UDK 536.24:621.175

Spremljanje prenosa toplote v kondenzatorju pare

Monitoring of Heat Transfer in a Steam Condenser

VLADIMIR REPIČ — MATIJA TUMA

Predstavljen je preprost način računanja vpliva umazanosti hladilnih površin kondenzatorja pare, ki v načelu velja tudi za vse vrste prenosnikov toplote, v katerih kondenzira para. Podanih je nekaj predlogov za spremljanje vpliva umazanosti, ki vključujejo tudi predlog za razvoj merilnega instrumenta v ta namen. Za podrobneje analiziran primer se izkaže, da samo eno stotinko milimetra debela obloga na strani hladilne vode ali pare zmanjša toplotno prehodnost na 85 do 92 odstotkov, eno do dve desetinki milimetra debela obloga na strani hladilne vode pa že na borih 33 do 50 odstotkov začetne vrednosti. To pomeni zmanjšanju toplotne prehodnosti ustrezno zvišanje temperature kondenzacije.

A simple way of calculating the influence of fouling of the cooling surfaces in a steam condenser is presented, generally valid for all types of heat exchangers in which steam condenses. Some suggestions for monitoring the influence of fouling, including a suggestion for developing a measuring instrument for this purpose, are given. A detailed analysis reveals than even a one-hundredth of a milimeter thick scale deposit on the cooling water side, or on the condensing steam side, reduces the overall heat transfer coefficient to a value of 85 to 92 percent of that on the beginning, while a scale deposit of up to two tenths on the cooling water side reduces it to a scanty 33 to 50 percent of the beginning value. This means an increase in the condensation temperature corresponding to the decrease in the overall heat transfer coefficient.

0 UVOD

Med obratovanjem energetskega postrojenja se poleg različnih neizbežnih nevšečnosti, kakršne so obraba, staranje, utrujanje, elektrokemična preobrazba materialov, pojavlja tudi zamazanje površin, prek katerih se prenaša toplota.

Spremljanje stanja hladilnih površin kondenzatorja temelji na merjenju temperature pare iz nizkotlačnega dela turbine, ki teče v kondenzator, in temperature hladilne vode iz kondenzatorja ter analiziranju spreminjanja vrednosti razlike teh dveh temperatur.

Naraščanje razlike obeh temperatur skozi daljši čas je znak nastajanja oblog na hladilnih površinah kondenzatorskih cevi. Neposredna posledica oblaganja hladilnih cevi je naraščanje temperature kondenzacije, ker se le-ta odvija na površinah, katerih toplotna upornost se s časom veča. Obloge na ceveh nastajajo med obratovanjem in jih na novem kondenzatorju ni bilo. Tudi po uspešnem čiščenju jih ni več.

Debelina oblog, velikosti nekaj stotink mm, nima večjega vpliva na konvekcijo v ceveh, ima pa odločujoč vpliv na prevajanje. Pri konvekciji imata najpomembnejšo vlogo hitrosti pare in hladilne vode, ki pa sta pri konstantnem delovanju stalni, ali natančneje povedano, vpliv rahlih sprememb hitrosti je zanemarljiv v primerjavi z vplivom nastajanja oblog.

0 INTRODUCTION

During operation of a power plant, along with various other problems such as wear, ageing, fatigue, and electrochemical transformation of materials, fouling also occurs on surfaces through which heat is transferred.

Monitoring of the condition of the cooling surfaces of a condenser is based on measuring the temperature at the steam outlet from the low-pressure part of the turbine and the temperature at the cooling water outlet from the condenser, as well as on analysis of the variation of the difference between these two temperatures.

An increase in the difference between these two temperatures over a longer period is a sign of scale deposits forming on the cooling surfaces of the condenser tubes. A direct consequence of the scale deposits is an increase in the temperature of condensation, since the thermal resistance of the surfaces increases with time. Scale deposits on the cooling surfaces are formed during operation and were absent in a new condenser. They also disappear after successful cleaning.

The thickness of the scale deposits is within the range of a few hundredths of a milimeter, and it has no significant influence on convection in the tubes, but it does have a decisive influence on conductivity. In convection, the most important factors are the velocities of steam and cooling water, which are constant during constant operation. More precisely, the influence of slight changes in velocity is negligible in comparison with the influence of scale deposit formation.

Sicer pa zmanjšanje pretoka hladilne vode iz drugih razlogov prav tako povzroča zvišanje temperature kondenzacije zaradi zvišanja temperature hladilne vode skozi kondenzator in zaradi zmanjšanja toplotne prestopnosti na strani vode. Premajhna hitrost vode v pretočnih hladilnih sistemih ima tudi druge kvarne vplive; povzroča povečano oblaganje cevi in neenakomerno porazdelitev vodnega toka v vse cevi. Slednje lahko sčasoma povzroči zamašitev določenega števila cevi. Takšno dogajanje zmanjša hladilno površino in povzroča erozijsko nevarno hitrost vode skozi nezamašene cevi.

1 PRIBLIŽEK KONDENZATORJA

Razlika med temperaturo kondenzacije in temperaturo izstopa hladilne vode je približek kondenzatorja, označen z ΔT_{min}.

Z $\Delta T_{min,o}$ označimo približek novega ali čistega kondenzatorja, ki je konstrukcijski podatek vsakega kondenzatorja, katerega vrednost je v mejah med 3 in 7 K. Velikost kondenzatorja preračunamo in poiščemo najugodnejšo rešitev. Ta je neposredno odvisna od približka in preostalih veličin, npr.: pretok pare, ki kondenzira, toplotna prehodnost, količina hladilne vode, izstopna hitrost pare iz turbine, vrsta turbine. Najugodnejša rešitev je rezultat tehnične, ekonomske in ekološke obravnave celotnega »hladnega konca« turbinskega postrojenja.

Enačba približka (sl. 1):

A decreased flow of cooling water (due to other reasons) also causes an increase in the condensation temperature due to a larger increase in the temperature of cooling water passing through the condenser and due to a decrease in the convective heat transfer coefficient on the cooling water side. Too low a velocity of water in open cooling systems can also have other detrimental effects: it causes increased formation of scale deposits on tubes and a non-uniform distribution of water flow in the tubes. The latter can, in time, cause occlusion of a certain number of tubes. Such events reduce the cooling surface and cause a dangerously high velocity of water through the non-occluded tubes, which can cause erosion damage to the tubes.

1 CONDENSER PITCH POINT

The difference between the condensation temperature and the temperature at the cooling water outlet is the condenser pitch point, denoted by ΔT_{min}.

$\Delta T_{min,o}$ is the pitch point of a new or a clean condenser the value of which lies between 3 and 7 K. The size of the cooling surface is calculated and optimized and is directly dependent on the condenser pitch point and all other quantities, such as: the flow of condensing steam, the overall heat transfer coefficient, the quantity of cooling water. The whole »cold end« of the turbine power plant is optimized from the technical, economic and ecological point of view.

The condenser pitch point equation, Fig. 1:

$$\Delta T_{min} = \frac{\Delta T_{hv}}{e^{k \Delta T_{hv} A/Q} - 1} \tag{1}$$

je izvedena iz enačbe za prenos toplote:

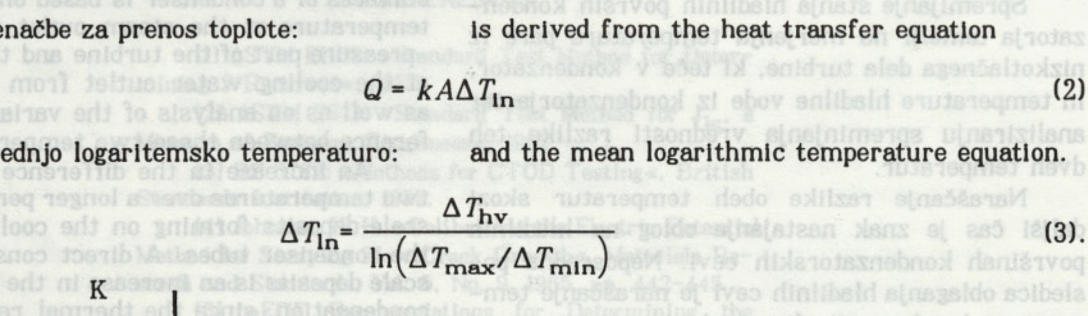
is derived from the heat transfer equation

$$Q = k A \Delta T_{ln} \tag{2}$$

in enačbe za srednjo logaritemsko temperaturo:

and the mean logarithmic temperature equation.

$$\Delta T_{ln} = \frac{\Delta T_{hv}}{\ln\left(\Delta T_{max}/\Delta T_{min}\right)} \tag{3}.$$



Sl. 1. *Temperaturne razmere v kondenzatorju pare*

Fig. 1. *Temperature conditions in a steam condenser*

Dober približek terja kondenzator z večjo površino, a omogoča nižjo temperaturo kondenzacije in s tem več pridobljenega dela.

V enačbi (1) je nespremenljiva le hladilna površina *A*. Vse druge veličine so med seboj odvisne, s tem, da se toplotna prehodnost *k* spreminja pretežno v odvisnosti od drugih veličin (vplivi prestopa toplote – pretoki vode in pare), ali pretežno neodvisno (vplivi prevoda toplote – obloge na ceveh).

2 NARAŠČANJE PRIBLIŽKA KONDENZATORJA ZARADI OBLOG

Toplota prehaja s kondenzirajoče pare na hladilno vodo. Pri prestopu s pare na cev, prevodu skozi cev in prestopu s cevi na vodo naleti na dodaten upor – na plast oblog. Ta s svojo slabo prevodnostjo povzroči precejšen temperaturni padec. Pri prenosnikih toplote na splošno to pomeni zmanjšanje toplotne moči. Tudi pri kondenzatorju je tako, vendar je to le prvi del dogajanja, ki je prehodnega značaja. Zmanjšanje toplotne moči pri nespremenjenem dotoku pare iz okrovov nizkotlačnih turbin dviguje tlak v kondenzacijskem delu – kondenzacija zamuja, količinsko in časovno.

Višjemu tlaku ustreza višja temperatura kondenzacije. Višja temperatura pomeni večji potencial, ki premaga povečano toplotno upornost pri prehodu toplote in kondenzacija se odvija nemoteno naprej, vendar pri višji temperaturi in pri ne bistveno spremenjeni količini prenesene toplote. Seveda je zaradi povišanega tlaka v kondenzatorju moč generatorja manjša. Termodinamično povedano: zaradi umazanja kondenzatorja se porabi več eksergije za odvod toplote, zato je ostane manj na gredi generatorja.

Zvišanje temperature kondenzacije zaradi nastajanja oblog v ceveh torej med obratovanjem zaznamo kot povečanje približka.

Povečevanje približka je eksponencialno, sprva položno, pri vse večji umazanosti pa postane strmo. Obratovanje brez čiščenja lahko privede do »infarkta« kondenzatorja in zaustavitve postrojenja.

Pretok hladilne vode je stalen. Tudi toplotna prestopnost na strani hladilne vode je stalna, saj je v največji meri odvisna od pretoka hladilne vode. Zaradi oblaganja notranjih sten cevi se seveda notranji premer nekoliko zmanjšuje, toda to zmanjšanje ima zanemarljiv vpliv na hitrost vode v ceveh; še celo takrat, ko ima debelina oblog že daleč največji vpliv na prehod toplote.

Zaradi višanja temperature kondenzacije se znižuje specifična prostornina in s tem hitrost pare, ki priteka v kondenzator. Ta hitrost ima vpliv na toplotno prestopnost na strani pare, saj je od nje odvisna turbulenca. Vplivi sprememb preostalih veličin zaradi povišanja temperature, npr.: sprememba gostote pare, sprememba toplotne prevodnosti kondenzata na ceveh in zaradi vsega tega

A condenser with a larger cooling surface enables a lower condensation temperature and more work is acquired, since the condenser pitch point is lower.

In equation (1), only the cooling area is constant. All other quantities are mutually dependent, bearing in mind that the overall heat transfer coefficient changes are predominantly dependent on other quantities (influences of heat convection – flows of steam and water) or predominantly independent (influences of heat conduction – scale deposits on/in the tubes).

2 INCREASE IN CONDENSER PITCH POINT DUE TO SCALE DEPOSITS

Heat meets additional resistance during transfer from condensing steam to a tube, through the tube wall and from the tube to the cooling water because of a deposited layer, which causes a substantial drop in temperature. In heat exchangers in general, this means a reduction in heat flow (thermal power). It is the same with the condenser, but this is only the first part of events, transitional in nature. The decrease in thermal power at a constant inflow of steam from the low-pressure turbine casing raises the pressure in the condensation part - condensation is late, in terms of quantity and time (partially observed).

A higher condensation temperature corresponds to this higher pressure. A larger temperature difference overcomes the increased thermal resistance in heat transfer and condensation goes on uninterruptedly, but, of course at a higher temperature. The quantity of transferred heat is not significantly changed. Naturally, due to the raised pressure in the condenser, the output power of the generator is lower. Thermodynamically: due to fouling of the cooling surfaces, more exergy is used to transfer heat, therefore less exergy is left at the generator shaft.

The increase in the condensation temperature due to the formation of scale deposits in tubes during operation is therefore detected as an increase in the condenser pitch point.

The condenser pitch point curve is exponential, increasing slowly at first, but becoming steep later with an increase in fouling of the cooling surfaces. Operation without cleaning leads to a condenser stroke and stoppage of the power plant.

The flow of cooling water is constant. The convective heat transfer coefficient on the cooling water side is also constant, since it is mostly dependent on the flow of cooling water. Because of scale deposits on the inner surfaces of the tubes, the inner diameter decreases slightly, but the influence of this reduction on the convective heat transfer coefficient can be neglected, even when the scale deposit thickness has a major influence on heat transfer. This is true insofar as there is no change in the cooling water temperature rise through the condenser.

Because of the increase in the condensation temperature the specific volume decreases and sprememba temperaturnega padca ter zmanjšanje toplotne prestopnosti na parni strani, so, glede na učinek zamazanja, manj pomembni. Toplotna prestopnost na parni strani je kljub vsemu večja od toplotne prestopnosti na vodni strani. Slednja vplivneje določa toplotno prehodnost, zato je pomembno, da ostane pretok hladilne vode stalen, in manj pomembno, če bo toplotna prestopnost na parni strani nekaj slabša.

Upoštevaje vse napisano pridemo do ugotovitve, ki jo je v praksi moč preprosto potrditi:

Povečevanje približka kondenzatorja med obratovanjem in zaradi tega zviševanje temperature kondenzacije je neposredna posledica zamazanja hladilnih površin.

Metoda torej temelji na spremljanju vrednosti približka kondenzatorja oziroma razlike $\Delta T_{min} - \Delta T_{min,0}$.

3 DOLOČITEV DEBELINE OBLOG V KONDENZATORSKIH CEVEH

Debelina oblog je vedno neznanka in v obratovanju sama kot taka niti ni pomembna. Pomembno je vedeti, da je treba kondenzator stalno čistiti in zagotavljati vse pogoje, ki zmanjšujejo nastajanje oblog.

Tukaj podajamo izračun debeline oblog predvsem zato, ker bi bil rezultat lahko izhodni podatek instrumenta za spremljanje umazanja hladilnih površin. Za ponazoritev je podan račun s številčnimi podatki določenega kondenzatorja med delovanjem.

Nov kondenzator obratuje pri trenutni temperaturi kondenzacije T_k = 30 °C.

Drugi podatki so: Q_0 = 156 000 kW, k_0 = 3 600 W/(m²K), A = 6 500 m², $\Delta T_{hv,0}$ = 8 K.

Približek, izračunan po začetnih podatkih po enačbi (1), znaša 3,5 K. To je konstrukcijski podatek. Če je tudi med delovanjem tako, potem vemo, da je kondenzator čist in je temperatura vstopa hladilne vode 18,5 °C.

Pri čistem kondenzatorju in stalnem pretoku pare in hladilne vode se temperatura kondenzacije spreminja tako, kakor se spreminja vstopna temperatura hladilne vode. Sčasoma se začne čutiti kvaren vpliv oblaganja hladilnih površin, temperatura kondenzacije prične naraščati. Z naravnim nižanjem temperature hladilne vode se seveda znižuje tudi temperatura kondenzacije, vendar pod vplivom oblog na ceveh narašča relativna temperaturna razlika — približek kondenzatorja.

Dejstvo, da so vse temperature preprosto merljive, izkoristimo za spremljanje dogajanj na hladilnih površinah kondenzatorja med delovanjem.

V diagramih na slikah 2 in 3 so prikazani rezultati računa po korakih, ki slede. Na sliki 2 je

with it, the velocity of steam entering the condenser. This velocity has an effect on the heat transfer coefficient at the steam side, since the occurrence of turbulent flow depends on it. The influence of changes in other quantities due to the increase in temperature, such as the density of steam, the change in termal conductivity of the condensed water layer on the tubes and the resulting change in the temperature drop, and the decreased convective heat transfer coefficient on the condensing steam side are less important compared with the effect of fouling. The convective heat transfer coefficient on the condensing steam side is nevertheless higher than the convective heat transfer coefficient on the cooling water side. The latter influences the overall heat transfer coefficient more, and it is therefore important to keep the cooling water flow constant. It is less important if the convective heat transfer coefficient on the condensing steam side is slightly lower.

Considering all the above mentioned factors we reach a conclusion, simple to confirm in practice:

An increase in the condenser pitch point during operation and the resulting increase in the temperature of the condensation is a direct consequence of fouling of cooling surfaces.

The method is therefore based on monitoring the condenser pitch point value or the difference $\Delta T_{min} - \Delta T_{min,0}$.

3 DETERMINATION OF SCALE DEPOSIT THICKNESS IN CONDENSER TUBES

The thickness of scale deposits is always an unknown quantity and is not important as such during operation. It is important to know that a condenser must be cleaned regularly and to ensure conditions for minimizing the formation of scale deposits.

A calculation of scale deposit thickness is given here because the result could serve as the output value for an instrument for monitoring fouling of cooling surfaces. As an illustration, a calculation with numerical data on a particular condenser in operation is given.

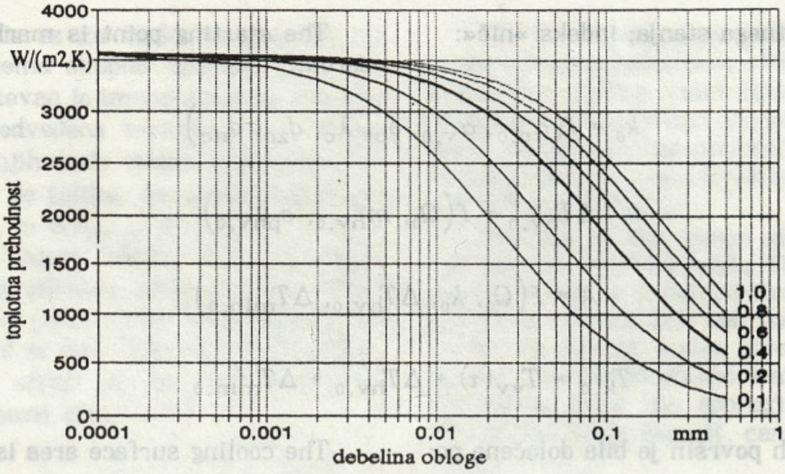
A new condenser operates at an instantaneous condensation temperature T_k = 30 °C.

The other data are as follows: Q_0 = 156,000 kW, k_0 = 3 600 W/(m²K), A = 6 500 m², $\Delta T_{hv,0}$ = 8 K.

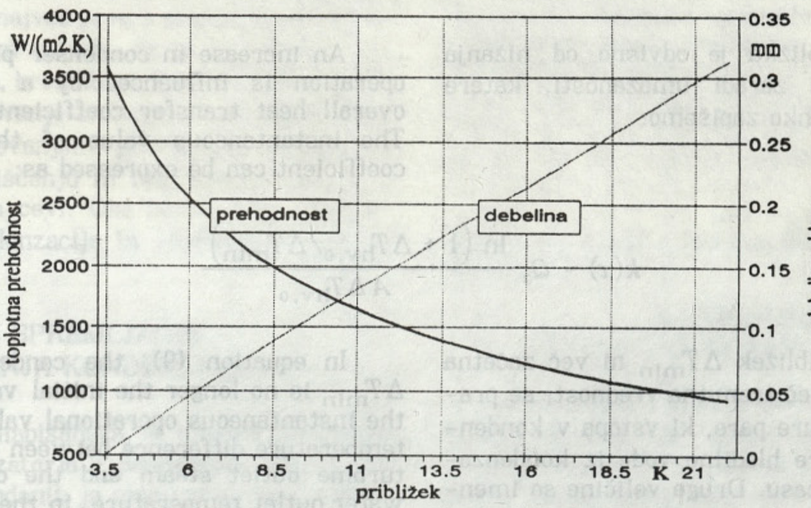
The numerical value of the pitch point, calculated by equation (1), is 3.5 K. This is the design struction data. If it is so during operation, we know the condenser is clean and the cooling water inlet temperature is 18.5 °C.

When the condenser is clean and cooling water flow is constant, the condensation temperature changes as the cooling water inlet temperature changes. In time, the influence of cooling surface fouling causes an increase in the condensation temperature, causing an increase in the temperature difference, which is defined as the condenser pitch point.

The fact that the temperatures are easily measurable can be used, therefore, for monitoring events on the condenser cooling surfaces during operation.



Sl. 2. *Toplotna prehodnost v odvisnosti od debeline oblog na notranji strani cevi*
Fig. 2. *Overall heat transfer coefficient as a function of the thickness and structure of the deposited layer on the inner tube wall*



Sl. 3. *Približek kondenzatorja v odvisnosti od toplotne prehodnosti*
Fig. 3. *Condenser pitch point as a function of the overall heat transfer coefficient*

prikazano zmanjševanje toplotne prehodnosti zaradi povečevanja debeline oblog na vodni strani pri različnih vrednostih toplotne prevodnosti oblog. Na sliki 3 pa povečevanje približka kondenzatorja zaradi zmanjševanje toplotne prehodnosti. S slike 2 je razviden vpliv tako debeline obloge kakor tudi toplotne prevodnosti obloge. Številčne vrednosti različnih toplotnih prevodnosti, za katere so narisane krivulje, so označene na desni strani ob krivuljah v W/(m.K). Iz diagrama na sliki 3 je moč razbrati trenutno toplotno prehodnost in debelino obloge v ceveh ob znanem trenutnem približku. Debelina obloge in prehodnost sta preračunani na toplotno prevodnost obloge λ = 0,4 W/(m.K).

K diagramu na sliki 3 se vrnemo še v poglavju 4.

Račun temelji na začetnih ali konstrukcijskih vrednostih, katerim so priključeni vplivi zaradi nastajanja oblog povečane toplotne upornosti hladilnih površin, kakor se dogajajo med obratovanjem.

Results of calculations are shown on diagrams in Fig. 2 and Fig. 3. In Fig. 2, a decrease in the overall heat transfer coefficient due to an increase in scale deposit thickness on the cooling water side, at different scale heat conductivity, is shown. In Fig. 3, the diagram shows the increase in pitch point caused by a decrease in the overall heat transfer coefficient. The instantaneous overall heat transfer coefficient can be read using this diagram, at a known instantaneous condenser pitch point. Scale thickness and overall heat transfer coefficient calculations take into account a scale heat conductivity of λ = 0.4 W/ /(m.K).

The above mentioned diagrams will be discussed in more detail in section 4.

Calculations are based on initial conditions and design data, with respect to increased thermal resistance of cooling surfaces due to scale deposit as it occurs during operation.

Izhajamo iz začetnega stanja; indeks »nič«:

$$k_0 = f\left(\alpha_{p,0}, \alpha_{v,0}, \delta_c, \lambda_c, d_{zc}, d_{nc}\right) \quad (4),$$

$$\Delta T_{hv,0} = f\left(Q_0, m_{hv,0}, c_{phv,0}\right) \quad (5),$$

$$A = f\left(Q_0, k_0, \Delta T_{hv,0}, \Delta T_{min,0}\right) \quad (6),$$

$$T_{k,0} = T_{vv}(\tau) + \Delta T_{hv,0} + \Delta T_{min,0} \quad (7).$$

Velikost hladilnih površin je bila določena po:

$$A = Q_0 \frac{\ln\left(1 + \Delta T_{hv,0}/\Delta T_{min,0}\right)}{k_0 \, \Delta T_{hv,0}} \quad (8).$$

Naraščanje približka je odvisno od nižanja toplotne prehodnosti zaradi umazanosti, katere trenutno vrednost lahko zapišemo:

$$k(\tau) = Q_0 \frac{\ln\left(1 + \Delta T_{hv,0}/\Delta T_{min}\right)}{A \, \Delta T_{hv,0}} \quad (9).$$

V enačbi (9) približek ΔT_{min} ni več začetna vrednost 3,5 K, temveč trenutna vrednost; se pravi, razlika temperature pare, ki vstopa v kondenzator, in temperature hladilne vode iz kondenzatorja v opazovanem času. Druge veličine so imenske.

Pri nespremenjenem delovanju ter ne bistveno spremenjenih vrednostih, ki jih združujeta enačbi (4) in (5), postane:

$$\Delta T_{min} = f\left[k(\tau)\right] \quad (10).$$

Trenutno toplotno prehodnost glede na začetno stanje, ki ga popisuje enačba (4), lahko zapišemo tudi takole:

$$k(\tau) = \frac{1}{1/k_0 + R(\tau)} \quad (11),$$

kjer $R(\tau)$ pomeni toplotno upornost zaradi umazanosti ali oblog na površinah cevi.

Izenačitev enačbe (9) z enačbo (11) da:

$$R(\tau) = \frac{A \, \Delta T_{hv,0}}{Q_0} \left[\frac{1}{\ln\left(1 + \Delta T_{hv,0}/\Delta T_{min}\right)} - \frac{1}{\ln\left(1 + \Delta T_{hv,0}/\Delta T_{min,0}\right)} \right] \quad (12).$$

The starting point is marked with subscript »zero«.

The cooling surface area is determined by:

An increase in condenser pitch point during operation is influenced by a decrease of the overall heat transfer coefficient due to scaling. The instantaneous value of the heat transfer coefficient can be expressed as:

In equation (9), the condenser pitch point ΔT_{min} is no longer the initial value of 3.5 K but the instantaneous operational value, which is the temperature difference between the low pressure turbine outlet steam and the condenser cooling water outlet temperature, in the time dealt with.

At constant and stable operation, when there are no major changes in the values listed in expressions (4) and (5), the condenser pitch point becomes:

Alternatively, the instantaneous heat transfer coefficient with respect to initial conditions expressed in equation (4) may be written:

where $R(\tau)$ represents heat resistance due to deposits on the tube surfaces.

Equating (9) and (11) and solving, will give:

Tako zapisan izraz za toplotno upornost na površinah cevi zajema skupno upornost na obeh straneh cevi. Upoštevan je imenski pretok hladilne vode in imenska odvedena toplotna moč. Kadar ena ali obe od slednjih dveh veličin nista imenski, se račun spremeni le toliko, da posebej upošteva deleže, npr. Q_x/Q_0 in $\Delta T_{hv,0}/\Delta T_{hv,x}$.

Umazanje na parni strani je minimalno, vendar sčasoma ne povsem zanemarljivo. Predpostavimo čistost na parni strani in pripišimo vso vrednost $R(\tau)$ vodni strani. Tako določimo debelino oblog na vodni strani δ_v ob vsaj približnem poznavanju prevodnosti oblog λ:

The heat resistance according to equation (12) is the common resistance of both sides of the tube at nominal cooling water flow and nominal transferred heat flux. When one or both of these operational values are not nominal, the calculation can be corrected in consideration of portions Q_x/Q_0 and $\Delta T_{hv,0}/\Delta T_{hv,x}$.

Fouling on the steam side of tubes is minimal but not entirely negligible during longer operation. It can be assumed that there are no deposits on the steam side and the value of $R(\tau)$ relates to the cooling water side only. So the thickness of the deposit on the water side of the tubes, bearing in mind the approximate heat conductivity of the scale deposit, can be determined:

$$\delta_v = \frac{1}{2}\, d_n\left[1 - e^{-2R(\tau)\lambda/d_n}\right] \qquad (13).$$

Približek kondenzatorja je torej tisti obratovalni podatek, ki največ pove o stanju hladilnih površin, pod pogojem seveda, da je vse drugo, npr. izsesovanje zraka, brezhibno. Po tem podatku lahko presojamo delovanje sistema za notranje čiščenje cevi med delovanjem, potrebo po morebitnem nenačrtovanem čiščenju in tudi potrebo po čiščenju zunanjih sten cevi. Obe obloženosti dvigujeta temperaturo kondenzacije in vnašata dodatno izgubo.

4 SPREMLJANJE DELOVANJA KONDENZATORJA

Na temelju napisanega je mogoče spremljati delovanje kondenzatorja s poudarkom stanja hladilnih površin. Podanih je nekaj predlogov tehničnemu osebju v termoenergetskih postrojenjih:

1) Ugotovitev konstrukcijskega približka kondenzatorja $\Delta T_{min,0}$. Ta podatek določa najmanjšo dosegljivo temperaturo kondenzacije glede na velikost kondenzatorja, pretok vode in pare in trenutno vstopno temperaturo hladilne vode.

2) Uvajanje posebne rubrike v obratovalnih poročilih za trenutni približek ΔT_{min}, ki pomeni razliko med temperaturo kondenzacije in temperaturo iztekajoče hladilne vode iz kondenzatorja.

3) Razvoj merilnega instrumenta za spremljanje vpliva zamazanja hladilnih površin, ki upošteva tudi vse druge vplive in temelji na naslednjih načelih:

a) merjenje trenutnega približka kondenzatorja;

b) preračun na prvotne vrednosti in obdelava razlik, programirano spremljanje vseh pomembnih obratovalnih veličin.

Načelna shema je prikazana na sliki 4. Instrument podaja podatek o debelini oblog in/ali odstotek umazanosti.

Condenser pitch point ΔT_{min} is therefore the most important operational data for giving information about condenser tube cleanliness, on the condition that everything is in order, of course. From this data, the working of the operational condenser tubes cleaning system can be estimated, as well as the need for unplanned maintenance or for cleaning the steam side of the tubes. Fouling on one or the other side raises the condensation temperature and increases the operational loss in the system.

4 MONITORING OF FOULING DURING OPERATION

On the basis of the above, the monitoring of fouling of condenser tubes can be organised. Some suggestions to technical personnel of thermal power plants are given below.

1) Find initial design condenser pitch point $\Delta T_{min,0}$. This value determines the lowest temperature of condensation in consideration of the size and structure of the condenser, water and steam flow and instantaneous cooling water inlet temperature.

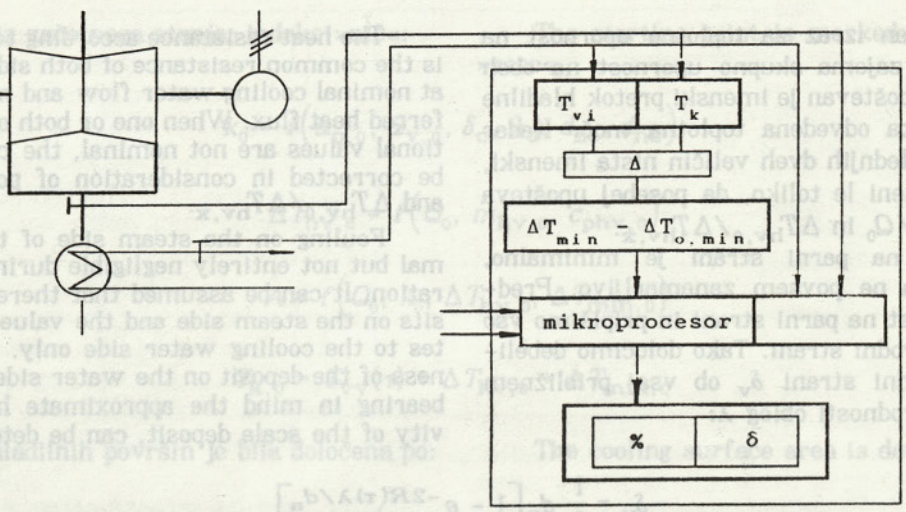
2) Provide a separate column in the operational report for instantaneous condenser pitch point ΔT_{min}, which means the temperature difference between the two outlets: low pressure turbine outlet steam temperature minus condenser cooling water outlet temperature.

3) Cooperate in the development of a measuring device for monitoring the influence of fouling, considering all other influences and based on the following principles:

a) measuring instantaneous condenser pitch point.

b) calculation and data treatment, with all important operational values included.

The principal scheme is shown in Figure 4. The instrument gives information about the deposited layer thickness and/or percent of fouling.



Sl. 4. *Spremljanje čistosti hladilnih površin kondenzatorja pare – idejna shema instrumenta*
Fig. 4. *Monitoring of fouling of a steam condenser – an idea for an instrument*

Za ponazoritev še enkrat poglejmo sliko 3. Po določenem času pri nespremenjeni temperaturi hladilne vode poteka kondenzacija pri 36 °C, namesto pri 30 °C. Približek se je torej povečal za 6 K in znaša 9,5 K. Iz diagrama na sliki 3 razberemo ustrezno toplotno prehodnost, ki ni več 3 600, temveč le še 1 850 W/(m².K), ali skoraj dvakrat manj. Takšno poslabšanje toplotne prehodnosti je povzročila nekaj več ko 13 stotink mm debela plast obloge na notranjih straneh cevi, kar razberemo z iste slike, če potegnemo navpičnico pri 9,5 K do krivulje za oblogo in od presečišča do navpične razdelitve na desni strani.

Ni treba posebej poudarjati, da 6 °C višja temperatura kondenzacije pomeni kar nekaj odstotkov manjšo izhodno moč elektrarne pri enaki količini porabljenega goriva.

Takšne obratovalne diagrame je moč izdelati za vsak kondenzator posebej. Za praktično uporabo so celo bolj primerni kakor brezdimenzijski splošni diagrami, npr. $k(\tau)/k_0$, saj je dogajanje v celoti povezano z določenim postrojenjem in okoljem.

5 SKLEP

V sestavku je prikazan vpliv oblog umazanije na ceveh kondenzatorja na prenos toplote in predlogi za spremljanje kondenzatorja med obratovanjem.

Kvaren vpliv oblaganja cevi na toplotno prehodnost je precejšen. Slabša toplotna prehodnost pomeni višjo temperaturo kondenzacije in s tem manjšo električno moč postrojenja. Potemtakem je za pravilno delovanje parnega postrojenja zelo pomembno, da se kondenzatorske cevi stalno čistijo in njihovo čistost redno preverja.

For illustration, the diagram in Figure 3 can be looked at again: Supposing that, after some time at a constant temperature of cooling water, the condensation temperature is 36 °C, instead of 30 °C. The condenser pitch point has increased by 6 K and is 9.5 K. From the diagram in Figure 3, the corresponding overall heat transfer coefficient can be read. It is not 3 600 W/(m².K) as before, but 1 850 W/(m².K), which is just over half. Such a decrease in the overall heat transfer coefficient is caused by a slightly more than 13 hundredths of a milimetre thick deposit layer on the tubes, which can be read from the same diagram.

It is not necessary to point out that a 6 K higher condensation temperature causes a not negligible percent of power plant output reduction for the same fuel consumption.

The above mentioned diagrams can be made for each condenser separately. For practical use, they are more convenient than general dimensionless diagrams, for instance $k(\tau)/k_0$, as the events are interconnected with a specific power plant and environment.

5 CONCLUSION

The article presents the influence of fouling of steam condenser cooling surfaces on the overall heat transfer coefficient, as well as some suggestions for monitoring heat transfer during operation.

The influence of fouling on heat transfer is considerable. A lower overall heat transfer coefficient causes a higher condensation temperature which leads to a lower output of the power plant and lower power plant efficiency. For proper operation of a power plant, therefore, continuous cleaning of the condenser tubes and monitoring of heat transfer is necessary.

Seznam označb

A	— površina	m^2
d	— premer	m
k	— toplotna prehodnost	$W/(m^2.K)$
m	— masni tok	kg/s
Q	— toplotni tok	W, kW
R	— toplotna upornost	$(m^2.K)/W$
T	— temperatura	K
α	— toplotna prestopnost	$W/(m^2.K)$
Δ	— razlika	
δ	— debelina	m, mm
λ	— toplotna prevodnost	W/(m.K)
τ	— čas	s, h, d

Seznam indeksov

o	— začetni
c	— cev
k	— kondenzacija
i	— izstop
ln	— logaritemski
max	— največji
min	— najmanjši
n	— notranji
p	— para
v	— voda
v	— vstop
z	— zunanji

List of symbols

A	— area
d	— diameter
k	— overall heat transfer coefficient
m	— mass flow
Q	— heat flow
R	— heat transfer resistance
T	— temperature
α	— convective heat transfer coefficient
Δ	— difference
δ	— thickness
λ	— conductive heat transfer coefficient
τ	— time

Index

o	— initial
c	— tube
k	— condensation
i	outlet
ln	— logarithmic
max	— maximum
min	— minimum
n	— inner
p	— steam
v	— water
v	— inlet
z	— outer

6 LITERATURA
6 REFERENCES

[1] Tuma, M.: Energetski sistemi. 2. pred. izd.. Fakulteta za strojništvo, Univerze v Ljubljani, Ljubljana, 1991.

[2] Welty, J.R.: Engineering Heat Transfer. John Wiley & Sons, New York, 1978.

Naslov avtorjev: prof. dr. Matija Tuma, dipl. inž.,
Vladimir Repič, dipl. inž.
Fakulteta za strojništvo
Univerze v Ljubljani
Aškerčeva 6, Ljubljana

Authors' Address: Prof. Dr. Matija Tuma, Dipl. Ing.,
Vladimir Repič, Dipl. Ing.
Faculty of Mechanical Engineering
University of Ljubljana
Aškerčeva 6
Ljubljana, Slovenia

Prejeto: 5.4.1994
Received:

Sprejeto: 5.5.1994
Accepted: