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Izboljšanje termodinamičnih lastnosti hladilnih stolpov na naravni vlek

Improvement of the Thermodynamic Properties in a Natural-Draft Cooling Tower

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Z uporabo metode CTP (Cooling Tower Profiler) v hladilnem stolpu na naravni vlek elektrarne Doel-3 (Belgija) smo določili hitrostna in temperaturna polja zraka nad izločevalniki kapljic. Meritve so pokazale, da so na obodu prečnega prereza stolpa področja z velikimi hitrostmi in nizkimi temperaturami zraka, kar ima za posledico manjšo učinkovitost v prenosu toplote in snovi. Postavljene pojavne povezave omogočajo rešitev problema s spremembo višine polnila in prerazporeditvijo masnega toka vode. Vpliv omenjenih parametrov smo preverili s simulacijo. Narejena je bila trirazsežna numerična simulacija enofaznega turbulentnega toka zraka. Lokalne izmerjene vrednosti hitrosti in temperature zraka so bile v model vključene prek izvirnih členov. Rezultati prikazujejo analizo vpliva lokalnih nepravilnosti na skupno značilko hladilnega stolpa. Predstavljeni so rezultati meritev, simulacija hitrostnega in temperaturnega polja po prerezu stolpa. Podani so ukrepi za odpravo nepravilnosti v delovanju stolpa, ki vključujejo povečanje višine polnil na obodu stolpa in ustrezno prerazporeditev celotnega masnega pretoka vode po prerezu stolpa. V numeričnem modelu smo ti dve spremenljivki opisali z lokalno spremembo izvirnih členov, kar vodi k ustreznejši porazdelitvi aerotermodinamičnih značilk in posledično k večji učinkovitosti hladilnega stolpa.

Na primeru izbranega hladilnega stolpa Doel-3 je v prispevku predstavljena celovita diagnostična metoda lokalnih anomalij, ki temelji na eksperimentalnem in numeričnem modeliranju prenosnih pojavov v hladilnem stolpu. Opisana metoda omogoča povečevanje učinkovitosti delovanja hladilnih stolpov. Izračunana povprečna gostota toplotnega toka se je v tem dejanskem primeru povečala za 2,8 odstotka.
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(Ključne besede: hladilni stolpi, naravni vlek, termodinamične lastnosti, numerične analize)

The velocity and temperature fields above droplet eliminators inside a natural-draft cooling tower of the Doel-3 powerplant (Belgium) were determined using the CTP (Cooling Tower Profiler) method. The measurements show regions of high velocities and low temperatures of air at the cooling tower circumference, leading to locally impaired heat and mass transfer. The established phenomenological relations enable the solution of this problem, which can be achieved by a variation of the fill height and the water mass-flow rate. The influence of these two parameters was analysed numerically. A 3D numerical simulation of a single-phase turbulent airflow was performed. Local values of the air velocity and air temperature were included in the numerical model through source terms. The numerical results present the analysis of local irregularities and their influence on the overall cooling-tower characteristics. Experimental and numerical results for the velocity and temperature fields in a cooling tower's transverse section are presented, followed by a procedure for reducing irregularities in the cooling tower's operation. This procedure includes the increase of the fill height and the rearrangement of the local cooling-water mass-flow rate in the cooling tower's transverse section. In the numerical model these two parameters were modelled by a local modification of the source terms. Modified source terms of the model lead to more uniform aero-thermodynamic properties in the tower and consequently to a higher cooling-tower efficiency.

The paper presents a complete diagnostic method of local anomalies, based on the case of a representative Doel-3 cooling tower. The method is based on experimental and numerical modelling of the transport phenomena inside the cooling tower. It makes it possible to increase the efficiency of the cooling tower's operation. The calculated mean heat-flux density was increased by 2.8% in this particular case.
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(Keywords: cooling towers, natural draft, thermodynamic properties, numerical analysis)

0 UVOD

V termoenergetskih sistemih se v kondenzatorju prenaša toplota iz parnega krožnega postopka na hladilno sredstvo. Le-ta je običajno voda, ki se jo lahko črpa iz reke ali jezera oz. se jo zaradi okoljevarstvenih razlogov neprekinjeno uporablja v zaprtih sistemih - ohlajevanje vode in njena ponovna uporaba. V tem primeru toplo vodo, ki zapušča kondenzator, hladimo v hladilnem stolpu. Ker delovanje hladilnega stolpa vpliva na temperaturo vode na vstopu v kondenzator, je njegov učinek bistvenega pomena za izkoristek celotnega sistema (delovanje kondenzatorja pri tem nižji temperaturi ima za posledico višji podtlak na parni strani, kar zagotavlja več pridobljenega dela iz turbine in večji izkoristek celotnega sistema).

Hladilni stolp na naravni vlek deluje na podlagi prenosa toplote in snovi med vodo in zrakom, ki sta v neposrednem stiku. Voda se hladi tako v področju polnil kakor tudi v področju prhe. V protitočnem hladilnem stolpu je opazen protitok med vodo in zrakom. Zrak vstopa na vznožju stolpa in teče skozi polnila ter področje prhe. Voda, ki teče v nasprotni smeri, se z uporabo šob razprši in steče v obliki plasti skozi polnila. Bistvenega pomena za učinkovit prenos toplote in snovi v hladilnem stolpu je velika stična površina med zrakom in vodo ter velik količnik prenosa toplote in snovi.

Prispevek prikazuje analizo delovanja hladilnega stolpa elektrarne Doel-3 z močjo 2040 MW. Možni problemi, ki se pojavljajo v hladilnih stolpih, so: omejen tlak prh, ki ga povzročajo odprti kanali, možnost prenapolnitve ob prehodnih pojavih – tveganje poškodbe polnil, poškodovanje polnil s peskom - zamašitev cevovodov in nalaganje nečistoč na polnilih, nerazprševanja hladilne vode zaradi odpadlih pršilnih glav, polomljene cevi in netesnosti razvodnih kanalov.

Opravljene so bile standardne meritve celostnih parametrov hladilnega stolpa [1] in tudi dodatne meritve temperature in hitrosti zračnega toka z metodo CTP [2] nad izločevalniki kapljic. Raziskava lokalnega delovanja hladilnega stolpa je bila osredotočena na lokalni prenos toplote in snovi ter na lokalne količnike izgub v polnilih. Hitrost zraka nad izločevalniki kaplic je odvisna od geometrijske oblike hladilnega stolpa (na primer

0 INTRODUCTION

In power-generation units (e.g., thermal and nuclear power plants) a circulating-water system supplies cooling water to a turbine condenser and thus acts as an instrument by which heat is extracted from the steam cycle to the environment. The turbine condenser is usually cooled with water from lakes or rivers, but often the use of cold, fresh water is limited for ecological reasons. Therefore, the continuous re-cooling and re-use of water in a closed system is necessary. In this case the warm water leaving the condenser is cooled in a cooling tower. The cooling tower's operation influences the water temperature at the condenser inlet, so its performance is vital for the efficiency of the entire system, because a condenser operating at the lowest temperature possible results in a higher sub-pressure on the steam side, which in turn makes possible a higher turbine work output and overall cycle efficiency.

The natural-draft cooling tower's operation is based on a principle whereby energy is removed from hot water in direct contact with relatively cool and dry air. The water is cooled in both the fill and rain regions. In a counterflow cooling tower a gaseous phase (air) flows upwards and a liquid phase (water), in variously sized droplets, falls downwards. The airflow enters the cooling tower at the bottom and flows through the fill and the rain regions. The water is sprayed through nozzles and flows as a film down the sheets of the fill. The key factors required for intensive heat and mass transfer in the cooling tower are a large air-to-water interface area and high heat- and mass-transfer coefficients.

In this study the operation of a Doel-3 (2040 MW) cooling tower was analysed. The problems that occur in the cooling tower are as follows: limited pressure of the sprayers caused by open channels, possible overflow during transients – risking fill damage and the fouling of fills by sand – clogging of the piping and deposit formation in fills, by-pass leaks due to lost end-caps, broken pipes, sprayers which have fallen off, and leaking baffles/distribution channels.

Accordingly, in order to establish the operation of a particular cooling tower's parts, standard integral measurements [1] as well as additional measurements of airflow temperature and velocity distribution above the droplet eliminators according to the CTP method [2] were performed. The investigation of the local operation of the cooling tower's parts was focused on a determination of locally transferred heat between the water and the air and the local value of the fill-loss coefficient. The air velocities above the drift eliminators depend on the cooling tower's geometry (e.g., the supporting walls, the water-distribution channels, etc.), on the local loss coefficient of the fill as well as on the difference between the air density inside and sten, porazdelitvenih kanalov itn.), tlačnih izgub v polnilih ter od razlike gostot zraka v stolpu in okolici. Količnik izgub polnil je funkcija masnih tokov vode in zraka ter gostote in višine polnil. Lokalni količnik izgub je bil določen posredno iz padca statičnega tlaka in lokalne hitrosti nad izločevalniki kapljic. Temperatura zraka nad izločevalniki kapljic je odvisna od lokalnega prenosa toplote in snovi med vodo in zrakom. Lokalna vrednost prenesene toplote in snovi je bila izračunana iz masnega toka zraka in sprememb njegove temperature in vlažnosti.

Glede na izmerjeni hitrostni in temperaturni polji zraka smo podali nekatere predloge za spremembe, ki bi se kazale v učinkovitejšem prenosu toplote in snovi med zrakom in vodo. Spremembe bi bilo mogoče doseči z zmanjšanjem tlačnih izgub v polnilih in z ustreznejšo porazdelitvijo vode po prerezu stolpa. Vpliv teh sprememb na lastnosti toka zraka je predmet tega prispevka.

1 PRENOS TOPLOTE IN SNOVI V HLADILNEM STOLPU

Prenos toplote in snovi v določenem delu hladilnega stolpa je v veliki meri odvisen od lokalnih masnih tokov vode in zraka. Predstavljeni so osnovni modeli prenosa toplote in snovi v opazovanem sistemu, dobljene zakonitosti pa so vključene v enofazni trirazsežni model turbulentnega toka zraka skozi hladilni stolp na naravni vlek.

Postopek hlajenja vode se odvija v območju pršil in polnil. Prenos toplote in snovi je v obeh primerih dosežen z neposrednim stikom med vodo in okolišnim zrakom. Mehanizem prenosa toplote in snovi je razlika delnim tlakov vodne pare v mejni plasti in obtekajočim zrakom ter v manjši meri razlika temperatur med vodo in zrakom ([1] in [3]). Ker se večina toplote prenese v območju polnil ([4] in [5]), lahko območje pršil in polnil obravnavamo kot eno območje.

Za ustaljene adiabatne pogoje zapišemo enačbo ohranitve energije v nadzorni prostornini dV [6]:

outside the cooling tower. For a particular fill the fill-loss coefficient is a function of the air and water mass-flow rates as well as of the density and the height of the fills. The airflow rate through the fill could be additionally obstructed because of broken or blocked fills and the mass-flow rate could be reduced because of sealed spray nozzles and broken or damaged splash-cups. The local loss coefficient was determined indirectly from the static pressure drop and the local velocity value above the droplet eliminators. The air temperatures above the droplet eliminators depend on the local transferred heat and mass between the water and the air. The local value of the transferred heat and mass was calculated from the air mass-flow rate and its temperature and humidity change.

According to the obtained air velocity and temperature field some corrections are suggested to achieve a more efficient heat and mass transfer between the water and the air. This could be achieved by decreasing the air resistance in the fill system and by appropriately rearranging the water mass-flow rate in the cooling tower's transverse section. The influence of these changes on the air-flow properties is reported in this paper.

1 TRANSFER PHENOMENA IN A COOLING TOWER

Transfer phenomena in particular segments of a cooling tower largely depend on the local water and air mass-flow rates. Basic models of heat and mass transfer in the observed system are presented later and the obtained relations are included in a single-phase 3D model of the turbulent airflow through the natural-draft cooling tower.

The process of water cooling takes place in the cooling tower's rain and fill region. In each of them the heat and mass transfer is accomplished by a direct contact between the water and the surrounding air. The heat and mass transfer is mostly driven by the difference between the partial pressures of the water vapour in the boundary layer and of the airflow, but the temperature difference between the water and the air also plays a role ([1] and [3]). Because the main heat exchange takes place in the fill region ([4] and [5]), the rain and fill regions are treated together as a fill system.

For stationary adiabatic conditions the conservation-of-energy equation for the differential control volume, dV, can be written in the following form [6]:

$$\dot{m}_{da} dh_a = \dot{m}_w c_{pw} dT_w + c_{pw} T_w d\dot{m}_w \qquad (1).$$

Iz enačbe 1 vidimo, da je toplotni tok, ki ga prejme zrak, enak toplotnemu toku, ki ga odda voda.

Eq. 1 states that the heat flux received by the air is equal to the heat flux delivered by the water.

Lokalno preneseni toplotni tok med vodo in zrakom je odvisen od masnih tokov vode in zraka skozi določeno področje hladilnega stolpa ter od lokalnih vrednosti količnikov prenosa toplote in snovi. Krajevna masna tokova vode in zraka skozi hladilni stolp sta odvisna tudi od konstrukcijskih in okolišnih razmer.

Različne predhodno navedene tehnične napake, ki se pojavijo po večletnem obratovanju hladilnega stolpa, vodijo k neustrezni omočenosti polnil ter k motenemu toku zraka skozi polnila. Značilnost teh anomalij je ta, da se pojavljajo na različnih mestih hladilnega stolpa in da jih je moč določiti le s krajevnimi meritvami temperaturnega in hitrostnega polja hladilnega zraka v stolpu. Prenos toplote in snovi ter tlačni padci v polnilih po prerezu hladilnega stolpa so bili analizirani z numerično simulacijo. Izmerjene vrednosti padca tlaka v polnilih in lastnosti zraka nad izločevalniki kapljic so bile uporabljene za izvirne člene v prenosnih in energijskih enačbah numeričnega modela.

Določitev prenosa toplote in snovi v določenem delu hladilnega stolpa temelji na toplotnem toku, ki ga prejme zrak. Izračunamo ga po enačbi [6]:

The locally transferred heat flux between the water and the air depends on the water and air mass flow through the particular segment of the cooling tower and on the local values of the heat- and mass-transfer coefficients. The water and airflow rates through a cooling tower also depend on the structural and surrounding conditions.

Various previously mentioned technical defects that occur in a cooling tower after years of operation lead to inappropriate fill-system moistening as well as to a disturbed airflow through the fill system. These anomalies can occur at various locations inside the cooling tower and can only be detected by the local measurements of velocity and temperature field of the cooling air across the cooling-tower area. The heat and mass transfer as well as the pressure drop in the fills across the cooling tower's transverse section were analysed numerically. The measured values of the pressure drop in the fill region and the properties of the air above the droplet eliminators were used as source terms in the transport and energy equations of the numerical model.

The determination of heat and mass transport in a certain segment of the cooling tower is based on the heat flux received by the air. The latter is calculated using the following equation [6]:

$$d\dot{Q}_a = \dot{m}_{da} dh_a \qquad (2).$$

Za rešitev enačbe (2) moramo poznati vstopno in izstopno temperaturo zraka, vlažnost zraka in masni tok zraka.

Vstopna temperatura zraka in njegova vlažnost sta bili izmerjeni v bližini stolpa – predpostavili smo, da se vrednosti na vstopu v stolp ne spreminjata. Na podlagi izkušenj prejšnjih meritev na različnih hladilnih stolpih [5] in priporočil standarda DIN-1947 [5] smo privzeli tudi, da je relativna vlažnost zraka nad polnili 100 odstotna. Temperatura zraka na izstopu iz polnil je bila izmerjena. Masni tok vlažnega zraka na krajevni ravni hladilnega stolpa je bil določen posredno z merjenjem hitrosti zraka. Entalpija vlažnega zraka je podana z vsoto entalpije suhega zraka in entalpije vodne pare:

The solution of Eq. 2 requires the inlet and outlet air temperatures, the air humidity and the air mass flow to be known.

The inlet temperature and the air humidity were measured in the vicinity of the cooling tower, supposing that these parameters remain constant over the inlet area of the cooling tower. It is also presumed that the relative humidity of the air that exits the fill system is 100%. This presumption is based on experience and from experimental results on various cooling towers [5], and is also in accordance with the standard DIN-1947 [5]. The temperature of the air exiting from the fill system was measured. The local mass flow of the humid air through the respective cooling-tower segment was determined indirectly by measuring the air velocity at the respective measurement points. The enthalpy of the humid air equals the sum of the dry-air enthalpy and the water-vapour enthalpy:

$$h_a = c_{pa} T_a + x(c_{pv} T_a + r) \qquad (3).$$

Če uporabimo znane izraze $\dot{m}_{da} = \dot{m}_a / (1 + x)$, $\dot{m}_a = \dot{V}_a \rho_a$ in $\dot{V}_a = S\, v_a$, lahko gostoto toplotnega toka iz vode na zrak izrazimo z:

Using the common relations $\dot{m}_{da} = \dot{m}_a / (1 + x)$, $\dot{m}_a = \dot{V}_a \rho_a$ and $\dot{V}_a = S\, v_a$ the heat-flux density from water to air can be expressed as:

$$\dot{q} = \frac{v_a \rho_a (h_{a1} - h_{a2})}{1 + x_1} \qquad (4).$$

Gostota vlažnega zraka je izračunana glede na izmerjeno temperaturo in predpostavko, da je relativna vlažnost zraka nad izločevalniki kapljic 100 odstotna. Izmerili smo lokalne vrednosti temperature zraka in njegove hitrosti, gostoto toplotnega toka v polnilih pa smo izračunali po enačbah (3) in (4).

The density of humid air is calculated with respect to the measured temperature and the assumption that the relative humidity of the air above the droplet eliminators is equal to 100%. The measurements were performed to obtain local values of the heat-flux density in the fill system. The air temperatures and velocity were measured and the heat-flux density was calculated using Eqs. (3) and (4).

2 KOLIČNIK IZGUB V POLNILIH

Količnik izgub v polnilih hladilnega stolpa je odvisen od padca tlaka v polnilih, ki ga lahko določimo s preizkusi. Količnik izgub je tudi odvisen od masnih tokov zraka in vode in je zato odvisen od vleka skozi hladilni stolp [7].

Padec statičnega tlaka v polnilih in količnik izgub sta povezana z [7]:

2 LOSS COEFFICIENT OF A FILL SYSTEM

The loss coefficient of the cooling tower’s fill system depends on the air-pressure drop across the fill, and this can be determined experimentally. The loss coefficient is also correlated with the air and water mass-flow rates and is therefore a function of the draft through the natural-draft cooling tower [7].

The static pressure drop through the fill system is coupled to the loss coefficient by the following relation [7]:

$$\Delta p_{fi} = k_{fi} \cdot \frac{\rho v^2}{2} \qquad (5).$$

3 POSTOPEK MERITEV

Hitrostna in temperaturna polja zračnega toka se v okviru metode CTP merijo z uporabo razvite daljinsko upravljane premične enote (sl. 1), s katero je mogoče izmeriti hitrosti in temperature izstopnega

3 MEASURING PROCEDURE

In a CTP method, the velocity and temperature fields of the airflow are measured by a remotely controlled mobile unit (Fig. 1), developed to enable the air velocity and the temperature of the exit air mapping meas-

Sl. 1. *Premična enota s krilnim anemometrom in Pt-100 termometrom v hladilnem stolpu jedrske elektrarne Doel - Belgija*

Fig. 1. *Mobile unit with a vane anemometer and a Pt-100 thermometer inside the Doel nuclear powerplant cooling tower (Belgium)*

zračnega toka po celotni površini hladilnega stolpa v poljubni točki nad izločevalniki kapljic.

Premična enota se giblje po površini izločevalnikov kapljic (sl. 2 (1)). Zaznavala so nameščena na premično enoto v skladu z zahtevami standarda DIN 1947 [7]. Na premično enoto sta nameščena krilni anemometer, prirejen za delovanje v okolju nasičene vlažnosti ter Pt-100 temperaturno zaznavalo. Premična enota izvaja meritve obeh parametrov med vožnjo.

Zunanji del (sl. 2 (8)) sestavljajo: računalnik, ki vsebuje strojno opremo za povezavo z računalnikom premične enote (sl. 2 (7)) in programska oprema za obdelavo dobljenih podatkov. Lega premične enote se določa z merjenjem radialne razdalje in kota od referenčne točke v merni ravnini (sl. 2 (2)).

Hkrati z izvedbo zgoraj opisanih meritev se izvajajo meritve celostnih parametrov po standardu DIN 1947 [7]. : vstopna in izstopna temperatura hladilne vode (sl. 2 (4) in (5)), pretok hladilne vode, parametri okolice (sl. 2 (6)) in izstopna moč termoenergetskega sistema.

Z uporabo merjenih hitrostnih in temperaturnih polj v merni ravnini hladilnega stolpa

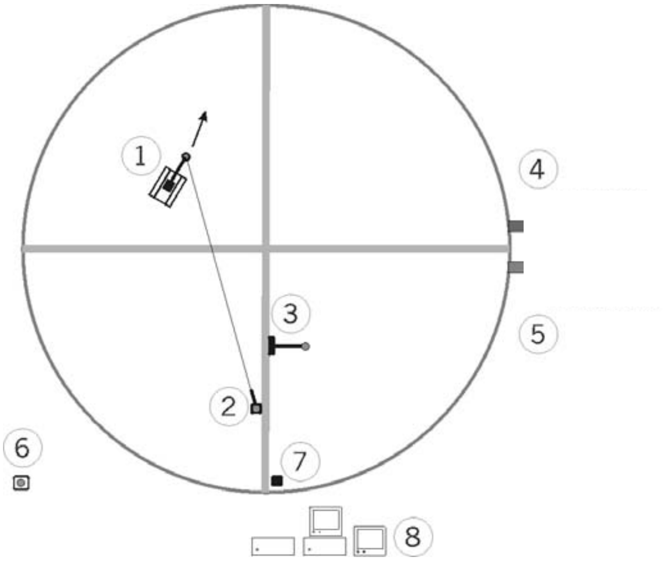
urements over the entire cooling tower area at an arbitrary measurement point above the droplet eliminators.

The mobile unit (Fig. 2 (1)) moves gradually over the entire measuring plane – the droplet eliminator surface. A vane-anemometer, designed to operate in 100% humidity, and Pt-100 thermometer sensor are mounted on the mobile unit according to the standard DIN 1947 [7]. The mobile unit measures both quantities simultaneously during its movement.

The external part of the equipment (Fig.2 (8)) comprises a PC with the appropriate hardware for the communications with the computer, mounted on the mobile unit (Fig. 2 (7)), and the software for processing the acquired data. The position of the mobile unit is determined by measuring the radial distance and the angle from a reference point in the measurement plane (Fig. 2 (2)).

Simultaneously, measurements of the integral parameters are carried out according to the DIN 1947 standard [14]: the inlet and outlet temperatures of the cooling water (Fig. 2 (4) and (5)), the cooling-water mass flow, the parameters of the surroundings (Fig. 2 (6)) and the output power of the thermo-energetic system.

The results of the velocity and temperature fields' measurements in the measurement plane of



Sl. 2. *Shema elementov meritev: (1) premična enota, (2) enota za merjenje položaja, (3) položaj merilnikov referenčnih meritev, (4) meritve temperature vstopne vode, (5) meritve temperature izstopne vode, (6) meritve parametrov okolice, (7) sistem za povezavo, (8) nadzorna meritev, obdelava podatkov in shranjevanje*

Fig. 2. *Schematic view of the measurement elements: (1) mobile unit, (2) position-measurement unit, (3) position of the measurement equipment for reference measurements, (4) inlet-water temperature measurement, (5) outlet-water temperature measurement, (6) measurement of surroundings parameters, (7) communication system, (8) measurement control, data processing and saving*

dobimo trirazsežne topološke porazdelitve hitrosti in temperature izstopajočega vlažnega zraka nad izločevalniki pri znanih celostnih parametrih elektrarne. Rezultati so osnova za določitev učinkovitosti prenosa toplote iz hladilne vode na okolišni zrak.

Merilna negotovost merjenja temperature na premični enoti je znašala 1,5 odstotka, merilna negotovost anemometra pa 2 odstotka. Za merjenje lege premične enote pa je bila ključnega pomena merilna negotovost koračnega merilnika kota, ki je znašala 0,5^{o} in je pri večjih oddaljenostih premične enote od izhodiščne točke značilno vplivala na določitev lege premične enote.

Podrobnosti o merilni opremi, njeni kalibraciji in merilnem sistemu so opisane v [8]. Pretok hladilne vode je bil merjen z ultrazvočnim merilnikom. Vlažnost in temperaturo okolišnega zraka smo merili v bilžini hladilnega stolpa.

Ker se obratovalni režim elektrarne med meritvami spreminja, smo hitrost in temperaturo zraka merili tudi v stalni točki. Te meritve so bila skupaj s celostnimi parametri, namenjene za popravo meritev na krajevni ravni.

Sliki 3 in 4 prikazujeta rezultate meritev hitrosti in temperature vlažnega zraka. Iz diagramov lahko razberemo očitno nehomogenost hitrostnega in temperaturnega polja, kar kaže na to, da prenesena toplota po prerezu hladilnega stolpa ni nespremenljiva. Neenakomeren prenos toplote in snovi vodi k manjši učinkovitosti hladilnega stolpa in slabšemu izkoristku celotnega postrojenja [9].

Iz rezultatov meritev lahko sklepamo, da je ugodna rešitev težav prerazporeditev toplotnega toka v hladilnem stolpu. Povečana hitrost pretakanja hladilnega zraka na obodu stolpa (zunanje področje kolobarja s prekinjeno črto na sliki 3) in razmeroma nizka temperatura zračnega toka (zunanje področje kolobarja s prekinjeno črto na sliki 4) navaja na potrebo po povečani količini polnil odnosno na povišano plast polnil, ter hkrati povečanje dotoka vstopne hladilne vode v to področje. Nasprotno bi bilo treba dotok vstopne hladilne vode v osrednjem delu stolpa (notranje področje omejeno s sklenjeno neprekinjeno krivuljo s slik 3 in 4) sorazmerno zmanjšati ob hkratnemu zmanjšanju aerodinamičnega upora strujanja skozi osrednji del stolpa. Navedeni predlogi so v nadaljevanju prispevka ocenjeni z numeričnim modeliranjem, ki vključuje predstavljene

the cooling tower provide essential data for obtaining 3D topological structures of the velocity and temperature distribution of the moist air above the droplet eliminators at known integral parameters of the powerplant. These results represent the basis for a determination of the heat-transfer efficiency between the cooling water and the surrounding air.

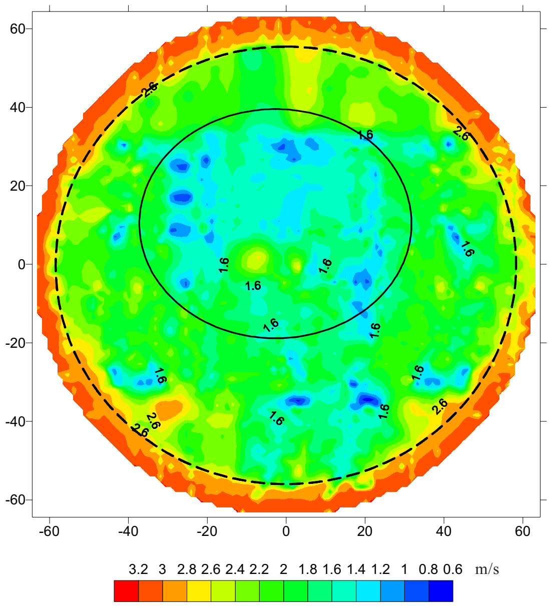
The measurement uncertainty for the temperature measurements on the mobile unit was in the range of 1.5%, whereas the uncertainty of the anemometer amounted to 2%. The measurement uncertainty of the increment-angle measurement system was crucial for the measurement of the mobile unit's position. Its value was 0.5^{o}, and it significantly influenced the determination of the mobile unit's position at greater distances from the origin point.

The details of the equipment, its calibration and the measurement system operation are described in [8]. The cooling-water flow rate was measured with an ultrasonic flowmeter. The air humidity and the air temperature were measured in the vicinity of the cooling tower.

The power plant's operating properties change during the measurements. For this reason the air velocity and the temperature at a stationary point were measured. The stationary data, together with the integral parameters and the power plant's operating data, serve as correction elements for the measurements on the local level.

Figs. 3 and 4 show the results of the moist-air velocity and temperature measurements. From the diagrams in Figs. 3 and 4 the non-uniform velocity and temperature field is obvious, which suggests that the transferred heat over the area of the cooling tower is not uniform. The non-uniform field of the heat-flux density indicates that the cooling tower does not operate equally well over the entire area. The non-uniformity of the heat and mass transfer leads to a lower efficiency of the cooling tower and thus to a lower efficiency of the entire powerplant [9].

It can be concluded from the measurement results that the problem of the mentioned non-uniformity could be solved by rearranging the heat flux inside the cooling tower. Higher cooling-air velocities at the cooling tower's peripheral region (i.e., the region radially outwards of the dashed curve in Fig. 3) and the relatively low temperatures of the airflow (i.e., the region radially outwards of the dashed curve in Fig. 4) address the need to increase the fill height and to increase simultaneously the amount of the inlet mass flow of the cooling water in this specific region. The other solution is to decrease the amount of cooling water in the central region of the cooling tower (i.e., the region radially inwards of the solid closed curve in Figs. 3 and 4) as well as to simultaneously decrease the aerodinamic drag in this central region. These suggestions are assessed later on by izmerjene vrednosti na slikah 3 in 4 kot dejanske robne pogoje v numerično shemo. V primeru drugih krajevnih anomalij, ki se kažejo kot naključne - krajevne nehomogenosti temperaturnega in hitrostnega polja na slikah 3 in 4, bi le-te morali odpraviti s krajevnim pregledom posameznih področij, npr. z uporabo pred kratkim razvite termovizijske metode za hitro odkrivanje anomalij [10], in ugotovitvijo dejanskih vzrokov, kakor so polomljeni razpršilniki kapljic, netesnosti razvodnih kanalov, zamašenih pretočnih kanalov polnil in izločevalnikov kapljic.



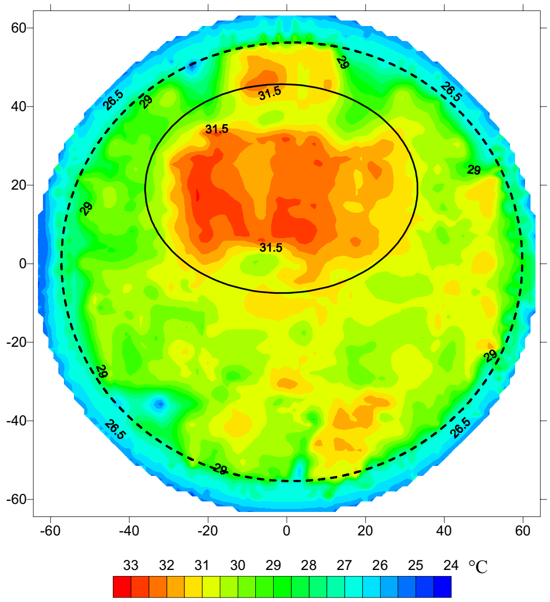
Sl. 3. *Hitrostno polje zraka nad izločevalniki kapljic*

Fig. 3. *Airflow velocity field above the droplet eliminators*

4 NUMERIČNA ANALIZA

Predstavljen je numerični model aero- in termodinamičnih značilnosti toka zraka v hladilnem stolpu. V model smo vključili vrednosti količnikov izgub v polnilih in gostoto toplotnega toka na krajevni ravni. Z analizo rezultatov numerične simulacije smo prišli do nekaterih sklepov o vplivu spremembe višine polnil in porazdelitve vode po prerezu stolpa. Numerična analiza tokovnih razmer v hladilnem stolpu je bila narejena s paketom za računalniško dinamiko tekočin CFX-5.6, ki uporablja numerične metode za reševanje Reynoldsovo povprečenih enačb ohranitve mase (enačba 6),

the numerical modelling, which introduces the presented measured values in Figs. 3 and 4 as real boundary conditions into the numerical scheme. The other local anomalies, which act as coincidental local inhomogeneities of the velocity and temperature fields in Figs. 3 and 4, should be suppressed through local inspections of particular regions, e.g., by applying the recently developed thermovision method for the rapid detection of anomalies [10], and through a determination of the actual causes, such as broken spray nozzles, leakages in dividing channels, clogged fill and droplet-eliminator passages.



Sl. 4. *Temperaturno polje zraka nad izločevalniki kapljic*

Fig. 4. *Airflow temperature field above the droplet eliminators*

4 NUMERICAL ANALYSIS

A numerical model of the thermo- and aero-dynamic characteristics of the air flow in a cooling tower is presented. Real fill-loss coefficients and heat-flux densities in the particular segments of the cooling tower are included in the numerical model. An analysis of the numerical results led to certain conclusions about the influence of the fill-height alterations and the distribution of water across the cooling tower's transverse section. A numerical analysis of the flow properties in the cooling tower was performed using the CFD software package CFX-5.6. Its solver uses numerical methods for solving the Reynolds Averaged equations, includmomenta (enačba 7) in energije (enačba 8) [11]. Vse simulacije so bile opravljene v časovno neodvisnem stanju, kar pomeni, da nismo upoštevali odvodov spremenljivk po času.

ing continuity (Eq. 6), momentum (Eq. 7), and energy (Eq. 8) equations, [11]. All the simulations were performed for steady-state cases only, so the terms with time derivatives can be omitted.

$$\frac{\partial\left(\rho\bar{u}_j\right)}{x_j}=0 \tag{6),}$$

$$\frac{\partial\left(\rho\bar{u}_j\bar{u}_i\right)}{\partial x_j}=-\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial\bar{u}_i}{\partial x_j}+\frac{\partial\bar{u}_j}{\partial x_i}\right)-\rho\overline{u_i'u_j'}\right]+S_M \tag{7),}$$

$$\frac{\partial\left(\rho\bar{u}_jc_pT\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\lambda\frac{\partial T}{\partial x_j}\right)+S_E \tag{8).}$$

Zaprtje sistema enačb je poenostavljeno na določitev turbulentne viskoznosti [12]:

The closure of the set of equations is simplified to the determination of the turbulent viscosity [12]:

$$\mu_t=C_\mu\rho\frac{k^2}{\varepsilon} \tag{9}$$

ki je podana z enačbami turbulentnega modela. V danem primeru smo uporabili standardni turbulentni model k-ε [11]:

This is determined by the introduction of equations of the turbulence model. For the present case a two-equation standard k-ε turbulence model was applied [11]:

$$\bar{u}_i\frac{\partial\left(\rho k\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial x_j}\right]+P_k-\rho\varepsilon \tag{10),}$$

$$\bar{u}_i\frac{\partial\left(\rho\varepsilon\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right]+\frac{\varepsilon}{k}\left(C_{1\varepsilon}P_k-C_{2\varepsilon}\rho\varepsilon\right) \tag{11).}$$

Dejanska viskoznost μ_{eff} je vsota stvarne in turbulentne viskoznosti, $\mu+\mu_t$; P_k je hitrost nastajanja turbulentne kinetične energije, ki nastane zaradi turbulence [11].

The effective viscosity μ_{eff} is the sum of the real and turbulent viscosities, $\mu+\mu_t$; P_k is the production rate of the turbulent kinetic energy as a result of turbulence [11].

Člen S_M v enačbi 7 pomeni vir oziroma ponor gibalne količine v nadzorni prostornini. S tem členom smo popisali padec tlaka v območjih polnil in prh, ki ju tu obravnavamo kot porozno plast, ta pomeni določen upor za tok zraka skozi hladilni stolp. Padec statičnega tlaka lahko izračunamo iz enačbe (5). Za sistem polnil znane višine L izračunamo izkustveni količnik izgub po enačbi [11]:

The term S_M in Eq. 7 represents the momentum source/loss in a control volume. This term was used to simulate the pressure loss within the fill and rain region. The fill and rain region could be regarded as a porous layer, which offers certain resistance to the airflow through the cooling tower. The resulting static pressure drop can be calculated using Eq. 5. For a fill system of known height L the empirical loss coefficient is calculated according to the following equation [11]:

$$k_{loss}=\frac{2\Delta p}{\rho v^2L} \tag{12).}$$

Padec tlaka smo modelirali z uporabo izvirnega člena $S_{M,i}$ v momentni enačbi (7) za vsako od treh koordinatnih osi:

The pressure loss was modelled by using an additional source term in the momentum Eq. 7 for each of the three coordinate axes, in the form of:

$$S_{M,i}=-C_{R2}\left|u_j\right|u_j \tag{13}$$

C_{R2} je količnik kvadratičnega upora in je za porozno snov podan z:

where C_{R2} denotes the quadratic resistance coefficient and is expressed for porous media as:

$$C_{R2}=k_{loss}\rho \tag{14).}$$

Upoštevali smo vpliva težnosti in konvekcije, ki igrata pri toku zraka skozi hladilni

The influences of gravitation and convection, both of which play an important role regarding the air-stolp pomembno vlogo. V enačbi (7) upoštevamo vzgonske sile z uporabo izvirnega člena, ki je podan z [11]:

$$S_{M,buoy} = \rho\beta(T - T_{ref})g \qquad (15).$$

Izvirni člen $S_{M,buoy}$ v momentni enačbi je odvisen od toplotne razteznosti tekočine in krajevne temperaturne razlike glede na vzgon pri referenčni temperaturi.

Člen S_E v enačbi (8) pomen izvir/ponor energije v nadzorni prostornini. Z njim smo popisali toplotni tok z vode na zrak v območjih polnil in prhe. Izvirni člen se spreminja glede na mesto v hladilnem stolpu in je izračunan iz gostote toplotnega toka (enačba 4). Za območji polnil in prhe znane višine *L* je vir energije *WATT* izračunan z:

$$WATT = \frac{\dot{q}}{L} \qquad (16).$$

Vir energije v enačbi (8) lahko zapišemo z:

$$S_E = WATT \qquad (17).$$

5 ROBNI POGOJI

Računsko območje smo diskretizirali s tremi različno gostimi mrežami. Na podlagi analize rezultatov (opazovali smo hitrostno polje zraka nad izločevalniki kapljic) smo se odločili, da območje diskretiziramo z nestrukturirano mrežo z 1 017 000 elementi, ki je v območju polnil zgoščena. Obravnavali smo tudi okolico v bližini vstopa in izstopa iz hladilnega stolpa. Diskretizacijsko napako smo ocenili na manj ko 0,8 odstotka. Ker je bila simulacija narejena za primer enofaznega suhega zraka, so bile vrednosti količine toplote, ki jo prejme vlažen zrak v hladilnem stolpu izračunane za tok suhega zraka. Simulirali smo tri primere zračnega toka skozi hladilni stolp. V vseh primerih smo definirali naslednje robne pogoje:

- Vstop v domeno smo definirali kot robni pogoj "vhod", s tlakom okolice 100 kPa, temperaturo 282,6 K in masnim tokom zraka 29 700 kg/s.
- Na izstopu iz območja smo uporabili robni pogoj "odprtine". Glede na tlak okolice na vstopu v stolp je relativni tlak znašal 0 Pa.
- Stene stolpa so bile obravnavane kot hidravlično gladke.

flow through the cooling tower, were taken into account as well. The buoyancy forces in Eq. (7) are expressed via the source term, which can be calculated as [11]:

The source term $S_{M,buoy}$ in the momentum equation is a function of the thermal expansivity of the fluid as well as of the local temperature difference with regard to the buoyancy at the reference temperature.

The term S_E in Eq. (8) represents the energy source/loss in a control volume. This term was used to simulate the heat flux from the water to the air within the fill and rain region. The value of the source term changes over the transverse section of the cooling tower and is calculated from the heat-flux density (Eq. 4). For fill and rain regions of known height *L* the energy source *WATT* is calculated according to the following equation:

The energy source in Eq. (8) can be written as:

5 BOUNDARY CONDITIONS

The calculation domain was discretized with three meshes of different density. According to the results of the analysis (the velocity field of the air above the droplet eliminators) a decision was made to discretize the domain of the calculation with an unstructured mesh of 1,017,000 elements, which was refined in the region of the fill system. At the cooling tower's inlet and outlet the surrounding was also modelled. The discretization error was assessed to be less than 0.8%. The simulation was executed for the case of single-phase dry air. Therefore, the amount of heat, which is received by the humid air inside the cooling tower, was calculated for the dry air. Three different cases of airflow through a cooling tower were calculated. In all cases the following boundary conditions were defined:

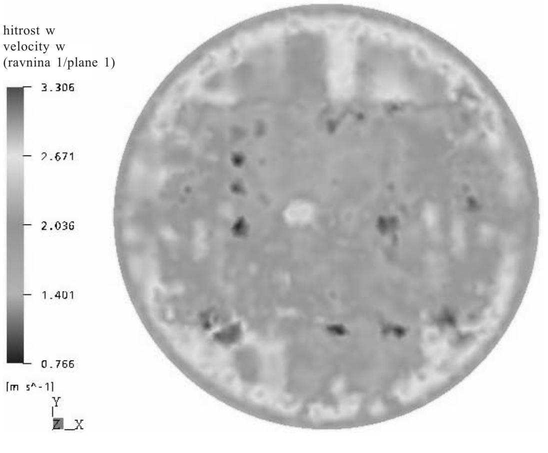
- The air inlet was modelled in the vicinity of the tower and was an "inlet" boundary condition, the ambient pressure was 100 kPa, the temperature was 282.6 K and the mass flow of the air was set at 29 700 kg/s.
- The air outlet was also modelled in the vicinity of the tower and was an "opening" boundary condition. According to the atmospheric pres-

- Zračni tok je bil turbulenten. Uporabili smo turbulentni model k-ε.
- Upoštevali smo naravno konvekcijo.
- Raven konvergence ostankov RMS je znašal 10^{-4}.
- Višina polnil je bila 2 m.
- Vrednost količnika izgub k_{loss} je po prerezu stolpa variirala med 4.8 in 151. Vrednosti smo dobili z meritvami.
- Izmerjene in uporabljene vrednosti *WATT* so se po prerezu stolpa gibale med 1 290 in 32 930.

Konvergenco smo določili na podlagi opazovanja različnih parametrov toka (hitrost zraka nad izločevalniki kapljic in temperatura nad izločevalniki kapljic). Parametra sta vedno konvergirala, ko je vsota razlik med iteracijami prenosnih enačb dosegla vrednost (ostanki spremenljivk: tlak, hitrost, turbulentna kinetična energija in hitrost raztrosa turbulentne kinetične energije) pod 10^{-3} (ko so se ostanki zmanjšali za tri velikostne rede). Preizkusili smo več kriterijev za konvergenco na koncu pa smo za rešitev vzeli stanje, ko je vsota ostankov padla pod 10^{-4}. Za skonvergirano rešitev je bilo potrebnih približno 350 iteracij. Iteracijsko napako smo ocenili na manj ko 0,08 odstotka [13].

6 REZULTATI NUMERIČNE SIMULACIJE

Najprej smo izvedli simulacijo v dejanskih razmerah. Vrednosti količnika izgub in prenesene toplote smo dobili iz rezultatov meritev. Sliki 5 in 6



Sl. 5. *Numerična napoved hitrostnega polja zraka nad izločevalniki kapljic*
Fig. 5. *Numerically obtained air-velocity field above the droplet eliminators*

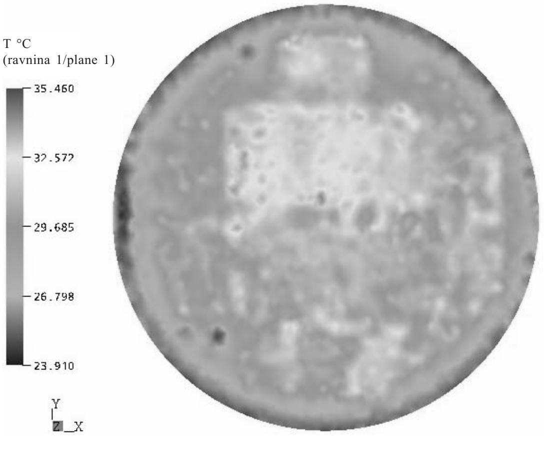
sure at the tower inlet, at the outlet the relative pressure was set to 0 Pa.

- The walls of the tower were considered as smooth.
- the airflow was considered as turbulent, the k-ε model was used to model the turbulent flow.
- The natural convection was considered.
- The level of convergence for the RMS residual was 10^{-4}.
- The fill system height was 2 m.
- The values of the loss coefficient k_{loss} changed over the area of the cooling tower and varied between 4.8 and 151. These values were obtained experimentally.
- The experimentally obtained values of *WATT* changed over the area of the tower and varied between 11290 and 32930.

The convergence was determined by observing different flow parameters (the air velocity and the temperature above the droplet eliminators). These parameters always converged in the case where the sum of the differences between the iterations of the transport equations (residua of p, v, k and Σ) amounted less than 10^{-3}, i.e., the residua dropped by three orders of magnitude. Several convergence criteria were tested. The chosen solution was the state where the sum of the residua dropped below 10^{-4}. For such a converged solution, approximately 350 iterations were needed. The iteration error was assessed to be less than 0.08% [13].

6 RESULTS OF THE NUMERICAL SIMULATION

In the first case the real conditions in the cooling tower were simulated. The values of the loss coefficient and the transferred heat were obtained



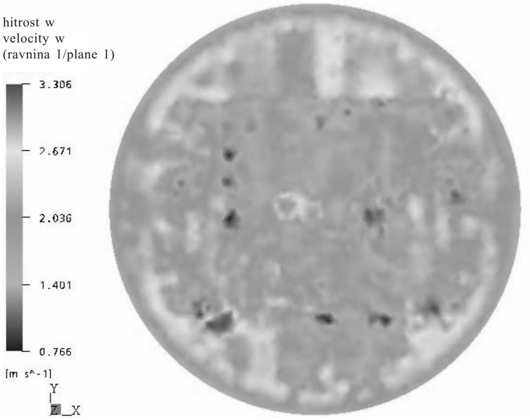
Sl. 6. *Numerična napoved temperaturnega polja zraka nad izločevalniki kapljic*
Fig. 6. *Numerically obtained air-temperature field above the droplet eliminators*

prikazujeta numerične napovedi stanja v hladilnem stolpu v sedanjih razmerah.

Napovedani hitrostno in temperaturno polje zraka nad izločevalniki kapljic (sl. 5 in 6) se nekoliko razlikujeta od rezultatov meritev (sl. 3 in 4), kar lahko razlagamo z numeričnimi napakami (napako konvergence, napako diskretizacije in napako modela), pa tudi kot posledico uporabljene merilne metode, saj meritve niso potekale zvezno po prostoru, pač pa v diskretnih merilnih točkah. Kljub temu pa so jasno vidna območja velikih hitrosti in nizkih temperatur na obodu stolpa. Nasprotni pojav (majhne hitrosti in visoke temperature) simulacija pravilno napove v srednjem zgornjem delu stolpa (sl. 5 in6). Glede na te rezultate smo v drugi simulaciji spremenili količnike izgub v srednjem delu in ob obodu stolpa. Da bi dobili večji toplotni tok na obodu stolpa, smo višino polnil povečali za 0,5 m. Količnik izgub v polnilih k_{fi} se spreminja linearno z višino polnil [8], torej se za naš primer poveča za 25 odstotkov. Med meritvami smo ugotovili, da so izločevalniki kapljic v zgornjem srednjem delu hladilnega stolpa poškodovani, kar povzroča povečan upor zraka. Ocenili smo, da bi se zračni upor z zamenjavo poškodovanih izločevalnikov zmanjšal za 10 %. Da bi dobili še

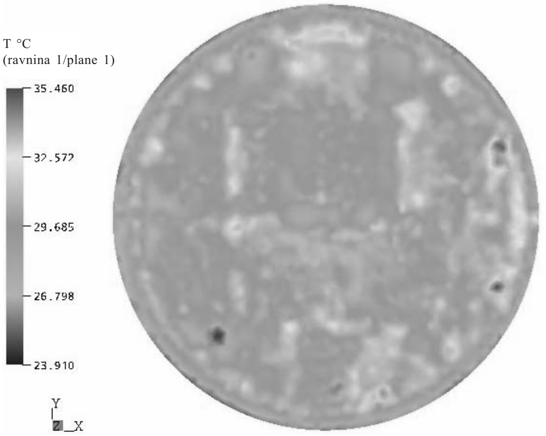
from the experimental data. Figs. 5 and 6 depict the numerical prediction of a state inside the cooling tower for particular conditions.

The air velocity and the temperature fields above the droplet eliminators obtained with the numerical simulation (Figs. 5 and 6) differ slightly from the experimental results (Figs. 3 and 4). The difference is due to numerical errors (convergence error, discretization error and model error), but is a consequence of the measurement method as well, because the measurements were carried out at discrete measurement points rather than being continuous. However, the regions of high velocities and low temperatures of air at the cooling tower's circumference can be perceived. The opposite phenomenon (lower velocities, higher temperatures of air) was correctly predicted by the numerical simulation in the upper central part of the cooling tower (Figs. 5 and 6). After considering these effects in the second study case the loss coefficients at the circumference and in the upper central part of the cooling tower were changed. The fill height was increased for 0.5 m in order to achieve a greater heat flux at the cooling tower's circumference. The fill system loss coefficient, k_{fi}, changes linearly with the fill height [8], so would in this case increase by 25 %. In the upper central part of the cooling tower the droplet eliminators are damaged, which results in an increased air resistance. The air resistance was estimated to decrease by 10 % when re-



Sl. 7. *Hitrostno polje zraka nad izločevalniki kapljic po spremembah (višina polnil na obodu je povečana, poškodovani izločevalniki so zamenjani, spremenjen je zračni upor in vrednost izvirnega člena energije)*

Fig. 7. *Air-velocity field above the droplet eliminators if the fill height is increased, the eliminators are replaced and the air resistance and energy sources are changed*



Sl. 8. *Temperaturno polje zraka nad izločevalniki kapljic po spremembah (višina polnil na obodu je povečana, poškodovani izločevalniki so zamenjani, spremenjen je zračni upor in vrednost izvirnega člena energije)*

Fig. 8. *Air-temperature field above the droplet eliminators if the fill height is increased, the eliminators are replaced and the air resistance and energy sources are changed*

bolj homogeno temperaturno polje, ki je posledica učinkovitejšega prenosa toplote in snovi, smo predlagali spremembo porazdelitve vode, kar se v numerični simulaciji kaže s spremembo vrednosti izvirnega člena energije, definiranega s stalnico *WATT*. V zgornjem srednjem delu stolpa smo vrednosti izvirnega člena zmanjšali, sorazmerno s tem pa povečali vrednosti izvirnega člena na obodu stolpa. Napovedani hitrostni in temperaturni polji zraka za popravljeno stanje sta prikazani na slikah 7 in 8.

Sliki 7 in 8 prikazujeta homogenejše temperaturno in hitrostno polje od tistih, prikazanih na slikah 5 in 6. Rezultat je torej učinkovitejše delovanje hladilnega stolpa, kar mora potrditi tudi celostna analiza numeričnega modela.

Z uporabo enačbe 4 za suh zrak lahko določimo povprečno gostoto toplotnega toka skozi celotni prerez hladilnega stolpa. Primerjava gostote toplotnih tokov pred uvedbo in po uvedbi sprememb kaže na povečanje gostote toka za 2,5 odstotka. Pričakujemo lahko, da se bo za enako vrednost povečala tudi učinkovitost hladilnega stolpa.

7 SKLEPI

V prispevku je bila predstavljena eksperimentalna metoda določanja krajevnih anomalij in numerična analiza izboljšav aero- in termodinamičnih lastnosti v hladilnem stolpu na naravni vlek elektrarne Doel-3. Za opis enofaznega trirazsežnega turbulentnega toka zraka skozi hladilni stolp smo uporabili računsko dinamiko tekočin (CFD) numerično simulacijo. V simulacijo so bili, z izvirnimi členi v momentni in energijski enačbi, vključeni rezultati meritev hitrosti in temperature zraka nad izločevalniki kapljic.

Opazili smo krajevne nepravilnosti hitrosti in temperatur zraka nad izločevalniki kapljic. Predlagani so bili nekateri ukrepi, ki bi vodili k bolj homogenemu temperaturnemu polju zraka nad izločevalniki kapljic. Preizkus predlaganih sprememb smo opravili s pomočjo numerične simulacije. Predlagane spremembe so sprememba porazdelitve hladilne vode, dodajanje polnil na obodu stolpa in sprememba značilke upora polnil. Rezultati kažejo na bolj homogeno hitrostno in temperaturno polje zraka nad izločevalniki kapljic,

placing the damaged droplet eliminators. To achieve an even more uniform temperature field, which is the consequence of the more efficient heat and mass transfer, a rearrangement of water distribution was proposed as well. Such a rearrangement influences the value of the energy source term (constant *WATT*) in the numerical simulation. In the upper central part of the tower the local temperatures are higher, so the energy sources were decreased in this area. Accordingly, the energy sources at the circumference of the tower were proportionally increased. The results of the proposed changes are shown in Figs. 7 and 8.

Figs. 7 and 8 show the temperature and velocity fields, which are more homogeneous when compared to those depicted in Figs. 5 and 6. Such a homogeneity results in the increased efficiency of the cooling tower's operation, which should in turn be confirmed by the integral analysis of the numerical model.

Using Eq. 4 for dry air the average heat-flux density through the cooling tower's transverse section can be established. According to the numerical results, the comparison of the heat-flux density before and after the reconstruction shows that after reconstruction the heat-flux density increased by 2.5 %. It is to be expected that the cooling tower's efficiency would increase by the same amount as well.

7 CONCLUSIONS

The experimental method for determining local anomalies and the numerical analysis of the improvement of the aero- and thermodynamic characteristics in a natural-draft cooling tower of the Doel-3 powerplant is presented. A computational fluid dynamics (CFD) numerical simulation was used to model the single-phase 3D turbulent air flow through the cooling tower. The experimental data of the local values of the air velocities and temperatures above the drift eliminators were introduced into the numerical simulation through source terms in the momentum and energy equations.

The local irregularities in the air-velocity and temperature fields above the droplet eliminators were detected. Certain technical measures were suggested in order to achieve a more uniform air-temperature field above the droplet eliminators. The influence of the suggested changes on the homogeneity of the air-temperature field was tested using a numerical simulation. The suggested changes comprised the rearrangement of the water distribution, the addition of fills at the cooling tower's circumference and the changing of the fill resistance's characteristics. The results show more uniform air-velocity and kar se kaže na večji učinkovitosti hladilnega stolpa.

Predstavljeni eksperimentalni in numerični postopki so splošni in jih lahko uporabimo na poljubnih že znanih stolpih kot mogoče metodo odkritja in napovedovanja popravnih ukrepov s ciljem doseganja večje učinkovitosti stolpov in termoenergetskih postrojenj.

temperature fields above the droplet eliminators, which results in a better cooling-tower efficiency.

The presented experimental and numerical procedures are universally applicable and can be applied to any cooling tower as a possible method of detecting and predicting correction measures in order to increase the efficiency of cooling towers and thermoenergetic systems.

8 SIMBOLI
8 NOMENCLATURE

specifična toplota pri nespremenljivem tlaku	c_p	J/kg K	specific heat at constant pressure
kvadratični koeficient upora	C_{R2}	$\mathrm{kg/m^4}$	quadratic resistance coefficient
stalnica turbulentnega modela k-ε, 1,44	$C_{\varepsilon 1}$		k-ε turbulence model constant, 1.44
stalnica turbulentnega modela k-ε, 1,92	$C_{\varepsilon 2}$		k-ε turbulence model constant, 1.92
stalnica turbulentnega modela k-ε, 0,09	C_μ		k-ε turbulence model constant, 0.09
težnostni pospešek	g	$\mathrm{m/s^2}$	gravitational acceleration
entalpija vlažnega zraka	h_a	J/kg	enthalpy of humid air
turbulentna kinetična energija na enoto mase	k	$\mathrm{m/s^2}$	turbulence kinetic energy per unit mass
količnik izgub sistema polnil	k_{fi}	/	fill-system loss coefficient
empirični količnik izgub	k_{loss}	$\mathrm{m^{-1}}$	empirical loss coefficient
višina polnil	L	m	fill height
masni tok	$\dot{m}$	$\mathrm{kg/m^3}$	mass-flow rate
statični tlak	p	Pa	static pressure
nastanek turbulence	P_k	$\mathrm{kg/m\ s^3}$	shear production of turbulence
gostota toplotnega toka	$\dot{q}$	$\mathrm{W/m^2}$	heat-flux density
toplotni tok	$\dot{Q}$	W	heat flux
latentna toplota	r	J/kg	latent heat
pretočna površina	S	$\mathrm{m^2}$	flux area
vir energije	S_E	$\mathrm{kg/m\ s^3}$	energy source
vir momenta	S_M	$\mathrm{kg/m^2\ s^2}$	momentum source
čas	t	s	time
temperatura	T	°C	temperature
hitrost	u	m/s	velocity
prostorninski tok	$\dot{V}$	$\mathrm{m^3/s}$	volume flow rate
hitrost	v	m/s	velocity
razmerje vlažnosti	x	kg/kg	humidity ratio
toplotna razteznost	β	$\mathrm{K^{-1}}$	thermal expansivity
raztrosna hitrost turbulence	ε	$\mathrm{m/s^3}$	turbulence dissipation rate
toplotna prevodnost	λ	$\mathrm{kg\ m/s^3\ K}$	thermal conductivity
molekularna viskoznost	μ	kg/m s	molecular viscosity
turbulentna viskoznost	μ_t	kg/m s	turbulent viscosity
dejanska viskoznost	μ_{eff}	kg/m s	effective viscosity
gostota tekočine	ρ	$\mathrm{kg/m^3}$	fluid density
stalnica turbulentnega modela k-ε, 1,0	σ_k		k-ε turbulence model constant, 1.0
stalnica turbulentnega modela k-ε, 1,3	σ_ε		k-ε turbulence model constant, 1.3
Indeksi			**Subscripts**
vlažen zrak	a		humid air
vzgon	$buoy$		buoyancy

suh zrak	*da*	dry air
sistem polnil	*fi*	fill system
koordinatna os	*i*	coordinate axes
primerjalna vrednost	*ref*	reference
vodna para	*v*	water vapour
voda	*w*	water

9 LITERATURA
9 REFERENCES

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