the cleaning balls from the cooling water. It is absolutely necessary to prevent the cleaning balls getting stuck on the screen surfaces and thereby disturbing the recirculation of other cleaning balls. The strainer configuration can vary in angle and screen bar width. In addition, the cleaning ball can be adjusted in size and hardness. This shows that the design and function of the cleaning balls is an extremely complex process which must consider the CTCS as a whole. [8]

In addition, the different types of fouling and tube materials in the heat exchanger must be observed. In the case of copper-alloyed tubes, for example, it is important that an oxide layer is formed to protect the material from corrosive attack. Therefore a cleaning ball without any abrasive effect is recommended.

In the case of titanium or stainless-steel tubes, the tube surfaces are very smooth, a slight abrasive effect is necessary to achieve a sufficient cleaning effect. Cleaning balls provided with polishing agents help keeping these tubes clean. The polishing agent has a lower hardness than the tube material and thus acts only as fouling abrasive. [8]

There are two different basic cleaning ball types for typical materials in tube bundle heat exchangers. Moreover, there are further possibilities to increase the abrasiveness of the cleaning balls. For this purpose, basic cleaning ball types are coated with different materials, such as polishing agents, synthetic granulate or corundum. The coating can be applied as total or as ring which effects in different ways. For a better distribution over the tube sheet, cleaning ball types with different sinking velocities are produced. Thus, the upper and lower tubes are reached in the same way. If necessary, a mixture of different types may also be recommended. [6, 8]

Experience has shown that the cleaning balls have a regular life time of up to four weeks. Within this time, the cleaning balls show two different typical wear patterns, depending on the tube surface condition.

In smooth tubes with a roughness of up to 5 μ m, no more abrasion is present and the cleaning balls are not worn down. The wear of the cleaning balls is caused by the continuous mechanical load in the tubes, on the screen of the strainer section, in the ball recirculation pump, in the piping, and also by various additives and characteristics of the cooling water. The diameters of the cleaning balls remain constant. The cleaning balls only become softer. This wear mechanism is typical for stainless-steel and titanium tubes.

Copper alloyed tubes typically have a higher roughness. The wear pattern is determined by the abrasion of the cleaning ball surface. The cleaning ball is oriented in the heat exchanger tube according to the least resistance. In order to clean the heat exchanger tubes effectively, the cleaning balls must have an oversize of at least 0.5 mm in diameter. Typical wear phases are shown in Fig. 3.



Fig. 3 wear phases of cleaning balls, as a result of tube roughness.

In the first wear phase, the cleaning balls are cigarshaped. The cleaning ball is oriented with the smallest diameter along the tube surface. The contact surface of the cleaning ball on the roughness surface is thereby increased. However, the smallest ball diameter and thus the contact pressure and the effect of the cleaning ball are significantly lower. For this type of cleaning balls, it is recommended to replace the cleaning balls in order to maintain the cleaning at an effective and efficient level, because starting from this wear phase the ball diameter is smaller than required.

In the second wear phase, the cleaning ball has an oval shape. The smallest ball diameter lies only with the heat exchanger tube inner diameter. The maximum diameter also decreases with time. The cleaning balls are no longer effective.

In the third wear phase, a round shape is obtained again. The cleaning ball diameter is smaller than the smallest inner diameter of the heat exchanger tubes. The cleaning ball has no more cleaning effect.

As far as worn cleaning balls are concerned, there is another problem besides the poor cleaning effect. Cleaning balls that are both too small and too soft are pushed through the screen bars of the strainer section more easily by the cooling water flow and thus disappear from the system. These are then found in the cooling tower or the corresponding water box.

When cleaning balls in stainless-steel or titanium tubes have a cigar shape, this is a strong indication that hard deposits are present in the tubes, whereby tube roughness increases. The cleaning ball is much more than just a cleaning tool, it is also an indicator of any changes and deposits in the heat exchanger tubes and thus for the entire heat exchanger.

PROTECTION LAYER

By reason of the high thermal conductivity (100 - 110 W/m K, at 20 °C), the corrosion resistance (corrosion rate ≤ 0.01 mm/a) and the favourable price, copper-alloyed tubes, such as material 2.0470 or 2.0460, were used in heat exchangers in the past. Their resistance to corrosive attack is caused by the formation of self-oxide layers. However, this protective layer is only surface-covering and resistant in salt-free cooling waters without any tendency to form deposits. The copper oxide layer has a thickness of up to 5 μ m. [3]

In chloride-rich cooling waters, the oxides of the protective layer are replaced by chlorides which increase the rate of corrosion [4]. The local increase in the electron conductivity increases the risk of pitting corrosion. Solid deposits, such as, calcium carbonate, or biological decomposition products, can also cause pitting corrosion. In this case, the establishment of an external protection layer is a successful measure.

On account of the susceptibility to corrosion of copperalloyed tubes, stainless-steels, like 1.4301, 1.4401 or 1.4436, have more and more been used since the 1960s. Their poorer thermal conductivity is almost eliminated by the lower wall thickness. The stainless-steels also form a passive layer which protects the material against corrosive attacks. This passive layer is an oxide film with a thickness of 1 to 4 nm [3]. Special care is required in the case of deposits because areas of corrosion and pitting can form. The same applies to clogged cooling tubes. Due to the low flow rate and the prevention of cleaning, the corrosion potential increases. [3]

Another option is to use titanium tubes. Their poor thermal conductivity is also compensated by the reduced wall thickness. Titanium is protected against corrosive attack by a passive layer. A special feature of the protective layers of stainless-steel and titanium tubes is the rapid renewal after mechanical injuries in oxygen-containing cooling waters. [3]

Cleaning process with protection layer

In the case of aggressive cooling waters, such as seawater, it is important to protect the heat exchanger tubes, especially copper-alloyed tubes, from corrosive attack. An iron-rich protective layer can be applied to the tube surface using iron sulphate dosing system. This is done in two phases: First, the layer is applied and then obtained. This means that the iron sulphate dosing must be continued otherwise the protective layer is destroyed again.

The thicker the protective layer is the better the corrosion resistance of the tube material. However, the saturation is obtained from a certain strength, approximately 2 mg/cm². In addition, the fouling rate increases with increasing strength of the protective layer because the natural toxicity of copper decreases. Furthermore, the task of the heat exchanger must also be considered. The stronger the protective layer the poorer the heat transfer. It is therefore absolutely necessary to form a very thin yet effective protective layer. [5]

The mechanism of iron sulphate dosing is based on the solubility of the salt. The oxidation of the iron ions from the dissolved iron sulphate produces colloidal iron(III)oxide-hydroxide, which accumulates on the surface of the tube. [5]

$$4 \operatorname{Fe}^{2+} + 8 \operatorname{OH}^{-} + \operatorname{O}_2 \to 4 \operatorname{FeO}(\operatorname{OH}) + 2 \operatorname{H}_2 \operatorname{O}$$
(1)

In order to obtain a compact, homogeneous, thin and adherent layer for protecting the tube material, the coordination between the iron sulphate dosing and the operation of an online CTCS is important. The optimized operation of the cleaning system in conjunction with the iron sulphate dosing (intermittently), results in a reddish-brown protection layer with a thickness of 10 to 50 μ m. This protection layer provides a good corrosion protection and causes low heat transfer losses (Fig. 4b). [5]



Fig. 4 Protection layer formation as a function of the online CTCS [5].

Without online CTCS the protective layer is soft, voluminous and porous. The heat transfer loss is up to 60 % (Fig. 4a). Continuous cleaning with online CTCS results in a compact, glossy and homogeneous surface of the protective layer (Fig. 4c). However, these two protective layer types (Fig. 4a and c) tend to burst in the event of dry downtimes.

Intermittent cleaning provides a good countermeasure, resulting in a dull, reddish brown layer, which is less sensitive to decommissioning and drying out. A successful operation with copper-alloyed tubes in conjunction with seawater is a cleaning mode of one hour a day. The cleaning system is adjusted to the usual ball frequency of 12 balls per tube per hour. According to the distribution of the cleaning balls in the heat exchanger, all heat exchanger tubes are cleaned mechanically 6 - 24 times a day by cleaning balls. [6]

In order for the iron sulphate protective layer to adhere optimally to heat exchanger tube surface, various cooling water conditions, such as pH-value, suspended solid fraction or temperature, must be satisfied. The tube material, the tube surface condition, the iron sulphate dosing and the sponge rubber cleaning procedure have also a considerable influence on formation of the optimum protective layer.

Iron(III)oxide-hydroxide is readily soluble in water in an acidic environment but is almost insoluble in a basic milieu. The ideal pH-value for forming and maintaining the protective layer is 8 [5].

The formation of iron(III)oxide-hydroxide is an endothermic reaction. From a temperature of 20 °C, which is usually achieved in heat exchangers (cooling water side), the reaction rate is sufficient. The cooling water inlet temperature is a variable which the plant operator cannot influence. During the winter months a suitable protective layer is difficult to apply with temperatures below 6 °C, for example, in the Northern Europe region. [5]

The formation of the optimum protective layer can be prevented by means of various particles in the cooling water such as sediments, dust or lime precipitates. The dissolved iron ions can bind to the particles and are thus no longer available for the protective layer. The particles can also be incorporated into the protective layer. As a result, the protective layer becomes damaged and inhomogeneous. The presence of particles must be prevented. [5]

Other factors are dissolved oxygen which is required for the reaction and inorganic compounds such as sulphides, ammonia or manganese, which shifts the reaction.

Before the protective layer is applied, the surface must be clean and free from deposits. Corrosion areas must be removed. If an intact protective layer already exists, this should be kept. If it is damaged, however, the layer should be removed and corundum balls should be used. Given that corundum is harder than copper-alloyed materials, corundum balls are both deposit and material abrasive. This also applies to aluminium-based tube materials. For this reason it is absolutely important to ensure that corundum balls are used correctly and not permanently. Ideally an inspection is performed to verify the tube condition before the start of the corundum ball cleaning procedure. In general, cleaning with sponge rubber balls must be carried out at least before the application of the protective layer in order to remove loose deposits. [5] For cleaning procedure during iron sulphate dosing, the sponge rubber ball is used without any abrasive effect. The sponge rubber cleaning is the instrument for the balance between the maintenance of the good heat transfer and the prevention of corrosion. The optimal cleaning frequency with sponge rubber balls is influenced by the various local conditions. The properties of the protective layer crucially depend on the cleaning frequency and duration. An intermittent cleaning frequency, like up to a few hours per day, is recommended as far as possible. However, in most cases the cleaning frequency is one hour per day. [6]

The proper protective layer must be monitored continuously. For this purpose regular visual checks are suitable. Another possibility, which also brings about much more detailed results, is the extraction of tubes with subsequent metallurgical examination. However, the extracted tube should be a representative tube so that the results can be transferred to the entire heat exchanger.

In order to perform an on-line check of the formation of the protection layer with aid of iron sulphate in copperalloyed tubes it is suitable to determine the copper content in the cooling water outlet.

According to this measurement method, suspended copper is determined, which is an indication of corrosion products. Copper content is increased by a corundum ball cleaning, as corrosion products are removed from the heat exchanger tube surface. During the formation of the protective layer, the copper content in the cooling water outlet is reduced.



Fig. 5 Copper content (dots) as a function of the iron sulphate dosing (grey areas) [5].

Fig. 5 shows an example of the interplay between copper content and iron sulphate dosing during the protective layer application. First, the copper content is over 50 ppb. In the course of the iron sulphate dosing, a first protective layer can be successfully be applied. The iron sulphate dosing is carried out in each case over a period of twelve hours. The influence of the iron sulphate dosage on the copper content is obvious and is demonstrated by the decrease of the copper emission to almost 10 ppb. Also after dosing, the copper content decreases even further. This shows the slow constant build-up of the protective layer in the heat exchanger tube, due to the sufficient concentration of iron sulphate in the cooling water. The pause interval between two dosing periods results from the system. When the copper content increases, iron sulphate is dosed again. In this case the interval is 8 - 13 hours. After 70 hours, the copper content in the cooling water output is less than 5 ppb. Now it is to be assumed that the protective layer is applied and the phase of the protective layer conservation is starting.

Other possibilities for checking the formation of the protection layer are the eddy current test and the measurement of the polarization resistance [5].

Possible problems of uniform protective layer formation occur particularly in the inlet area of the heat exchanger tubes. If the protective layer is not formed sufficiently, erosion corrosion becomes possible. Countermeasures are the reduction of the amount of cooling water, the reduction of the ball frequency or the increase of iron sulphate dosing.

In the case of a reduction of the heat transfer, which can be recognized by the deterioration of both the U-value and the terminal temperature difference (TTD), either the iron sulphate dosing is reduced or the ball frequency is increased or both are supplemented. [2]

Due to the fact that, especially in power stations, just little attention is paid to the cooling water side of heat exchanger tubes, comparatively rough protection layer structures result. These are first evident by the increased cleaning ball wear. With a roughness of, for example, 50 µm, the ball life time is reduced to only two days. These rough protection layers must be removed. With the help of a corundum ball cleaning procedure, the rough protection layers are removed and the tubes are smoothed. By the use of corundum cleaning balls with subsequent polishing cleaning balls an end roughness of 8 µm is achieved. The life time of the cleaning ball is thus increased again to up to four weeks. If the cleaning balls are not checked carefully and exchanged in time, they will lose their effect and efficiency. After only four months, the protective layer can be damaged again in such a way that the ball life time is again two days. Due to the damaged protective layer, corrosion can also occur again.

The following procedure is recommended for the build-up of a cooling water side protection layer with good corrosion protection and long cleaning ball life time:

- 1. Preparation of the heat exchanger tube surface by means of corundum balls for smoothing the surface and removing deposits and corrosion products. A maximum tube material roughness of $10 \ \mu m$ is applied.
- 2. Intermittent tube cleaning procedure, depending on the conditions of the system and cooling water type, with sponge rubber balls, polishing balls or a mixture of both types of cleaning balls.
- 3. For circuit cooling water systems, a copper inhibitor can also be added.

The smoothing of the tube surface by means of a corundum ball cleaning and the subsequent continuous effective cleaning with polishing balls is also recommended for the heat transfer tube materials like stainless-steel and titanium. The passive-protective layers of these tube materials are built so quickly and comprehensively with the help of the oxygen in the cooling water that no further protective layers have to be applied for these tube materials. In the case of titanium, corrosion problems have been unknown so far. Corrosion is also rare in stainless-steel heat exchangers. The cause of corrosion in stainless-steel tubes are deposits on the tube surface or clogged tubes. This can be successfully be prevented by means of a continuous, effective tube cleaning, if necessary with an additional debris filter installed directly in front of the heat exchanger for the protection of the same.

Cleanliness factor

An important factor for verifying the condition of the heat exchanger is the cleanliness factor (CF). The CF is defined by the ratio of the actual and design heat transfer coefficients:

$$CF = \frac{U_{actual}}{U_{design}}$$
(2)

With the help of the actual heat transfer coefficient compared to the design heat transfer coefficient, degradation of the heat flow, for example by deposits or too thick protection layers, is detected. The CF is 95 - 100 % for clean heat exchanger tubes for stainless-steel and titanium materials. For copper-alloyed tubes, depending on the type of cooling water, for sea and brackish water 85 - 95 % and for cooling tower and fresh water 95 - 100 % are reached. The CF can be measured directly in the heat exchanger tube which is a very accurate way of determination. A further possibility is to calculate this indirectly via the transferred heat flow, by means of steam temperature or steam pressure, cooling water temperatures, cooling water flow rate and other system values. Due to the various parameters, with the respective measurement errors, this method is imprecise. Often the measured steam data does not produce any thermodynamically meaningful results. As a result of the necessary assumptions, further error sources are added. [6]

In a power plant, the heat transfer coefficient was measured directly in the heat exchanger tube (Fig. 6). The influence of the cleaning balls is shown on basis of this data.

In the months from September to the beginning of November, a maximum CF of 87 % is reached. By the use of a new cleaning ball charge, characterized by the grey triangle, this CF is reached.



Fig. 6 Recording of the CF, measured directly in the heat exchanger tube, over time, including display of the ball exchange (grey triangles and dot) [5].

Within one week after exchange of cleaning balls, the CF and thus the cleaning effect remains constant at 85 - 87 %. The heat exchanger tubes are cleaned well. Subsequently, the wear of the cleaning balls and thus the clear reduction in the cleaning effect can be seen. The CF decreases continuously. This means that the heat exchanger tubes are no longer sufficiently cleaned. Contamination of heat exchanger tubes increases. The CF decreases to 80 %. The cleaning ball exchange interval is three to five weeks and is much too long. To achieve continuously effective cleaning, the cleaning ball exchange interval should be reduced to one week.

Due to poor result for the CF, a CF of 95 - 100 % is expected. The calculation of the cleaning balls was checked again. In the middle of November the optimized cleaning ball type was used, shown with the help of the grey dot. In this case the ball diameter was adjusted, among other things. This increased the CF to 96 %. Immediately after addition of the new optimized cleaning balls the CF drops again. This is due to very strong contamination and the associated high cleaning ball wear. For this reason, the cleaning ball exchange must first take place more quickly until the deposits from the tubes have been completely removed. [5]

This example demonstrates the importance of the timely exchange and the correct layout of cleaning balls and the influence of the cleaning ball wear on the efficiency of the cleaning in the heat exchanger. Even when using non-optimal cleaning balls, the CF is increased by 6 % by the use of a new cleaning ball charge. The increase with the help of the optimized cleaning ball resulted in a further increase of almost 10 %. If the cleaning is carried out correctly, the heat exchanger is kept clean and the heat transfer is optimized.

Efficiency enhancement

The heat transfer impairs due to clogged or polluted heat exchanger tubes. The discharge heat quantity, of the fluid to be cooled, decreases. The required temperature cannot be achieved. To compensate this, the cooling water flow may be adjusted. The poorer the heat transfer, the more cooling water is required. Only a certain proportion is compensated for by means of the cooling water flow, that is also limited, because the temperature increases despite an increased amount of cooling water. For power stations with turbine condensers, this means that the steam temperature and thus the steam pressure in the condenser increase. By reducing the vacuum, the entire circuit process is affected, and the power output of the power plant is reduced.

In a power plant, with a design power output of $1033 \ 10^6$ W and a design vacuum on the steam side in the condenser of 7600 Pa_{abs}, data was recorded as shown in Table 1. The power output, the steam pressure in the condenser and the cooling water flow are measurements. Among other data from these measured data, the calculated loss data, which is respectively related to the loss of the vacuum, and the CF, which describes the state of the heat exchanger tubes at the same time, are pointed. The pure loss data of the steam pressure and the power output are determined by the difference between the actually measured data and the design data. Depending on the loss of the steam pressure and the loss of the power results in 0.07 10^2 %/Pa respectively 0.74 10^4 W/Pa.

load	pressure	flow _{cw}	loss		CF
$10^6 \mathrm{W}$	$10^2 Pa_{abs}$	kg/s	10 ⁻² %/Pa	10 ⁴ W/Pa	%
1 003	116.4	7 380	0.072	0.748	91.0
1 007	110.3	7 156	0.075	0.773	88.1
1 010	104.8	7 440	0.077	0.794	90.4
1 013	102.2	7 296	0.076	0.782	88.8
1 017	97.1	7 276	0.074	0.766	87.7
1 019	95.4	7 322	0.070	0.727	88.1
1 022	91.2	7 085	0.068	0.701	85.3
1 0 2 6	86.3	7 482	0.063	0.654	89.2
1 029	82.7	7 428	0.065	0.673	87.7

 Table 1:
 Loss of power output as a function of condenser steam pressure.

In accordance to Table 1 it seems that the CF and the vapor pressure loss are independent of each other. This is due to the strong influence of the cooling water flow. In this case, the CF was not measured directly in the heat exchanger tube but was calculated with the aid of the transferred heat flow. As already shown in Eq. (2), the CF is dependent on the actual and the design heat transfer coefficients. The heat transfer coefficient is determined according to the Eq. (3).

$$U = \frac{\dot{m}_{cw} \cdot c_{p,cw}}{A_{cond}} \cdot \ln\left(\frac{T_{s} \cdot T_{in,cw}}{T_{s} - T_{out,cw}}\right)$$
(3)

The following connections of the variables result from the assumption that the specific heat capacity ($c_{p,cw}$), the heat transfer area (A_{cond}) and the cooling water inlet temperature ($T_{i,cw}$) are constant. The steam temperature increases with decreasing vacuum. The actual heat transfer coefficient drops and thus the CF. With decreasing cooling water outlet temperature ($T_{o,cw}$), the transferred heat quantity, the heat transfer coefficient and the CF decrease. If the cooling water flow is increased, the transferred heat quantity can be increased again, thus the heat transfer coefficient is again increased and the CF becomes apparently better. This does not reflect the reality, but compensates for the poorer heat transfer with more cooling water. This is also the reason why the CF partially increases despite vacuum loss. Despite better CF the tube condition still remains in a non-optimal state.

The cooling water inlet temperature is dependent on the season. With decreasing cooling water inlet temperature, the transferred heat quantity, heat transfer coefficient and CF increase. There are better conditions in winter than in summer months.

Table 2: Data from typical power station losses related to
condenser vacuum (GEC Alsthom case study) [7].

Type of unit	Performance variation	Output difference	
$10^6 \mathrm{W}$	10 ⁻² %/Pa	10 ⁴ W/Pa	
330	0.07	0.23	
600	0.09	0.54	
900	0.12	1.08	

The power output losses from Table 1 are also confirmed by a case study by GEC Alsthom (Table 2). There are similar contexts. The efficiency loss is not just related to the power output of the power plant, but also CO₂ emissions are important factors and are gaining importance. Resulting from a continuous loss of the vacuum of only 1000 Pa_{abs} in turbine condenser is a power loss of 7.4 10⁶ W results. With the assumption of specific CO₂-emission of 1 10⁻³ kg/Wh and an operating time of 6000 h/a this results in a CO₂-emission of 43 10⁶ kg/a. This could be saved just by a clean turbine condenser, at the same power output. [7]

CONCLUSIONS

For tube bundle heat exchangers which are operated with cooling water, the use of online CTCS is the state of the art. If they are operated without sufficient attention larger disturbances may arise which could be minimized by a better and timely consideration. Examples such as corrosion or bad protective layer formation have been explained. For each system, different operating modes for online CTCS result from individual circumstances.

The wear behaviour of the cleaning balls determines the state of the tubes and also of the corresponding protective layer in a manner of approximation. The CF is an indication of the cleanliness and condition of the heat exchanger tubes.

The aim of the online cleaning systems is to keep the heat exchanger tubes clean and to allow as high heat transfer as possible. This also increases the life time of the heat exchangers and their tubes and manually cleaning procedures of heat exchanger tubes are no longer necessary. Furthermore, the efficiency of the heat exchanger remains constant at a good level. In order to achieve this, the cleaning ball must be optimal adjusted to the system, which means the components of the CTCS, heat exchanger, and cooling water conditions.

NOMENCLATURE

А	Area, m ²
BRM	Ball Recirculation Monitor
CF	Cleanliness Factor, %
cp	specific heat capacity, J/kg K
CTCS	Condenser Tube Cleaning System
d	diameter, m
ṁ	Mass flow, kg/s
Т	Temperature, K
TAPIS	TAPROGGE Intake System
TTD	Terminal temperature difference, K
U	U-Value, thermal Transmittance, W/m ² K
Subscript	

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abs	absolute
actual	measurement values
cb	cleaning ball
cond	condenser
cw	cooling water
design	design values
S	steam
i	inner
in	inlet
out	outlet

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