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Statistični pristop k analizi hladilnih sistemov s hladilnimi stolpi na naravni vlek

A Statistical Approach to the Analysis of Cooling Systems with Natural-Draft Cooling Towers

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Povečevanje in zaostrovanje zahtev pri obratovanju termoelektrarn, z namenom da bi pocenili proizvodnjo električne energije in zagotovili čistejše okolje, je pripeljalo do potrebe po optimizaciji celotnega postopka. Leta je v načelu sestavljen iz dovoda toplote v krožni proces, iz samega krožnega postopka in iz odvoda toplote v okolico. Optimizacija vseh treh sklopov energetskega postrojenja zagotavlja najboljše rezultate.

Prispevek se nanaša na analizo meritev energijskih parametrov bloka 4 Termoelektrarne Šoštanj in prikazuje vpliv hladilnega sistema na izkoristek termoelektrarne. Analiza obsega statistične pristope analize termoenergetskega postrojenja, ki omogočajo vpogled v medsebojno odvisnost posamičnih parametrov in vplive na povečevanje izkoristka termoelektrarne. V našem primeru je glavni element hladilnega sistema hladilni stolp na naravni vlek, saj pomeni povezavo termoelektrarne z okolico. Približevanje optimalnejšemu obratovanju hladilnega sistema tako prispeva znatne prihranke pri porabi goriva in zmanjšani emisiji dimnih plinov. Prispevek vsebuje potrditev značilne linearne soodvisnosti med prenesenim toplotnim tokom na okolico in močjo na sponkah generatorja.

(Ključne besede: sistemi hladilni, stolpi hladilni, analize sistemov, postopki statistični)

Changes to the operating requirements at power plants, with the intention of lowering energy costs and ensuring a cleaner environment, have brought optimization to the whole process. In principle, the process consists of an inlet heat stream to the process, the steam cycle itself and the rejected heat stream to the environment. The optimization of all three parts of the energetic system will ensure the best results. This study relates to an analysis of the measurements of energetic parameters at Block 4 of the Šoštanj power plant and shows the influence of the cooling system on the power plant's efficiency.

The paper includes a statistical approach to the analysis of a thermo-energetic system that enables an understanding of the relations between the parameters and shows guidelines for enlarging the thermo-energetic efficiency. The main part of the cooling system is the natural-draft cooling tower, which represents the interaction between the power plant and the environment. Approaching the optimal operating point of the cooling system contributes to fuel savings and decreasing the amount of exhaust-gas pollution. This paper also includes a verification of the typical linear relation between the heat transferred to the environment and the generation of power.

(Keywords: cooling systems, cooling towers, systems analysis, statistical approach)

0 UVOD

Optimalno delovanje hladilnega sistema se izraža v največjem pridobljenem delu iz turbine in tako večjem celotnem izkoristku termoelektrarne zaradi najmanjše odvedene toplote iz sistema. Učinkovitost delovanja hladilnega sistema je eden

0 INTRODUCTION

The optimal operating condition of a cooling system results in the maximum acquired work from the turbine and overall power-plant efficiency because of the minimal amount of heat rejected to the environment. The efficiency of the cooling system izmed odločilnih dejavnikov, ki pomembno vplivajo na izkoristek termoenergetskega sistema kot celote. Kakovosten hladilni sistem pomeni manjšo izgubo toplote, kar omogoča manjše hladilne naprave in manj hladilne vode.

Količina toplote, odvedene s hladilnim sistemom, je večja od toplote, ki se v parnem krožnem postopku spremeni v delo. V današnjih hladilnih sistemih, novih in starih termoelektrarn, je odvedena toplota od 1,3 do 2,5-krat večja od koristno pridobljenega dela iz termoelektrarne.

Pri načrtovanju stolpov je najpomembnejši parameter izkoristek hlajenja hladilnega stolpa. Z zmanjšanjem odvedene toplote se izkoristek krožnega postopka sam po sebi izboljša. Za ocenjevanje omenjenih izboljšav se med drugim uporablja tudi koeficient $\dot{Q}_{od} / P$ [1]. Z zmanjšanjem koeficienta je mogoče izboljšati učinkovitost celotnega termoenergetskega postrojenja, kar pa je odvisno od celovitih in lokalnih karakteristik hladilnega sistema, pri katerem je v analiziranem primeru glavni element hladilni stolp.

Večina današnjih hladilnih stolpov je starih 30 do 50 let in njihovo obratovanje ni več optimalno. Naletimo na velike temperaturne in hitrostne neenakosti, ki se kažejo v različnih temperaturnih in hitrostnih stanjih zraka po prečnem prerezu hladilnega stolpa, kar ima za posledico manjšo učinkovitost stolpa ([2] in [6]). Anomalije so odvisne od konstrukcijskih lastnosti delilnih vodnih sistemov, prenosnikov toplote v hladilnih stolpih ali od vplivov okolja na hitrostne razmere zraka, ki vteka v stolp. Z odpravo krajevnih nepravilnosti hitrostnega in temperaturnega polja se izkoristek hladilnega stolpa poveča, kar posledično povečuje izkoristek celotnega termoenergetskega sistema.

Dosedanje analize delovanja hladilnih stolpov večinoma temeljijo le na poznavanju parametrov okoliškega zraka ter parametrov vstopne in izstopne hladilne vode. S takšno analizo je mogoče ugotoviti le celotne lastnosti delovanja hladilnega stolpa, ki pa so vsekakor odvisne od učinkovitosti prenosa toplote na krajevni ravni. Analiza obsega proučevanje povezave med učinkovitostjo prenosa toplote na krajevni in celoviti ravni z močjo generatorja. Povezanost parametrov je prikazana z uporabo statističnih orodij. Prispevek vsebuje tudi predloge za izboljšave učinkovitosti prenosa toplote v hladilnih stolpih.

is one of the most important parameters that have a large impact on the power plant's efficiency. A high-quality cooling system represents lower heat losses, which leads to smaller cooling devices and less demand for cooling water.

Heat rejected with the cooling system is larger than the heat converted by the steam cycle into useful work. In currently operating systems, old and new, the heat extracted varies from 1.3 to 2.5 times the useful work extracted from the thermodynamic system.

When constructing a cooling tower the most important parameter is the tower's efficiency. With the reduction of heat rejected to the environment, the overall power-plant efficiency improves by itself. For estimating this kind of improvement the coefficient $\dot{Q}_{od} / P$ [1] is often used. With a reduction of this coefficient it is possible to increase the efficiency of the power plant, which depends on the local characteristics of the cooling system, which in our case is the main part of the natural-draft cooling tower.

The majority of today's cooling towers are 30 to 50 years old, and their operation is no longer optimal. We come across large inhomogeneities in the air, which are shown in different temperatures and velocities across the cross-section of the cooling tower. This has the consequences of lower efficiency of the tower ([2] and [6]). The anomalies depend on the construction properties of the distribution water system, the heat exchangers in the cooling towers or the atmospheric influences on the air velocity distribution entering the cooling tower. Cooling-tower efficiency increases with the elimination of local irregularities of the temperature and velocity fields, which consequently increases the overall efficiency of the thermo-energetic system.

Previous operation analyses of the cooling towers were mostly based just on measurements of atmospheric quantities and the parameters of the inlet and outlet cooling water. This kind of analysis enables only a determination of the integral characteristics of cooling towers that depend on heat and mass transfer on a local basis. Our analysis compared the research of the correlation between heat-transfer efficiency on a local and integral basis with the power of the generator. The connection between the parameters is shown with the help of statistical tools. The paper also includes proposals for heat-transfer improvement in cooling towers.

1 ODVISNOST DELOVANJA HLADILNEGA STOLPA IN GENERATORJA

Hladilni stolpi na naravni vlek se pogosto uporabljajo v industriji in kot sestavni del termoelektrarn. Ker je hladilni stolp sestavni del celotnega postrojenja termoelektrarne, njegova učinkovitost delovanja vpliva na toplotni izkoristek celotnega postrojenja. V elektrarnah so energijski tokovi veliki, kar pomeni, da že majhne izboljšave izkoristka na postrojenju pomenijo velik prihranek pri porabi goriva in zmanjšanju emisije dimnih plinov.

V hladilnem stolpu poteka hlajenje vode z neposrednim stikom med vodo in hladilnim zrakom [3]. Pri tem se zrak segreje, njegova relativna vlažnost se poveča, zniža pa se temperatura hladilne vode. Za dosego največjega odvoda toplote iz vode na okolico je potrebno optimalno delovanje hladilnega stolpa pri njegovih imenskih karakteristikah.

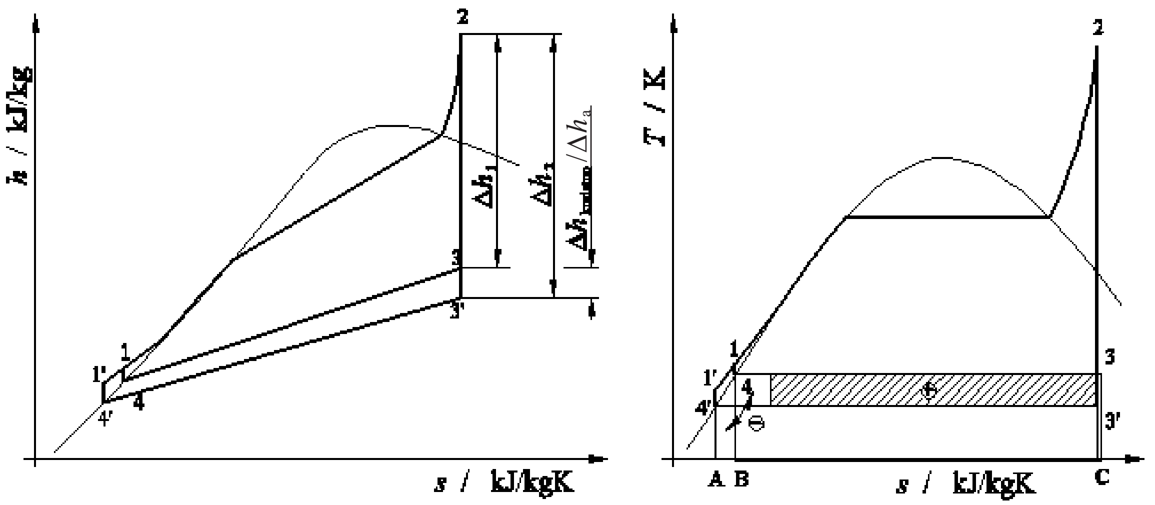
Na sliki 1 si poglejmo vpliv hladilnega sistema na količino pridobljenega dela iz termodinamičnega krožnega procesa. Naloga hladilnega sistema je odvod toplote v okolico pri temperaturah, ki so čim bližje temperaturi okolice. Intenzivnejši odvod toplote na sedanjem hladilnem sistemu se kaže v nižji temperaturi in tlaku v kondenzatorju, kar prinaša večjo entalpijsko razliko, npr. iz Δh_1 na Δh_2, in s tem dodatno pridobljeno delo $\Delta h_{\text{koristno}}$ iz turbine. Učinkovit hladilni sistem tako omogoča manjše izgube toplote na enoto pare, ta se je na primeru s slike 1 zmanjšala iz površine 4-3-C-B, ki pomeni

1 THE OPERATIONAL DEPENDENCE BETWEEN COOLING TOWER AND GENERATOR

Natural-draft cooling towers are usually used in the process industry and are often part of a thermal power plant. Because it is a part of the whole thermo-energetic system, its efficiency has an influence on the overall power-plant efficiency. In power plants we are faced with large energetic flows, which means that little efficiency improvements in the system represent large fuel savings and a reduction in pollution from exhaust gases.

In natural-draft cooling towers the heat is transferred by direct contact between the water and the cooling air that flow in opposite directions [3]. The air temperature rises and the humidity increases through the cooling-tower packings, where, on the other hand, the water temperature decreases. To achieve the largest heat transfer from the water to the air on a given cooling tower, it has to operate at its optimum point

Figure 1 shows the influence of the cooling system on the work extracted from thermodynamic steam cycle. The task of the cooling system is rejecting heat to the environment at temperatures that should be close to atmospheric temperature. More intensive heat rejection for the given cooling system results in a lower water temperature and lower pressure in the condenser, which brings a larger enthalpy difference, for example, from Δh_1 to Δh_2, and more acquired work, Δh_a, from the turbine. A more efficient cooling system enables less heat loss, which is reduced in Figure 1 from the area 4-3-C-B,



Sl. 1. *Povezava med pridobljenim delom in odvodom toplote*
Fig. 1. *Connection between acquired work and rejected heat*

odvedeno toploto na površino 4'-3'-C-A. Senčena ploskev ponazarja razliko toplote, ki se je pri tem spremenila v koristno pridobljeno delo.

Odvedeno toploto iz hladilnega sistema lahko ocenimo po sledeči enačbi [1]:

which represents the rejected heat, to area 4'-3'-C-A. The hatched area represents the heat difference that was additionally converted to useful work.

The rejected heat from a cooling system can be estimated by the equation [1]:

$$\dot{Q}_{od} = \left(\frac{1}{\eta} - 1\right) \cdot P \quad (1),$$

kjer so: $\dot{Q}_{od}$ odvedena toplota iz hladilnega sistema, P moč generatorja in η izkoristek krožnega postopka.

Povezavo med močjo generatorja in hladilnim stolpom lahko utemeljimo tudi s statističnimi orodji na podlagi meritev. Odvisnost pridobljenega dela generatorja s parametri, ki vplivajo na delovanje stolpa, lahko dobimo z matričnim zapisom koeficientov odvisnosti, ki povedo medsebojne odvisnosti posamičnih spremenljivk. Na podlagi matrike koeficientov odvisnosti lahko sistematično določimo parametre, ki pomembno vplivajo na delovanje hladilnega stolpa. S tovrstnimi izračuni se ukvarja regresijska analiza [7].

where $\dot{Q}_{od}$ is the rejected heat from the cooling system, P is the generator power and η is the efficiency of the thermodynamic system.

The connection between the generator and the cooling tower can also be shown with statistical tools based on measurements. The dependence of the generated power on parameters that influence the cooling-tower operation can be acquired with a matrix of correlation coefficients that tell us the mutual dependence between two variables. With the help of a correlation matrix we can systematically determine the parameters that have a significant impact on the operation of the cooling tower. This kind of analysis can be described as a regression analysis [7].

2 OPIS MERITEV IN MERILNE OPREME

Meritve obsegajo podatke na bloku 4 Termoelektrarne Šoštanj [9] in ustreznem hladilnem stolpu bloka 4 [8]. Celoviti parametri, ki so simultano merjeni po standardu DIN 1947 [5] so: vstopna in izstopna temperatura hladilne vode iz hladilnega stolpa, celotni masni pretok vode, ki je merjen z ultrazvočnim merilnikom pretoka in izhodna moč generatorja. Merilni sistem obsega še naprave za zbiranje merjenih podatkov v hladilnem stolpu.

Merilna negotovost temperaturnih zaznaval je bila ocenjena na manj ko 0,25 °C. Meritve so obsegale različne režime obratovanja, tj. pri različnih močeh generatorja ter 34000 m^3/h prostorninskem pretoku hladilne vode. Sočasno so potekale meritve parametrov okoliškega zraka, ki so obsegale hitrost okoliškega zraka v štirih točkah (v_A, v_B, v_C, v_D), temperaturo okolice v bližini hladilnega stolpa (t_Z) in gostoto zraka v bližini hladilnega stolpa (ρ).

V preglednici 1 so predstavljene povprečne vrednosti okoliških parametrov, izmerjenih v celotnem času trajanja meritev. Iz preglednice 1 je razvidno, da se parametri okolice niso bistveno spreminjali in zaradi tega tudi niso vplivali na rezultate meritev znotraj hladilnega stolpa.

2 DESCRIPTION OF THE EXPERIMENT AND THE MEASUREMENT EQUIPMENT

Measurements include data acquired at Block 4 of the Šoštanj power plant [9] and the corresponding cooling tower of Block 4 [8]. The integral parameters that are simultaneously measured by the DIN 1947 standard [5] are as follows: inlet and outlet cooling-water temperature from the cooling tower; the total water-mass flow rate, which is measured with an ultrasonic flow meter and the power on the generator. The measurement system also includes equipment for collecting data in the cooling tower.

The measurement uncertainty of the temperature sensors was estimated to be less than 0.25°C. The measurements included different operating points, i.e., from different power outputs on the generator, and were conducted by a constant volumetric water flow of 34000 m^3/h. Simultaneously, we measured atmospheric parameters, which included the air velocity at four points (v_A, v_B, v_C, v_D), the ambient temperature near the cooling tower (t_0) and the air density near the cooling tower (ρ_0).

Table 1 shows the average values of the atmospheric parameters measured through the whole duration of the measurement. From the table it is clear that the variations of the parameters were not significant, which means that the measurements in the cooling tower were not influenced by the environmental conditions.

Preglednica 1. *Parametri okoliškega zraka*
Table 1. *Parameters of ambient air*

kvadrant quadrant	*1*	*2*	*3*	*4*
v_A **[m/s]**	1,8	2,2	2,1	2,3
v_B **[m/s]**	2,2	1,9	2,7	2,4
v_C **[m/s]**	1,6	2,2	1,8	1,9
v_D **[m/s]**	2,2	2	2,1	1,8
t_Z **[m/s]**	21,8	22,8	21,4	20,9
ρ **[kg/m^3]**	1,17	1,17	1,16	1,16

3 MERITVE LOKALNIH PARAMETROV NA NAVPIČNEM SEGMENTU

Za določitev osnovnih karakteristik prenosa toplote in snovi opazovanega hladilnega stolpa so bile izvedene meritve aerodinamičnih in termodinamičnih veličin na navpičnem segmentu, prikazanem na sliki 2. Segment je bil izbran kot primerjalna točka v področju hladilnega stolpa, kjer imamo brezhibne konstrukcijske lastnosti in je obsegal tlorisno površino okoli 9 m^2. Namen segmenta je tudi določitev prenosa toplote na lokalni ravni v hladilnem stolpu. V osnovi je izkoristek krajevnega delovanja stolpa moč izračunati samo prek krajevnih meritev parametrov vlažnega zraka ali vode, ki ga popisuje enačba [10]:

3 MEASUREMENT OF THE LOCAL PARAMETERS IN A VERTICAL SEGMENT

To determine the basic characteristics of heat and mass transfer in the cooling tower we conducted measurements of the aero- and thermo-energetic quantities in the vertical segment shown in Figure 2. The segment was chosen as a reference point in the cooling tower where the construction characteristics were fault-free and the segment was occupying a ground plane of approximately 9 m^2. The purpose of the vertical segment is also to determine the heat transfer on a local base in the cooling tower. In principle, this can be the local efficiency, calculated by measurements of moist air or water parameters, and its definition can be written as [10]:

$$\varepsilon = \frac{h_{w1} - h_{w2}}{h_{w1} - h_{wm}} \qquad (2),$$

kjer so: h_{w1} vstopna specifična entalpija vode, h_{w2} izstopna specifična entalpija vode, h_{wm} specifična entalpija vode ovrednotena pri temperaturi mokrega termometra okoliškega zraka, ki predstavlja največji temperaturni potencial, do katerega lahko vodo ohladimo.

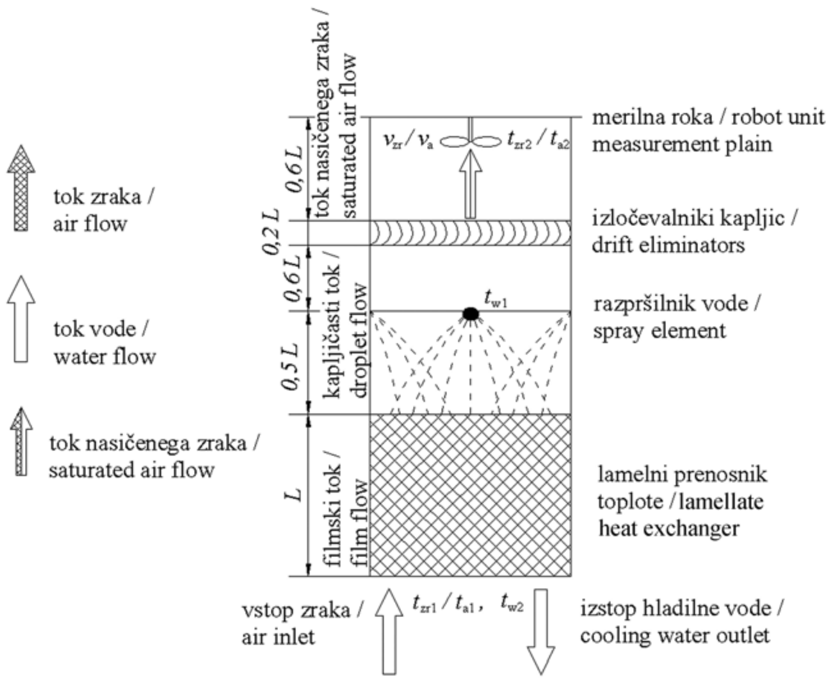
Navpični segment na sliki 2 je sestavljen iz lamelnega prenosnika toplote, ki je v spodnjem področju, razpršilnika vode, ta je v sredini in izločilnikov vodnih kapljic v zgornjem delu segmenta. Na opazovanem delu so bili merjeni naslednji parametri: vstopna temperatura vlažnega zraka t_{zr1}, izstopna temperatura nasičenega zraka t_{zr2}, vstopna temperatura vode t_{w1}, izstopna temperatura vode t_{w2}, masni pretok vode $\dot{m}_w$, masni pretok vlažnega zraka $\dot{m}_{zr}$.

Merilna negotovost temperaturnih zaznaval Pt-100 je manjša od 0,25 °C. Hitrost vlažnega zraka

where h_{w1} is the inlet-specific enthalpy of the water, h_{w2} is the-outlet specific enthalpy of the water, h_{wm} is the specific enthalpy of the water evaluated at the wet-bulb temperature of atmospheric air, which represents the maximum temperature potential to which water can be cooled.

The vertical segment in Figure 2 consists of a lamellate heat exchanger, which is at the bottom, spray elements, which are in the middle, and drift eliminators, which are placed at the top of the segment. For the observed segment we conducted measurements of the following parameters: inlet temperature of moist air t_{a1}, outlet temperature of saturated air t_{a2}, inlet water temperature t_{w1}, outlet water temperature t_{w2}, mass flow of water $\dot{m}_w$, mass flow of air $\dot{m}_{zr}$.

The measurement uncertainty of the Pt-100 temperature sensors was estimated to be less than 0.25°C. The air velocity was measured with a pre-



Sl. 2. *Navpični segment v hladilnem stolpu [4]*
Fig. 2. *Vertical segment in the cooling tower [4]*

se je merila s predhodno umerjenim anemometrom na vetrnico. Perioda vzorčenja je bila 1 min in celotni čas zbiranja podatkov je bil 3,4 dni.

Vlažnost vstopnega zraka je bila določena s temperaturami suhega in mokrega termometra. Relativna vlažnost okolice in prav tako temperatura okolice sta bili dobljeni z meritvami v meteorološki postaji Šoštanj. Vse meritve v hladilnem stolpu so bile izvedene v skladu s standardom DIN 1947 [5].

calibrated vane anemometer. The period of the data sampling was 1 min, and the total measurement time was 3.4 days.

The relative humidity of the inlet air was determined with the help of a dry-bulb and a wet-bulb thermometer. The relative humidity and the temperature of the ambient air were acquired from the Šoštanj meteorological station. All the measurements in the cooling tower were carried out according to the DIN 1947 standard [5].

4 ODVISNOST PARAMETROV, POVEZANIH Z OBRATOVANJEM HLADILNEGA STOLPA

Pri iskanju povezav med močjo generatorja in hladilnim stolpom smo uporabili statistične postopke, pri katerih smo s korelacijskimi koeficienti dobili stopnje odvisnosti med posamičnimi spremenljivkami. Povezanost parametrov z delovanjem hladilnega stolpa in posredno z močjo generatorja je prikazana v preglednici 2, kjer smo za izračun koeficientov odvisnosti izbrali naslednje parametre: moč generatorja P; celotni odvedeni toplotni tok Q_{od} iz hladilnega stolpa; krajevni toplotni tok Q_{lok}, ki se prenese iz vode na hladilni zrak; temperaturo okolice t_{ok}; tlak okolice p_{ok}; relativno

4 DEPENDENCE OF THE PARAMETERS ASSOCIATED WITH THE COOLING TOWER'S OPERATION

When seeking a connection between the generator and the cooling tower we used statistical methods to determine the degree of correlation between the variables. The connections of the parameters to the cooling-tower operation and indirectly to the power generation are shown in Table 2, where for the calculation of the correlation coefficient we used the following parameters: power at the generator P, total rejected heat from the cooling tower Q_R, local heat transfer at the vertical segment Q_{loc}, ambient temperature t_0, ambient pressure p_0, relative humidity of ambient φ_0, outlet temperature of moist air

Preglednica 2. *Tabela koeficientov odvisnosti, ki povezujejo moč generatorja s celovitim in krajvenim prenosom toplote v hladilnem stolpu*
Table 2. *Table of correlation coefficients that associate the power on the generator with integral and local heat transfer in the cooling tower*

	P	Q_{od}/Q_R	Q_{lok}/Q_{loc}	t_{ok}/t_0	p_{ok}/p_0	φ_{ok}/φ_0	t_{zr2}/t_{a2}	t_{zr1}/t_{a1}	$t_{wv}/t_{w,i}$	$t_{wiz}/t_{w,o}$	$t_{wvk}/t_{w,i,c}$	$t_{wizk}/t_{w,o,c}$
P	1,00	**0,99**	**0,95**	0,22	-0,61	-0,90	0,98	0,24	0,98	0,96	0,94	0,97
Q_{od} / Q_R	0,99	1,00	**0,95**	0,20	-0,57	-0,89	0,99	0,21	0,99	0,96	0,95	0,98
Q_{lok} / Q_{loc}	0,95	0,95	1,00	-0,01	-0,67	**-0,95**	**0,97**	0,01	**0,97**	**0,97**	0,95	0,95
t_{ok} / t_0	0,22	0,20	-0,01	1,00	-0,02	-0,14	0,20	1,00	0,19	0,19	0,22	0,21
p_{ok} / p_0	-0,61	-0,57	-0,67	-0,02	1,00	0,82	-0,61	-0,03	-0,61	-0,63	-0,61	-0,57
φ_{ok} / φ_0	-0,90	-0,89	-0,95	-0,14	0,82	1,00	-0,93	-0,15	-0,93	-0,94	-0,93	-0,90
t_{zr2} / t_{a2}	0,98	0,99	0,97	0,20	-0,61	-0,93	1,00	0,21	1,00	0,99	0,98	0,99
t_{zr1} / t_{a1}	0,24	0,21	0,01	1,00	-0,03	-0,15	0,21	1,00	0,21	0,20	0,23	0,23
t_{wv} / $t_{w,i}$	0,98	0,99	0,97	0,19	-0,61	-0,93	1,00	0,21	1,00	0,99	0,98	0,99
t_{wiz} / $t_{w,o}$	0,96	0,96	0,97	0,19	-0,63	-0,94	0,99	0,20	0,99	1,00	0,99	0,99
t_{wvk} / $t_{w,i,c}$	0,94	0,95	0,95	0,22	-0,61	-0,93	0,98	0,23	0,98	0,99	1,00	0,99
t_{wizk} / $t_{w,o,c}$	0,97	0,98	0,95	0,21	-0,57	-0,90	0,99	0,23	0,99	0,99	0,99	1,00

vlažnost okolice φ_{ok}; temperaturo vlažnega zraka t_{zr2} na izstopu iz navpičnega segmenta nad izločevalniki kapljic; temperaturo zraka na vstopu v navpični segment t_{zr1}, tj. v laminarni prenosnik toplote; temperaturo hladilne vode na vstopu v hladilni stolp t_{wv}; temperaturo hladilne vode na izstopu iz hladilnega stolpa t_{wiz}; temperaturo hladilne vode na vstopu v kondenzator t_{wvk} in temperaturo hladilne vode na izstopu iz kondenzatorja t_{wizk}. Matrika koeficientov odvisnosti je zaradi velikega števila obravnavanih spremenljivk in preglednosti zapisana v pregledni čni obliki v preglednici 2. Preglednica je simetrična, kar pomeni, da se lahko osredotočimo na vrednosti nad glavno diagonalo ali pod njo.

Odvisnost med močjo generatorja in celotnim odvedenim toplotnim tokom znaša 0,99, kar pomeni izredno veliko odvisnost. Ta podatek ponazarja izredno tehtno informacijo, ki potrjuje pomembnost kakovostnega obratovanja hladilnega sistema na celotni izkoristek termoelektrarne. Seveda pa je treba za učinkovito delovanje hladilnega stolpa kot celote zagotoviti dober prenos toplote na krajevni ravni.

Osredotočimo se na vrednosti koeficientov odvisnosti med celotnim odvedenim toplotnim tokom iz hladilnega stolpa in krajevnim toplotnim tokom, merjenim na navpičnem segmentu. Odvisnost med njima znaša kar 0,95. Vrednost koeficienta odvisnosti je v tako dinamičnem okolju izredno velika, kar nakazuje predvsem na dva pojava. Prvi je ta, da je krajevni toplotni tok v hladilnem stolpu odvisen od moči generatorja, kar tudi potrjuje koeficient odvisnosti med njima, oz. da morebitne spremembe

from the vertical segment t_{a2}, inlet temperature of the moist air in the vertical segment t_{a1}, inlet cooling-water temperature to the cooling tower $t_{w,i}$, outlet cooling-water temperature from the cooling tower $t_{w,o}$, inlet cooling-water temperature to the condensator $t_{w,i,c}$, outlet cooling-water temperature from the condensator $t_{w,o,c}$. Because of the large number of studied variables and for clarity, the matrix is written in tabular form in Table 2. The table is symmetrical, which means that we can concentrate on the values above or under the main diagonal.

The correlation between the power on the generator and total heat transfer from the cooling tower is 0.99, which represents a very high dependence. This data gives us very powerful information that confirms the importance of the quality of the operation of the cooling system on the overall efficiency of the power plant. Of course, we have to, for effective operation, ensure good heat transfer on a local basis.

It is reasonable for the next step to focus on the correlation coefficient between the total heat transfer from the cooling tower and the local heat transfer measured on a vertical segment. Their correlation coefficient is 0.95. This value is in a very dynamic environment, which gives us two important pieces of information. First of all, we know that the local heat transfer in the cooling tower depends on the power generation, which tells us the correlation between them, or that the potential construction element modifications of the cooling tower has an influence on the state in the condensator, and consequently on power generation. Secondly, we konstrukcijskih elementov hladilnega stolpa vplivajo na stanje v kondenzatorju in s tem na moč generatorja. Drugi sklep, ki ga omenjeni koeficient podaja, je, da je prenos toplote po celotni površini razmeroma enakomeren. Segment je namreč izbran v področju hladilnega stolpa, kjer imamo brezhibne konstrukcijske lastnosti. Izmerjene vrednosti temperatur vode na navpičnem segmentu so zelo podobne temperaturam vode, ki vstopajo in izstopajo iz stolpa, kar govori o relativni enakomernosti prenosa toplote po celotni površini v danih razmerah obratovanja. V nasprotnem primeru lahko sklepamo, da bi drugačne vrednosti izmerkov nad opazovanim segmentom glede na celotno dejansko površino nakazovale na področja velikih nehomogenosti v temperaturnem in hitrostnem polju. Posledica tega bi bila nizka odvisnost med celotnim odvedenim toplotnim tokom Q_{od} in krajevnim prenosom toplote Q_{lok}.

V naslednjem koraku je primerno pogledati parametre, ki pomembno vplivajo na krajevni prenos toplote Q_{lok}, saj smo ugotovili, da s tem vplivamo posredno na moč generatorja. Prenos toplote je povezan s stanjem okolice, od katerih sta pomembna relativna vlažnost φ_{ok} in temperatura okolice t_{ok}, ter vstopnimi parametri hladilne vode, ki predstavljajo robne pogoje. Relativna vlažnost je zelo povezana s prenosom toplote, in sicer manjša ko je relativna vlažnost, večji je mogoči preneseni toplotni tok, kar pove tudi negativni predznak. Temperatura okolice in krajevni toplotni tok sta šibko povezana. To trditev je treba podrobneje proučiti. Dinamika prenosa toplote v hladilnem stolpu je bistveno večja glede na spremembe stanja okolice, kar se kaže v slabi odvisnosti. Medtem ko je znano, da je temperatura vlažnega okoliškega termometra izrednega pomena pri razpoložljivi temperaturni razliki za prenos toplote, kar vpliva na velikostni red prenosa toplote. Nižja ko je temperatura okolice, nižja je temperatura vlažnega zraka na vstopu v polnilo in večja je temperaturna razlika pri danem obratovalnem stanju nad izločevalniki in okolico za prenos toplote.

Poleg relativne vlažnosti so zelo povezani parametri še temperatura vlažnega zraka nad izločevalniki t_{zr2}, temperatura izstopne t_{wiz} in vstopne t_{wv} hladilne vode v hladilni stolp. Temperatura nad izločevalniki je neposredno odvisna od temperature hladilne vode na vstopu, kar pove tudi odvisnost med njima, ki ima vrednost 1. Večja ko je temperatura nad izločevalniki glede na dano stanje okolice, več

know that the homogeneity of heat transfer through the entire cross-sectional area of cooling tower is relatively good. Namely, we have chosen the vertical segment in the area of the cooling tower where the construction elements are fault-free. The measured temperatures of the water on the vertical segment are very similar to those measured at the inlet and outlet positions of the tower, which tells us about the relative homogeneity of the heat transfer through the entire tower surface for given operational conditions. In the opposite case we could consider that we would have different measured values on a vertical segment relative to the entire area of the tower, indicating very large areas of air temperature and velocity inhomogeneities. The consequence would be a low correlation between the total Q_R and the local Q_{loc} heat transfer in the cooling tower.

In the next step we can concentrate on parameters that importantly influence the local heat transfer Q_{loc} because we have discovered that it has an indirect influence on power generation. The heat transfer is connected with the state of the atmosphere, of which the most important are the relative humidity φ_0, the ambient temperature t_0, and the inlet water temperature $t_{w,I}$, which represent the boundary conditions. The relative humidity is closely correlated with heat transfer, i.e., the lower relative humidity gives a larger potential for heat transfer that tells us a negative sign. The ambient temperature and the local heat transfer are not closely correlated. This statement should be closely investigated. The dynamics of heat transfer in the cooling tower is significantly higher relative to the state of the ambient, which gives us a low correlation. But it is known that the wet-bulb temperature of the ambient signifies the maximum potential to which cooling water can be cooled. Consequently, it follows that a lower temperature of the ambient results in a lower inlet-air temperature in the cooling tower, and that gives a larger temperature difference between the state above the drift eliminators and the ambient for heat transfer for given cooling-tower characteristics.

In addition to the relative humidity the local heat transfer is closely correlated with the outlet-air temperature t_{a2}, the inlet $t_{w,i}$ and the outlet $t_{w,o}$ cooling-water temperature. The air temperature above the drift eliminators is directly connected with the inlet-water temperature, which tells us the correlation between them, i.e., 1. The higher is the air temperature above the drift eliminators relative to the state of the ambient toplote nam je uspelo prenesti na zrak, kar se kaže v nižji temperaturi hladilne vode na izstopu iz hladilnega stolpa.

Veliko odvisnost opazimo tudi med preneseno toploto in temperaturo hladilne vode na izstopu t_{wizk} in vstopu t_{wvk} v kondenzator. Ta povezava je fizikalno povsem logična, saj lahko praktično enačimo vstopno in izstopno temperaturo hladilne vode iz hladilnega stolpa z izstopno in vstopno temperaturo v kondenzator, kar med drugim nakazujejo tudi odvisnosti med njimi.

5 REGRESIJSKI MODEL MED MOČJO GENERATORJA IN CELOTNIM TOPLOTNIM TOKOM IZ HLADILNEGA STOLPA

V prejšnem poglavju smo ugotovili veliko odvisnost med prenesenim toplotnim tokom in močjo generatorja. Slika 3 prikazuje njuno medsebojno odvisnost, ki je linearna in jo tako lahko približamo z regresijsko premico.

Graf na sliki 3 prikazuje odvisnost med močjo generatorja in celotnim odvedenim tokom iz hladilnega stolpa. Enačba linearnega regresijskega modela za dani primer je:

the more heat was successfully transferred from the water to the air, which results in a lower outlet-water temperature from the cooling tower.

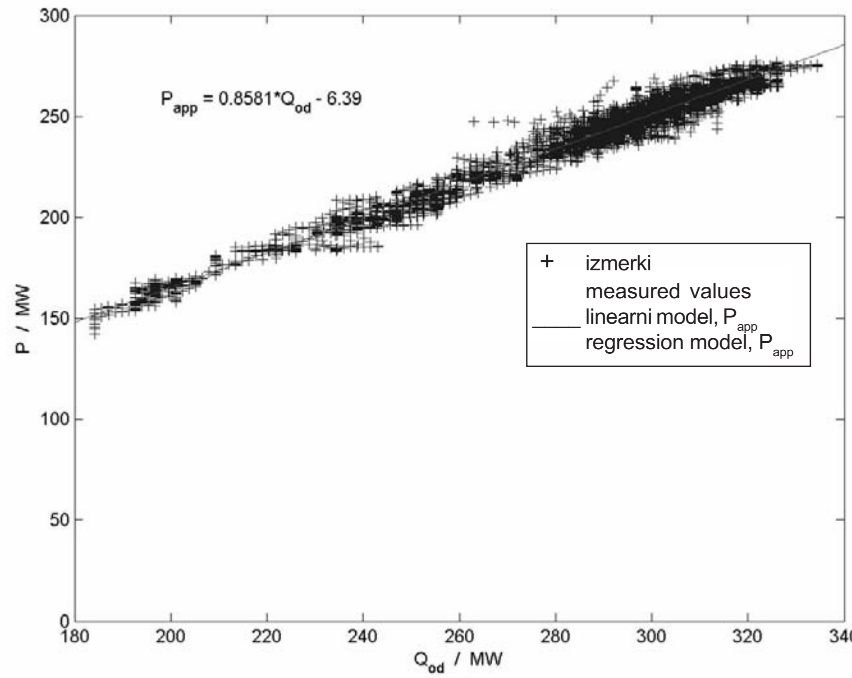
A high correlation can also be seen between the heat transfer, the outlet $t_{w,o,c}$ and the inlet $t_{w,i,c}$ water temperature to the condensator. This connection is physically very logical because we can practically equal the inlet and outlet water temperatures from the cooling tower with the outlet and inlet water temperatures to the condensator, which indicates the correlations between them.

5 REGRESSION MODEL BETWEEN THE POWER GENERATION AND THE REJECTED HEAT FROM COOLING

In earlier sections we discovered a close dependence between the heat transfer and power generation. Figure 3 shows their relationship, which is linear, and that is why we can approximate it with a linear regression model.

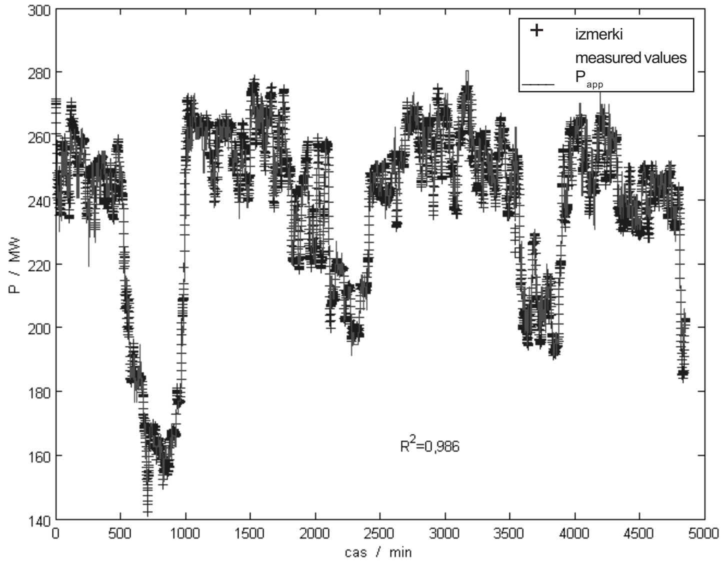
The equation that describes the relationship between the power generation and the rejected heat is:

$$P = 0,8581\ Q_{od} + 6,39 \tag{3}$$



Sl. 3. *Regresijska premica med močjo generatorja in celotnim odvedenim toplotnim tokom*

Fig. 3. *Linear regression model between the power generation and rejected heat from the cooling tower*



Sl. 4. *Izmerjena in približna moč generatorja*
Fig. 4. *Measured and approximated power on the generator*

Razpršenost izmerkov okoli regresijske premice je posledica naključnosti nihanj moči generatorja, ki je prikazana na sliki 4, in spreminjanja stanja okolice v času merjenja, ki je trajalo 3,4 dni. Regresijski model predstavlja karakteristično funkcijo za blok 4 Termoelektrarne Šoštanj. Strmina in presečišče regresijske premice z osjo *y* podajata tudi informacije o kakovosti obratovanja termoelektrarne. In sicer bolj ko je strma regresijska premica in bolj ko je premica premaknjena navpično navzgor, boljše je obratovanje postrojenja. Slika 4 prikazuje rezultate izmerjene in približne moči po enačbi (3).

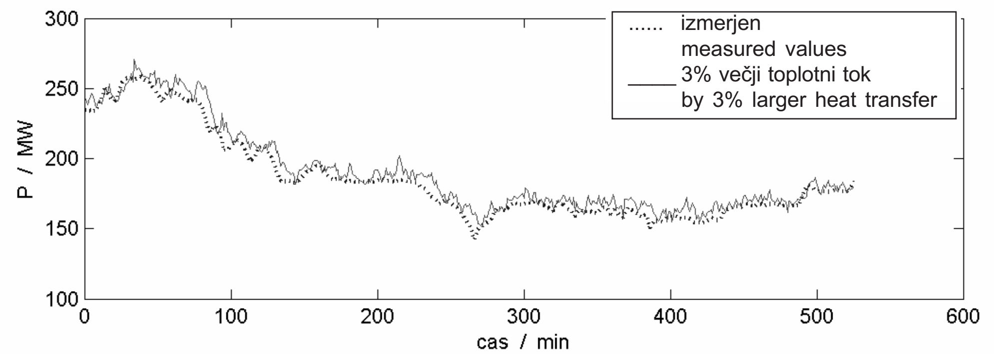
S slike 4 opazimo zelo dobro približnost moči z linearnim regresijskim modelom, kjer je koeficient odvisnosti 0,986. Enačba (3) je lahko izhodišče za morebitne spremembe na hladilnem stolpu, ki imajo posredno vpliv na moč generatorja.

Velik koeficient odvisnosti med močjo generatorja in krajevnim toplotnim tokom nakazuje visoko raven enakomernosti v delovanju hladilnega stolpa. To pomeni, da lahko predpostavimo nespremenljiv prenos toplote po celotni dejanski površini pri morebitnih spremembah konstrukcijskih elementov stolpa. Na podlagi sočasnega merjenja veličin pri večjem številu konstrukcijsko spremenjenih navpičnih segmentih lahko ugotovimo, katera kombinacija elementov največ prispeva k moči generatorja in za koliko. Pri tem je treba paziti, da so izbrani segmenti pravilno razporejeni glede na razmerje masnih tokov vode in zraka v hladilnem

Dissipation around the regression model is a consequence of the random oscillation of power on the generator, which can be seen in Figure 4, and the variation of the ambient conditions through the duration of the measurements, which took us 3.4 days. The regression model represents the characteristic function for Block 4 of the Šoštanj power plant. The gradient and *y*-axis cross-section of the regression model gives information about the quality of the power-plant operation. The steeper and higher regression model is better, as is the operation quality. Figure 4 shows the results of the measured and the approximated (Equation 3) values of the power on the generator.

Figure 4 shows a very good approximation with the linear regression model of the power on the generator, where the correlation coefficient is 0.986. Equation (3) can be a guideline for potential modifications in the cooling tower, which have an indirect influence on the generator.

The high correlation coefficient between the power on the generator and the local heat transfer indicates a high level of homogeneity in the operation of the cooling tower. This means it can be assumed to have constant heat transfer through the entire area of the cooling tower by a potential construction-element modification. On the basis of simultaneous measurements on different modified vertical segments we can determine which combination of construction elements contributes the most to the power generation, and for what quantity. We



Sl. 5. *Moč generatorja pri 3-odstotnem večjem odvodu toplote iz hladilnega stolpa*
Fig. 5. *Power on generator by 3 % heat transfer improvement in cooling tower*

stolpu. Ta razmerja morajo biti enaka, kar zagotavlja enake robne pogoje pri analizi različnih spremenjenih navpičnih segmentih. Tako lahko na primeru izračuna, ki ga predstavlja slika 5, ugotovimo, da je bil prenos toplote na najučinkovitejšem spremenjenem navpičnem segmentu za 3 % večji kakor v normalnih razmerah. Teoretično to pomeni: če bi izbrano kombinacijo elementov uporabili po celotni dejanski površini hladilnega stolpa, bi se v danih obratovalnih in okoliških razmerah moč generatorja povečala za povprečno 7,02 MW. To pomeni za blok, ki ima moč 250 MW in izkoristek 35 %, dvig celotnega izkoristka za 0,98 %, kar dolgoročno pomeni pomembne prihranke pri porabi goriva in zmanjšani emisiji dimnih plinov.

Diagram na sliki 5 prikazuje časovno zvečanje moči pri 3-odstotnem večjem prenesenem toplotnem toku iz hladilnega stolpa v danih obratovalnih in okoliških razmerah.

6 KOMENTAR K UČINKOVITOSTI HLADILNEGA STOLPA BLOKA 4 TERMOELEKTRARNE ŠOŠTANJ

Analiza delovanja hladilnega stolpa bloka 4 termoelektrarne Šoštanj pri približno stalni moči generatorja, ki je povprečno znašala 260 MW, je pokazala dobre rezultate. Za merilo kakovosti obratovanja hladilnega stolpa je bil izbran koeficient $\dot{Q}_{od}/P$. Manj odvedene toplote pri dani moči generatorja pomeni, da nam je uspelo spremeniti več toplote na enoto pare v koristno pridobljeno delo, kar pomeni nižje vrednosti koeficienta $\dot{Q}_{od}/P$. Pri danjašnjih hladilnih sistemih, odvedena toplota se spreminja od 1,3 do 2,5-kratne vrednosti iz krožnega postopka pridobljenega dela. Na podlagi koeficienta lahko ugotovimo, da je obratovanje hladilnega stolpa

have to be careful to choose vertical segments so that the water-to-air mass-flow rate is constant, by which we ensure the same boundary conditions. In the example of figure 5 we can see that the heat transfer in the cooling tower was 3% higher than before the modifications were made. This, theoretically, means that if the best combinations of elements would be used on the entire area of the cooling tower for given operating and atmospheric conditions, the power generation would be raised on average by 7.02 MW. This means for a block with 250 MW of power and 35% efficiency, an improvement in the total thermodynamic efficiency of the power plant by 0.98%, which in the long term represents significant fuel savings and less environmental pollution with exhaust gases.

Figure 5 shows the power raised by 3% and the heat-transfer improvement from the cooling tower for given operational and atmospheric conditions.

6 COMMENT ON THE EFFICIENCY OF THE COOLING TOWER AT BLOCK 4 OF THE ŠOŠTANJ POWER PLANT

Our operational analysis of the cooling tower at Block 4 of the Šoštanj power plant by constant power generation, the value of which on average is 260 MW, has shown good results. For the purpose of quality evaluation we chose the coefficient $\dot{Q}_{od}/P$. Less rejected heat at a constant power generation means that more heat is successfully transformed into useful work, which represents the lower value of the coefficient $\dot{Q}_{od}/P$. For today's cooling systems the rejected heat varies from 1.3 to 2.5 times the work extracted from the thermodynamic cycle. On the basis of the coefficient we can determine that the operation of cooling tower at Block 4 of the na bloku 4 Termoelektrarne Šoštanj učinkovito, saj znaša povprečna vrednost koeficienta $\dot{Q}_{od} / P$ 1,45, kar uvršča hladilni sistem Termoelektrarne Šoštanj v sodobnejši razred. Vrednost koeficienta tudi potrjuje, da je bila rekonstrukcija stolpa na bloku 4 učinkovita.

7 SKLEP

Na učinkovitost delovanja hladilnega stolpa vpliva mnogo dejavnikov, ki prispevajo k celotni in krajevni učinkovitosti stolpa. Celotne dejavnike predstavljata predvsem stanje okolice in režim obratovanja termoelektrarne, ki vplivata na velikostni red izkoristka hladilnega stolpa. Iz zgornjih analiz je bilo ugotovljeno, da ima vpliv temperature okolice velik pomen pri učinkovitosti prenosa tolpote, pri kateri njena vrednost vpliva predvsem na entalpijo vstopnega zraka v hladilni stolp in na razliko gostot okoliškega zraka in zraka v hladilnem stolpu. Sama moč generatorja ima vpliv na raven temperatur vstopne hladilne vode v hladilni stolp in na temperature vlažnega zraka v hladilnem stolpu. Večja temperatura zraka v hladilnem stolpu pomeni v danih razmerah večjo količino prenesene toplote iz vode na zrak, kar pomeni večje hlajenje vode. Iz zgornjih ugotovitev lahko sklepamo, da se nižja temperatura okolice, oz. vstopnega zraka, in višja temperatura zraka v hladilnem stolpu izražata v večji učinkovitosti delovanja hladilnega stolpa.

Krajevne dejavnike predstavljajo konstrukcijske karakteristike sestavnih elementov hladilnega stolpa. Učinkovitejša kombinacija konstrukcijskih elementov se kaže v večjem prenosu toplote oz. večjem hlajenju vode. Na krajevni prenos toplote vplivajo tudi hitrostne razmere zraka blizu stolpa, ki predstavljajo robne pogoje in imajo vpliv na homogenost hitrostnega in temperaturnega polja aktivne površine hladilnega stolpa. Hitrostne razmere zraka pa so predvsem odvisne od podnebnih razmer in namestitve stolpa.

Prikazana je pomembnost hladilnega sistema, pri katerem je glavni element hladilni stolp kot izredno pomemben del termoelektrarne. Poiskali smo statistično povezanosti med močjo generatorja in krajevnim ter celovitim odvedenim toplotnim tokom iz hladilnega stolpa. Na podlagi regresijskega modela smo podali domnevo, ki pove, da lahko izboljšanje učinkovitosti obravnavanega hladilnega stolpa za, npr. 3 %, izkaže pri polni obremenitvi 250 MW bloka v dvigu celotnega izkoristka termoelektrarne za 1 %, kar pomeni znatne prihranke v porabi goriva in zmanjšani emisiji dimnih plinov.

Šoštanj power plant is quite efficient. The average value of the coefficient $\dot{Q}_{od} / P$ is 1.45, which classifies the cooling tower in the higher class. The value of the coefficient confirms that the reconstruction of tower at Block 4 was successful.

7 CONCLUSION

Cooling-tower operational efficiency depends on many variables that contribute to the integral and local operating conditions. The integral variables come mostly from the atmospheric state, and power-plant operational points that influence on the high cooling-tower efficiency. From the above analysis we concluded that the ambient temperature has a great influence on heat-transfer efficiency, where its value had an impact on the inlet-air enthalpy to the cooling tower and on the density difference between the cooling tower and the atmospheric air. The power on the generator has an influence on the level of the inlet-water temperature and the moist air temperature in the cooling tower. A higher air temperature in the tower is given by the operating condition, and represents a larger amount of heat transferred from the water to the air, which means better cooling of the water. It can be concluded that a lower atmospheric temperature or a lower inlet-air temperature and a higher air temperature in the cooling tower results in a higher cooling-tower efficiency.

Local factors are the construction characteristics of the elements in the cooling tower. A more efficient combination of construction elements results in a larger heat transfer and a lower water temperature. Local heat transfer also depends on the air velocity near the cooling tower, which represents the boundary conditions that have an influence on the temperature and the velocity homogeneity of the cooling tower's cross-sectional area. The air velocity near the tower depends on the climate characteristics and the location of the cooling tower.

Our study shows the importance of the cooling system where the main element is a natural-draft cooling tower. We searched statistically the connections between the power generation and the local and integral heat transfer from the cooling tower. On the basis of a regression model we presented the hypothesis that tells us that a 3% heat-transfer improvement in the cooling tower can increase the overall efficiency of a 250 MW block by 1%, which represents a large fuel saving and less environment pollution with exhaust gases.

Regresijska analiza je pokazala, kateri parametri so najbolj vplivni na delovanje hladilnega stolpa. Pri danih konstrukcijskih karakteristikah hladilnega stolpa so to obremenitev termoelektrarne ter temperatura in relativna vlažnost okoliškega zraka. Ugotovili smo, da večje ko so obremenitve termoelektrarne, nižja temperatura in večja suhost okoliškega zraka, večja je učinkovitost prenosa toplote in boljši je izkoristek hladilnega stolpa pri danih konstrukcijskih karakteristikah.

Prikazano je, da z linearnim regresijskim modelom, s katerim določimo karakteristično funkcijo termoelektrarne, lahko ocenimo kakovost delovanja postrojenja kot celote. Ta ugotovitev odpira možnost ocenjevanja učinkovitosti stolpov in neposreden vpliv na moč generatorja. S pomočjo regresijske analize je mogoče napovedati področja neenakosti v delovanju po površini hladilnega stolpa.

The regression analysis has shown which parameters are significant for the cooling tower's operation. From the given construction characteristics of the cooling tower these parameters are the load of the power plant, the temperature and the relative humidity of the atmospheric air. A higher load of the power plant, lower temperature and relative humidity of the air give a higher heat-transfer efficiency and efficiency of the cooling tower for the given construction characteristics.

Our analysis shows that it is possible with a simple linear regression model, which represents the characteristics of the power plant, to estimate the quality of the overall thermodynamic process. This statement opens new opportunities for estimating cooling-tower efficiency and evaluating the direct influence of the modifications on power generation. With regression analysis it is also possible to predict the areas of operating non-homogeneities in the cooling tower.

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8 REFERENCES

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