© Strojniški vestnik 45(1999)2, 75-84 © Journal of Mechanical Engineering 45(1999)2, 75-84
ISSN 0039-2480 ISSN 0039-2480
UDK 621.18:662.614:536.5 UDC 621.18:662.614:536.5
Strokovni članek (1.04) Speciality paper (1.04)

Vpliv netesnosti kotlovskih naprav na njihovo učinkovitost

The Influence of Air Leakage on the Efficiency of Boilers

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Izkoristek pretvorbe toplote v mehansko delo je zelo pomemben parameter toplotnih strojev, zato moramo skrbeti, da se tudi primarno spreminjanje notranje energije goriva v toploto izvede s čim boljšim izkoristkom. Pri parnih kotlih se s predgrevanjem zgorevalnega zraka v grelnikih zraka del izstopajoče nizkotemperaturne toplote dimnih plinov ponovno vrača v zgorevalni proces, s čimer se zveča izkoristek kotla. Grelniki zraka so pri večjih postrojenjih običajno Ljungströmovi rotacijski regeneratorji, katerih značilnost je določena netesnost in mešanje tokov zraka in dimnih plinov. Prispevek se ukvarja z vplivom netesnosti grelnika zraka in vplivom količine zgorevalnega zraka, ki se segreva v grelniku zraka, na izkoristek kotlovskega postrojenja. Raziskane so značilne vrste netesnosti na grelniku zraka in na samem kotlu. Teoretična razlaga je podprta z rezultati meritev na termoelektrarniških grelnikih zraka.

(Ključne besede: kotli parni, grelniki zraka, netesnost, meritve)

The coefficient of efficiency of the conversion of heat into mechanical work is a very important parameter for heat engines. We must therefore ensure that the primary conversion of the fuel's internal energy into heat is performed at the highest possible efficiency. In steam boilers, part of the low-temperature output heat of flue gases is returned into the combustion process when used for preheating the combustion air in air heaters, thereby increasing the boiler's efficiency. The air heaters used for large plants are usually Ljungström rotary regenerators, which are characterised by a certain degree of leakage and mixing of air flows and flue gases. This paper deals with the influence of leakage in an air heater and the influence of the amount of combustion air heated in an air heater on the coefficient of efficiency of a boiler plant. Characteristic types of leakage in an air heater and in a boiler itself are studied. The theoretical explanation is supported with the results of measurements on air heaters in a thermal power plant.

(Keywords: steam boilers, airheaters, leakage, measurements)

1 PREDSTAVITEV

V energetskih postrojenjih je pomembno, da notranjo energijo goriva s čim večjim izkoristkom spremenimo v druge oblike energije, torej v toploto in nato še v mehansko delo oziroma električno energijo. V parnih kotlih poteka primarno spreminjanje kemične notranje energije goriva v toploto in nato prenos toplote na delovno snov. Izkoristek kotla je merilo uspešnosti energijske spremembe toka goriva v toplotni tok delovne snovi. Največji del izgub parnega kotla pomeni toplota v izstopajočih dimnih plinih. Bistvena parametra, ki vplivata na velikost izgube toplote dimnih plinov, sta temperatura in količina dimnih plinov na izstopu iz kotla. Slednja je pri enakem masnem toku goriva odvisna od količine dovedenega zgorevalnega zraka, pri zniževanju katere pa smo omejeni zaradi pojava nepopolnega zgorevanja in s tem nastanka izgub z nezgorelim gorivom. Prav tako je tudi temperatura dimnih plinov na izstopu iz kotla navzdol omejena

1 PRESENTATION

In power plants it is important to convert the internal energy of fuel into other forms of energy, i.e. into heat and then mechanical work and electrical power, with the highest possible efficiency. In steam boilers, primary conversion of the internal chemical energy of fuel into heat takes place first, followed by transfer of heat to the working fluid. Boiler efficiency is a measure of the success of energy conversion of fuel flow into the heat flow of the working fluid. Heat output via flue gases represents the greatest share of loss in a steam boiler. The major parameters affecting the magnitude of flue gas heat loss are temperature and quantity of flue gases at the boiler outlet. At equal fuel mass flow, the latter depends on combustion air input quantity; if this is reduced, efficiency decreases due to incomplete combustion and heat loss resulting from uncombusted gas. The minimum temperature of the flue gas at the boiler outlet is limited (e.g. to 150 °C in coal flue (npr. na 150 °C pri premogovih dimnih plinih) zaradi možnosti pojava nizkotemperaturne korozije kotlovskega postrojenja in zaradi potrebnega vzgona dimnih plinov ob vstopu v ozračje. V kotlih z grelnikom vode je temperatura dimnih plinov na izstopu iz kotla odvisna od temperature v grelniku vode. Pri visokotlačnih postrojenjih, ki imajo regenerativno segrevanje napajalne vode, je temperatura vode, ki vstopa v kotel, lahko višja od 250 °C. Če tej temperaturi dodamo še potrebno temperaturno razliko za prehod toplote iz dimnih plinov, na primer 100 °C, dobimo temperaturo dimnih plinov za zadnjim grelnikom vode, ki je višja od 350 °C. Izstopna temperatura dimnih plinov bi bila v takem primeru za 200 °C višja, kakor to zahteva tehnološki minimum. Posledica takih temperatur so pretirano velike izgube s toploto dimnih plinov, npr. prek 20 % pri uporabi velenjskega lignita. Zmanjšamo jih z regenerativnim gretjem zraka, pri katerem se del toplote dimnih plinov prenaša na svež zgorevalni zrak in se tako vrača v proces zgorevanja. Pri večjih kotlih so grelniki zraka običajno rotacijski Ljungströmovi regeneratorji. Njihov glavni del je rotor, sestavljen iz paketov valovite pločevine, ki zaradi vrtenja prehajajo iz toka vročih dimnih plinov, od katerih sprejemajo toploto, v tok hladnega zraka, kateremu oddajajo shranjeno toploto. Bistvena posledica regenerativnega gretja zraka je zmanjševanje izgub s toploto dimnih plinov in s tem zvečanje izkoristka kotla. Višja temperatura zgorevalnega zraka pa poleg tega dviga srednjo razpoložljivo temperaturo dimnih plinov in s tem njihovo eksergijo. Žal pa večje eksergije dimnih plinov ne moremo neposredno izkoristiti, ker je temperaturni nivo sveže pare od 400 °C do 500 °C nižji od temperatur v kurišču. So pa zaradi višje srednje temperature dimnih plinov in višjih temperaturnih razlik med dimnimi plini in vodno paro ogrevalne površine v kotlu manjše.

V prispevku je teoretično predstavljen vpliv netesnosti kotla in regenerativnega grelnika zraka na uspešnost postopka regeneracije. Raziskan je tudi vpliv spremembe količine zraka, ki se segreva v grelniku zraka. Kot praktičen primer so prikazane spremembe delovnih razmer po večletnem obratovanju termoelektrarniških grelnikov zraka.

2 PRETOKI ENERGIJ SKOZI GRELNIK ZRAKA

V grelniku zraka dimnim plinom odvzamemo določeno količino toplote in jo vrnemo v proces zgorevanja. S tem zvečamo entalpijo dimnih plinov pri zgorevanju H_{th}, ki je določena z enačbo:

gases) due to the possibility of low-temperature corrosion of the boiler plant and the required buoyancy of flue gases on their entry into the atmosphere. In boilers with air heaters, the temperature of the flue gases at the boiler outlet depends on temperature in the economizer. In high-pressure plants with regenerative heating of feed water, the temperature of the water entering the boiler can exceed 250 °C. If the required temperature difference for heat transfer from flue gases, e.g. 100 °C, is added to this temperature, a flue gas temperature of more than 350 °C is obtained after the last water heater. The flue gas outlet temperature would in this case be 200 °C higher than required by the technological minimum. The result of such temperatures are excessively large losses of flue gas heat, e.g. over 20 % if Velenje lignite is used. These can be reduced using regenerative air heating, whereby part of the flue gas heat is transferred to fresh combustion air and is thus returned to the combustion process. In large boilers, the air heaters are usually rotary Ljungström regenerators. Their main part is a rotor composed of packets of corrugated sheet metal which due to the rotation pass from the flow of hot flue gases, from which they receive heat, into the flow of hot air, into which they emit stored heat. The most important result of regenerative air heating is a reduction of loss via flue gas heat and the resulting increase in boiler efficiency. In addition, the higher temperature of the combustion air also increases the mean available flue gas temperature and therefore their exergy. Unfortunately, the higher exergy of flue gases cannot be exploited directly because the temperature of the fresh steam is 400 °C to 500 °C lower than the temperature in the combustion chamber. However, due to the larger mean flue gas temperature and higher temperature differences between the flue gases and the steam, the heating surfaces in the boiler are smaller.

This paper presents a theoretical analysis of the influence of boiler leakage and regenerative air heaters on the success of the regeneration process. The influence of changes in the quantity of air heated in the air heater is also studied. Changes in operating conditions after several years of operation of air heaters in thermal power plants are presented as a practical example.

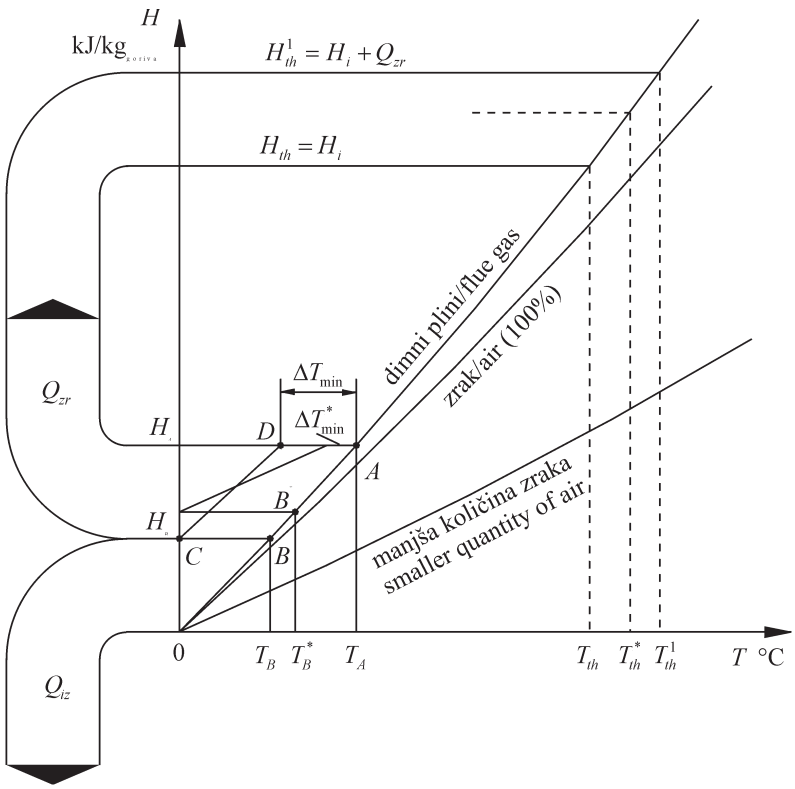
2 ENERGY FLOWS THROUGH THE AIR HEATER

In the air heater, a certain amount of heat is taken from the flue gases and returned to the combustion process. This increases the enthalpy of flue gases in combustion H_{th}, which is determined by the equation:

$$H_{th} = H_i + h_g\left(T_g\right) + \lambda m_{z,\min} h_z\left(T_z\right) \quad \text{kJ/kg}_{\text{goriva/fuel}} \qquad (1).$$

Kurilnost goriva H_i je konstantna, entalpija goriva h_g pa je zelo majhna v primerjavi z drugima dvema členoma. Zato lahko povečamo entalpijo dimnih plinov H_{th} samo s segrevanjem zraka, torej s povečevanjem entalpije h_z. Enačbo (1) lahko predstavimo grafično v entalpijskem diagramu na sliki 1.

The calorific value of fuel H_i is constant, while fuel enthalpy h_g is very small in comparison with the other two terms. The flue gas enthalpy H_{th} can therefore be increased only by heating air, i.e. by increasing enthalpy h_z. Equation (1) is presented graphically in the enthalpy diagram in Figure 1.



Sl. 1. *Energijska bilanca grelnika zraka*
Fig. 1 *Energy balance in the air heater*

V diagramu *H - T* je prikazana entalpijska odvisnost dimnih plinov in zgorevalnega zraka od temperature. Vrisane so tri entalpijske krivulje: za dimne pline, celotno količino zgorevalnega zraka in zmanjšano količino zgorevalnega zraka. Ker je pretok dimnih plinov vedno večji od pretoka uporabljenega zgorevalnega zraka, poleg tega pa imajo dimni plini tudi večjo specifično toploto, ima entalpijska krivulja dimnih plinov večjo strmino kakor entalpijska krivulja zgorevalnega zraka in vedno leži nad entalpijsko krivuljo zgorevalnega zraka.

Ohlajevanje dimnih plinov od temperature v kurišču, ki je dejansko nižja od T_{th}, skozi kotel poteka po vrisani krivulji do točke *A*, s katero je označeno stanje dimnih plinov na vstopu v grelnik zraka. Tu dimni plini oddajo še toploto $Q_{zr} = H_A - H_B$ in se pri tem ohladijo od temperature T_A na temperaturo T_B, s katero izstopajo v dimnik. Toplota Q_{zr} se kontinuirano vrača v proces zgorevanja.

Svež zgorevalni zrak z entalpijo 0 kJ/kg vstopa v grelnik zraka, v katerem se segreje do temperature T_D. Grafično to v diagramu predstavimo

The *H - T* diagram shows the enthalpy variation of flue gases and combustion air with temperature. Three enthalpy curves are given: for flue gases, the entire quantity of combustion air, and the reduced quantity of combustion air. Since the flow of the flue gases is always greater than the flow of used combustion air, and since the flue gases also have a higher specific heat, the enthalpy curve of the flue gases always has a greater inclination than the enthalpy curve of the combustion air, and always lies above the enthalpy curve of the combustion air.

The cooling of the flue gases from the combustion chamber temperature (which is actually lower than T_{th}) through the boiler takes place following the curve to point *A*, which denotes the state of the flue gases at the air heater inlet. Here, the flue gases emit heat $Q_{zr} = H_A - H_B$ and cool from temperature T_A to temperature T_B, at which point they exit into the stack. Heat Q_{zr} is continuously returned to the combustion process.

Fresh combustion air with an enthalpy of 0 kJ/kg enters the air heater, in which it is heated to a temperature of T_D. This is graphically presented in tako, da entalpijsko krivuljo za 100-odstotno količino zgorevalnega zraka prenesemo iz točke 0 v točko *C*. V presečišču z entalpijo H_A dobimo točko *D*, ki pomeni stanje zgorevalnega zraka na izstopu iz grelnika zraka.

Kakor je razvidno iz diagrama, se pri takšnem protitočnem segrevanju zgorevalnega zraka pojavi na vroči strani grelnika zraka najmanjša temperaturna razlika med dimnimi plini in predgretim zrakom, ΔT_{min}.

Z manjšanjem količine zgorevalnega zraka, ki se predgreva v grelniku zraka, postaja entalpijska krivulja zraka v diagramu *H* - *T* vedno bolj položna. Manjša količina zraka se v grelniku zraka segreje na višjo temperaturo, hkrati pa se dvigne tudi temperatura izstopajočih dimnih plinov. Ko se pri zmanjšani količini zraka ΔT_{min} zmanjša na $\Delta T^*_{\mathrm{min}}$, se temperatura dimnih plinov T_{B} dvigne na T^*_{B}. To pomeni, da pri manjšem pretoku zgorevalnega zraka skozi grelnik izstopajo dimni plini iz grelnika z višjo temperaturo.

3 RAČUNSKI MODEL GRELNIKA ZRAKA

Za teoretično analizo razmer v grelniku zraka je bil narejen preprost računski model, s katerim lahko ugotavljamo vpliv mešanja zraka in dimnih plinov v samem grelniku, kakor tudi vpliv dodatne količine zraka, ki vdira v kotel, na izkoristek kotla. Pomembni sta predvsem temperaturi dimnih plinov in zraka na izstopu iz grelnika. Za posamezne tipe prenosnikov so izpeljane empirične enačbe, s katerimi lahko izračunamo ti temperaturi [6]. Ker

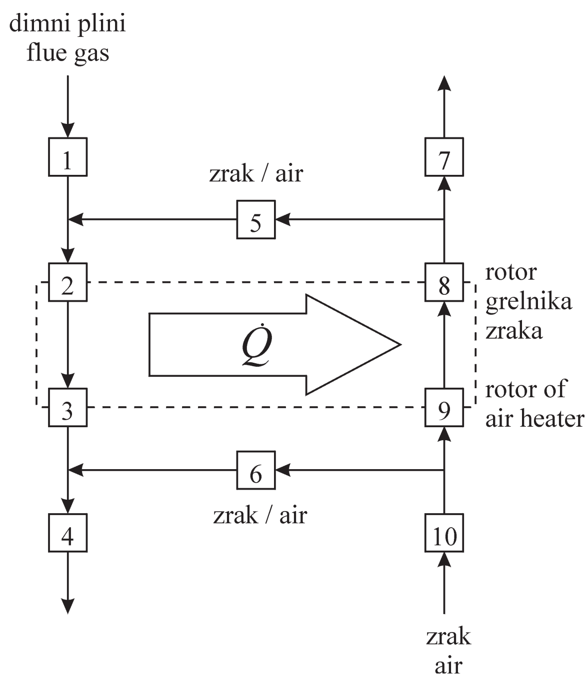
the diagram by transferring the enthalpy curve for a 100 % quantity of combustion air from point 0 to point *C*. At the point of intersection of this curve with the enthalpy curve H_A, point *D* is obtained which represents the state of the combustion air exiting air heater.

As can be seen from the diagram, a minimum temperature difference between the flue gases and preheated air ΔT_{min} occurs in such counter-current heating of combustion air on the hot side of the air heater.

While the quantity of combustion air (which is preheated in the air heater) is decreasing, the enthalpy curve for air in the *H* - *T* diagram is becoming less and less steep. A smaller quantity of air is heated in the heater to a higher temperature, and at the same time the temperature of the exiting flue gases increases. When at a reduced quantity of air ΔT_{min} decreases to $\Delta T^*_{\mathrm{min}}$, the temperature of the flue gases T_{B} increases to T^*_{B}. This means that at smaller combustion air flow through the heater, the flue gases leave the heater at a higher temperature.

3 MATHEMATICAL MODEL OF THE AIR HEATER

For a theoretical analysis of conditions in the air heater a simple mathematical model was made, which enables us to examine the influence of the mixing of air and flue gases in the heater, as well as the influence of additional amounts of air entering the boiler, on the boiler's efficiency. The temperatures of the flue gases and air at the heater outlet are especially important. Empirical equations for individual types of heat exchangers have been derived which enable the calculation of these temperatures [6].



Sl. 2. *Tokovi v grelniku zraka*
Fig. 2 *Flows in the air heater*

so te enačbe izpeljane na podlagi laboratorijskih preskusov, kjer je mogoče zagotoviti precej dobro tesnost Ljungströmovih grelnikov, je treba netesnosti grelnika upoštevati posebej. V ta namen grelnik zraka razdelimo na več delov, kakor to prikazuje slika 2.

Za določanje temperatur v točkah 3 in 8 upoštevamo izraz za učinkovitost prenosnika toplote, ki je v [6] definirana kot:

Since these equations are derived only on the basis of laboratory experiments, in which fairly good sealing of Ljungström heaters can be ensured, leakages of the heater should be taken into account separately. For this purpose, the air heater was divided into several segments, as shown in Figure 2.

The temperatures at points 3 and 8 are determined by taking into account the expression for heat exchanger efficiency, which is defined in [6] as

$$\varepsilon=\frac{\dot{m}_2 c_{p,dp}\left(T_2-T_3\right)}{\left(\dot{m}c_p\right)_{\min}\left(T_2-T_9\right)}=\frac{\dot{m}_9 c_{p,z}\left(T_8-T_9\right)}{\left(\dot{m}c_p\right)_{\min}\left(T_2-T_9\right)} \qquad (2),$$

kjer $\left(\dot{m}c_p\right)_{\min}$ označuje manjšo izmed toplotnih kapacitet toka zraka $\dot{m}_9 c_{p,z}$ in dimnih plinov $\dot{m}_2 c_{p,dp}$. Indeksi pri veličinah se nanašajo na sliko 2. Učinkovitost grelnika je odvisna od njegove oblike, velikosti prenosnih površin, hitrosti tokov, temperatur itn.

Preostale neznane temperature nato lahko določimo z energijskimi bilancami v posameznih točkah, ki so označene na sliki 2. Pri izračunu entalpije dimnih plinov po zgorevanju pa upoštevamo še količino zraka, ki dodatno vdira v kotel. Delež toplote, ki se v kotlu prenese na vodo in vodno paro, izračunamo z izrazom:

where $\left(\dot{m}c_p\right)_{\min}$ denotes the lower of the heat capacities of the air flow $\dot{m}_9 c_{p,z}$ and flue gases $\dot{m}_2 c_{p,dp}$. The indexes with the symbols refer to Figure 2. A heater's efficiency depends on its shape, size of transfer surfaces, flow rates, temperatures, etc.

Unknown temperatures can be determined using the energy balances for individual points as shown in Figure 2. The amount of air additionally entering the boiler is also taken into account in the calculation of flue gas enthalpy after combustion. The share of heat transferred in the boiler to water and water vapour is calculated with the following expression:

$$\eta_Q=\frac{H_{th}-H_A}{H_i} \qquad (3),$$

pri katerem se označbe nanašajo na sliko 1. Ta vrednost je približno enaka izkoristku kotla. Rezultati izračunov z uporabo tega modela so predstavljeni v poglavju 5.

where the symbols refer to Figure 1. This value approximately equals the boiler's efficiency. The results of calculations using this model are presented in section 5.

4 NETESNOST KOTLA

Celotno kotlovsko postrojenje je pri večjih energetskih objektih izredno zapleten sistem, pri katerem je nemogoče zagotoviti popolno tesnost. Pri popolnoma tesnem sistemu bi ves zgorevalni zrak vstopal v proces zgorevanja nadzorovano. Zaradi netesnosti se v kurišču in dimnih kanalih vzdržuje podtlak, da se prepreči uhajanje dimnih plinov v okolico kotla. Zaradi podtlaka prihaja do nenadzorovanega vdora zraka. Tisti zrak, ki vdira v kotel pred končanim procesom zgorevanja, tudi sodeluje v procesu zgorevanja, medtem ko zrak, ki vdira kasneje, ne vpliva na zgorevanje, ampak navidezno povečuje razmernik zraka in znižuje temperaturo dimnim plinom. Zaradi ohranitve primernega razmernika zraka v kurišču, je treba ustrezno zmanjšati količino zraka, ki ga nadzorovano dovajamo v kotel. Z manjšo količino predgretega zraka se v grelniku zraka dimnim plinom odvzame manj toplote, zaradi česar dimni plini izstopajo z višjo temperaturo. Nenadzorovani vdori zraka v kotel torej bistveno negativno vplivajo na izkoristek kotla.

4 BOILER LEAKAGE

In large energy facilities, boiler plants are extremely complex systems in which it is impossible to ensure total sealing. In a completely sealed system, the entire quantity of combustion air would enter the combustion process in a controlled manner. However, due to leaking, underpressure is maintained in the combustion chamber and flues in order to prevent the leakage of flue gases into the boiler's surroundings. This underpressure results in uncontrolled air leakages. The air entering the boiler before the combustion process is completed also participates in the combustion process, while air entering later does not affect combustion, but apparently increases the excess air ratio and reduces the temperature of the flue gases. In order to maintain a suitable excess air ratio in the combustion chamber, the quantity of air fed to the boiler in a controlled manner needs to be appropriately reduced. A smaller quantity of preheated air in the air heater takes less heat away from fuel gases, resulting in flue flue gases exiting at a higher temperature. Uncontrolled entries of air into the boiler therefore have a marked negative effect on the boiler's efficiency.

Že pri načrtovanju kotlovskega postrojenja je treba oceniti, koliko zraka bo nenadzorovano vstopalo v kotel, predvsem pri mlinih za premog, dodajalnikih, sesalnih glavah, dogorevalni rešetki itn. Sčasoma se omenjene netesnosti lahko povečajo in vse več zraka nenadzorovano vdira v kotlovsko postrojenje.

5 VPLIVI NENADZOROVANIH VDOROV ZRAKA

V prejšnjih poglavjih so opisane termodinamične značilnosti netesnosti v grelniku zraka in kotlu ter spremljajoči pojavi. Za analizo netesnosti potrebujemo izhodiščne vrednosti, glede na katere izvedemo analizo, npr. podatki garancijskih meritev, podatki pred predelavo oz. remontom itn.
Značilni vplivi posameznih netesnosti so:

- Netesnost kotla se kaže v tem, da se zmanjša količina zraka skozi grelnik zraka, zaradi česar se pri "normalno" tesnem grelniku zraka zviša izstopna temperatura dimnih plinov ob nespremenjeni ali zmanjšani temperaturni razliki ΔT_{min} med dimnimi plini in predgretim zrakom. Vpliv netesnosti kotla na temperature in delež prenesene toplote η_Q prikazuje slika 3. Za primerjavo teoretičnih in dejanskih vrednosti so na sliki prikazane tudi izmerjene vrednosti iz preglednice 1.
- Netesnost grelnika zraka na hladnem delu povzroči znižanje izstopne temperature dimnih plinov ob nespremenjeni temperaturni razliki ΔT_{min} med dimnimi plini in predgretim zrakom. Omenjena netesnost termodinamično sploh ne vpliva na izkoristek kotla, ker se mešanje zraka in dimnih plinov dejansko izvede za mestom regeneracije. Če je netesnost velika, se lahko temperatura dimnih plinov zniža pod tehnološki minimum.
- Netesnost grelnika zraka na vročem delu povzroči znižanje izstopne temperature dimnih plinov ob nespremenjeni ali zvišani temperaturni razliki ΔT_{min} med dimnimi plini in predgretim zrakom. Vpliv netesnosti na temperature in delež prenesene toplote η_Q prikazuje slika 4.

Diagrama na slikah 3 in 4 sta narisana z modelom, predstavljenim v poglavju 3. Pri tem je za učinkovitost prenosnika privzeta konstantna vrednost $\varepsilon = 0{,}96$, ki približno velja za prenosnik toplote, na katerem so bile izvedene meritve, predstavljene v poglavju 6. Predpostavljeno je še, da je grelnik zraka zmožen prenesti povečane toplotne tokove zaradi primešavanja ogretega zraka dimnim plinom.

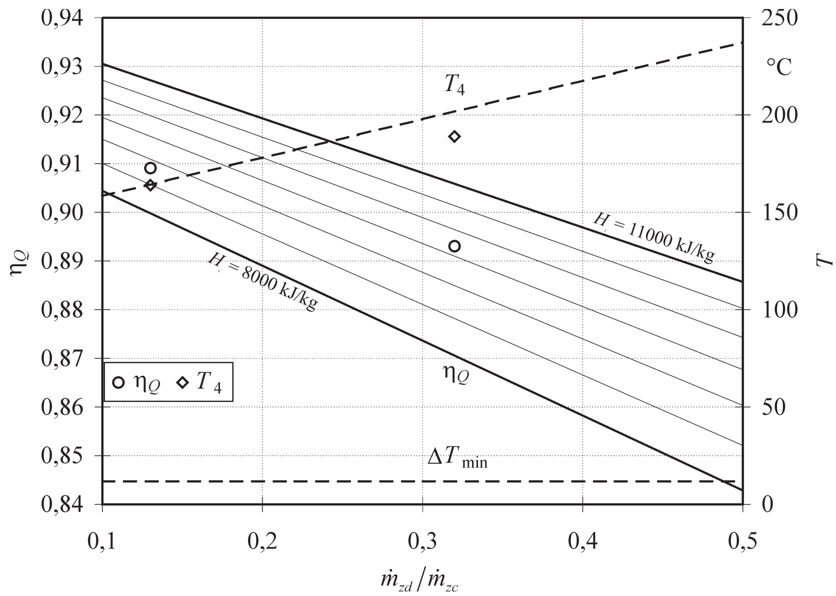
The quantity of air which is expected to enter the boiler uncontrollably needs to be estimated when the boiler plant is designed, especially in coal mills, feeders, drying gas pipes, grates, etc. These leakages may increase with time and an ever greater amount of air uncontrollably enters the boiler plant.

5 INFLUENCES OF UNCONTROLLED ENTRIES OF AIR

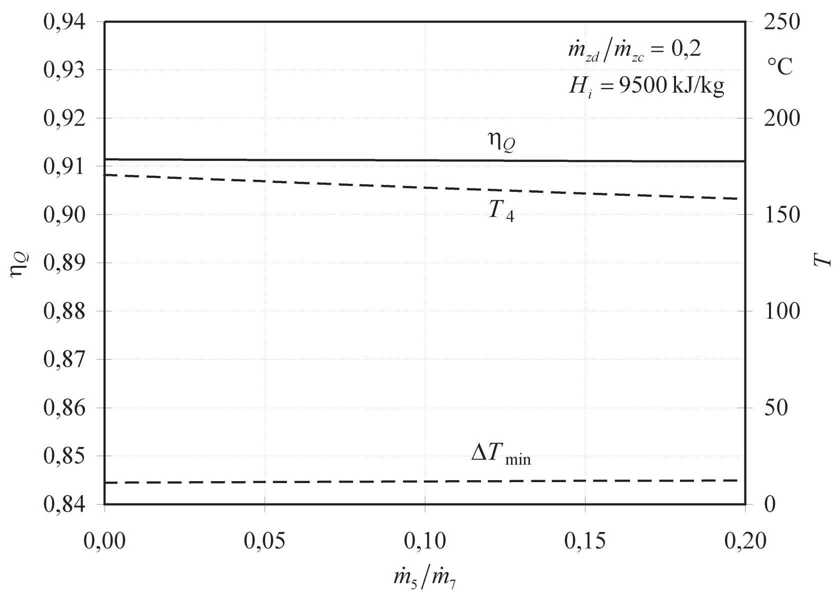
The thermodynamic characteristics of leakage in an air heater, in a boiler, and the accompanying phenomena were described in the previous sections. To analyse leaking, we need initial values with regard to which analysis is performed, (e.g. data from acceptance tests, data prior to remodelling or refits, etc.).
The characteristic influence of individual types of leakage are:

- Boiler leakage is expressed through reduction in the quantity of air passing through the air heater, resulting in an increase in flue gas outlet temperature that occurs at unchanged or reduced temperature difference ΔT_{min} between flue gases and preheated air in a "normally" sealed air heater. The influence of boiler leakage on temperatures and share of transferred heat η_Q are presented in Figure 3. The figure also shows the measured values from Table 1 for the comparison of theoretical and actual values.
- Air heater leakage in the cold part causes a reduction of flue gas outlet temperature at an unchanged temperature difference ΔT_{min} between the flue gases and the preheated air. The above-mentioned leakage does not at all affect the boiler's thermodynamic efficiency, since the mixing of air and flue gases actually occurs after the site of regeneration. If leakage is high, temperature may decrease below the technological minimum.
- Air heater leakage in the hot part causes a reduction of flue gas outlet temperature at an unchanged or increased temperature difference ΔT_{min} between the flue gases and the preheated air. The influence of leakage on temperatures and share of transferred heat η_Q are shown in Figure 4.

Figure 3 and Figure 4 were drawn using the model which was presented in section 3. Constants, that approximately apply to the conditions at which measurements referred to in Section 6 were performed, were assumed for the calculations using the model. The properties of the fuel were also similar to the measured cases. It was also assumed that the air heater is capable of handling increased heat fluxes due to the admixture of heater air with the flue gases.



Sl. 3. *Vpliv netesnosti kotla*
Fig. 3. *Influence of boiler leakage*



Sl. 4. *Vpliv netesnosti grelnika zraka*
Fig. 4. *Influence of air heater leakage*

Kakor je razvidno s slik 3 in 4, je z vidika deleža prenesene toplote η_Q na delovno snov, oziroma izkoristka kotla, najpomembneje, da se preprečijo nenadzorovani vdori zraka v kotel. Vpliv mešanja že ogretega zraka in dimnih plinov v grelniku zraka na izkoristek kotla je približno 17-krat manjši od vpliva nenadzorovanih vdorov zraka.

Na sliki 3 vidimo, da se izmerjene vrednosti približno ujemajo z računsko določenimi. Pri tem je treba upoštevati, da tako na temperature, kakor tudi na delež prenesene toplote, vpliva večja vrsta prametrov, na sliki pa je prikazana samo odvisnost od deleža dodatnega zraka in kurilnosti goriva.

As can be seen from Figures 3 and 4, it is most important from the standpoint of the share of heat transferred η_Q to the working medium, i.e. boiler efficiency, to prevent uncontrolled entries of air in the boiler. The influence of mixing of already heated air and flue gases in the air heater on the boiler's efficiency is approximately 17 times lower than the influence of uncontrolled entries of air.

Figure 3 shows that the measured values approximately match those determined by calculation. It must be taken into account that both temperatures and the share of transferred heat are influenced by a series of parameters and that the curve in the figure represents only variation with the share of additional air and the fuel's calorific value.

6 MERITVE NA GRELNIKU ZRAKA

Kot praktičen primer so v preglednici 1 zbrani podatki o dolgoletnem obratovanju termoelektrarniških grelnikov zraka. Za primerjavo imamo na voljo rezultate meritev pri novem grelniku zraka in rezultate po večletnem obratovanju. Označbe v preglednici se nanašajo na model s slike 2.

6 MEASUREMENTS ON THE AIR HEATER

As a practical example, Table 1 gives collected data on long-term operation of air heaters in thermal power plants. For comparison we used the results of measurements of a new air heater and results after several years of operation. Symbols in the table refer to the model in Figure 2.

Preglednica 1. *Parametri grelnika zraka*
Table 1. *Air heater parameters*

		nov grelnik zraka new air heater [4]	po več letih after several years [5]
T_1	°C	325	337
T_4	°C	164	189
T_{10}	°C	40	40
T_7	°C	290	325
$\dot{m}_1$	kg/s	490	506
$\dot{m}_4$	kg/s	500	530
$\dot{m}_{10}$	kg/s	375	304
$\dot{m}_7$	kg/s	365	287
$\dot{m}_5+\dot{m}_6$	kg/s	10	17
$\dot{m}_{zd}$	kg/s	40	136
$\dot{m}_1/\dot{m}_7$		1,34	1,76
$\dot{m}_1/\dot{m}_{zc}$		1,21	1,20
$(\dot{m}_5+\dot{m}_6)/\dot{m}_{10}$		3 %	6 %
$\dot{m}_{zd}/\dot{m}_{zc}$		10 %	32 %

Eden bistvenih parameterov, ki vpliva na velikost izgube s toploto dimnih plinov, je njihova temperatura. Kakor je razvidno iz preglednice 1, se je ta s časom zvišala s 165 °C na 189 °C, hkrati se je temperaturna razlika med dimnimi plini in ogretim zrakom ΔT_{min} zmanjšala s 35 °C na samo 12 °C. To nakazuje, da se sedaj v grelniku zraka segreva manjša količina zgorevalnega zraka, kar je razvidno tudi iz rezultatov v spodnjem delu preglednice 1, kjer so prikazana različna razmerja masnih tokov. Kakor vidimo, se razmerje med dimnimi plini in zgorevalnim zrakom $\dot{m}_1/\dot{m}_{zc}$, ki je samo funkcija razmernika zraka λ, ne spreminja in je približno 1,2.

Bistveno se je spremenilo razmerje med količino dimnih plinov pred grelnikom zraka in količino zraka za grelnikom zraka $\dot{m}_1/\dot{m}_7$. To razmerje se je zvišalo za 31 odstotkov v korist dimnih plinov, kar pomeni, da se je krepko povečal delež zraka, ki vstopa v kotel mimo grelnika zraka. To je razvidno tudi iz razmerja $\dot{m}_{zd}/\dot{m}_{zc}$, ki označuje delež celotnega zraka, ki gre mimo grelnika zraka. Kot vidimo, se je delež zraka, ki gre skozi grelnik zraka, z leti zmanjšal za 22 odstotkov, kar ima za posledico višje izstopne temperature dimnih plinov.

Netesnost grelnika zraka lahko izrazimo z razmerjem $(\dot{m}_5+\dot{m}_6)/\dot{m}_{zp}$. Kakor vidimo iz preglednice, se je to razmerje z leti povečalo s 3 na

The temperature of the flue gases is an essential parameter influencing the magnitude of flue gas heat loss. As can be seen in Table 1, this increased over time from 165 to 189 °C, and at the same time the temperature difference between the flue gases and heated air ΔT_{min} decreased from 35 °C to only 12 °C. This indicates that a smaller amount of combustion air is now being heated in the air heater, which is also evident from the results in the lower part of Table 1, which shows various mass flow ratios. As can be seen, the ratio of flue gases to combustion air $\dot{m}_1/\dot{m}_{zc}$, which is a function only of the excess air ratio λ, does not change and is approximately 1.2.

The ratio of the quantity of flue gases before the air heater to the quantity of air behind it $\dot{m}_1/\dot{m}_7$ has changed considerably. This ratio increased by 31 % in favour of the flue gases, which means that the share of air entering the boiler and bypassing the air heater was considerably increased. This is also evident from the ratio $\dot{m}_{zd}/\dot{m}_{zc}$, which denotes the share of total air bypassing the air heater. As can be seen, the share of air going through the air heater decreased over the years by 22 %, which resulted in higher flue gas outlet temperatures.

Air heater leakages can be expressed by the ratio $(\dot{m}_5+\dot{m}_6)/\dot{m}_{zp}$. As can be seen from the table this ratio increased over the years from 3 to 6 %, but

6 odstotkov, kar pa je glede na rezultate obratovanja za še vedno sprejemljivo. Povečanje vdora zraka v dimne pline v grelniku zraka ne vpliva pomembno na izkoristek kotla, temveč le na velikost toplotnega toka, ki se prenaša v grelniku zraka. Vpliv primešanega zraka postane pomemben, ko se toplotni tok približa zmogljivosti grelnika zraka. Zato mora biti glavna skrb vzdrževanja tesnosti kotlovskih kanalov usmerjena v zagotavljanje projektne količine zgorevalnega zraka, ki se segreva v grelniku zraka.

this is still acceptable with respect to the performance of the plant. The increased entry of air into the flue gases in the air heater does not have a significant influence on boiler efficiency, but only on the magnitude of heat flux which occurs in the air heater. The influence of admixed air becomes important when the heat flux approaches the capacity of the air heater. The basic task of maintaining seals on boiler ducts must be geared towards ensuring planned quantities of combustion air heated in the heater.

7 SKLEPI

Predstavljene in analizirane so tri vrste netesnosti kotlovskih naprav, nenadzorovani vdori zraka v kotel ter mešanje zraka in dimnih plinov na hladnem in vročem delu grelnika zraka. Za analizo vpliva netesnosti na delež koristno prenesene toplote iz dimnih plinov na vodo in vodno paro je predlagan preprost model, s katerim se lahko obravnavajo poljubna stanja v grelniku zraka. Izkazalo se je, da ima vsaka od analiziranih netesnosti svoj karakteristični vpliv na temperaturne razmere v grelniku zraka. Nenadzorovani vdori zraka v kotel pri običajno tesnem grelniku zraka povzročijo zvišanje izstopne temperature dimnih plinov ob zmanjšani temperaturni razliki ΔT_{min} med dimnimi plini in predgretim zrakom. Mešanje na vročem delu grelnika zraka povzroči znižanje izstopne temperature dimnih plinov ob nespremenjeni ali zvečani temperaturni razliki ΔT_{min}. Mešanje zraka in dimnih plinov na hladnem delu grelnika zraka povzroči znižanje izstopne temperature dimnih plinov ob nespremenjeni temperaturni razliki ΔT_{min}. Izkazalo se je, da imajo nenadzorovani vdori zraka v kotel največji vpliv na izkoristek kotla, medtem ko netesnosti v grelniku zraka le malenkostno vplivajo na izkoristek kotla. Primer realnega obratovanja termoelektrarniškega grelnika zraka je pokazal, da se je v obravnavanem primeru sčasoma zmanjšala količina zraka, ki se segreva v grelniku zraka, zaradi česar je izkoristek kotla manjši. Hkrati se je netesnost grelnika zraka zvečala od 3 na 6 odstotkov, kar pa nima bistvenega vpliva na izkoristek kotla.

7 CONCLUSIONS

Three types of air leakage in a boiler (uncontrolled entries of air into the boiler, and mixing of air and flue gases in the cold and hot parts of the air heater) are presented and analysed. A simple model is proposed for the analysis of the influence of leaking on the share of usefully transferred heat from flue gases to water and water vapour, which can be used to analyse any state in the air heater. It turns out that each of the analysed types of leakage has a characteristic influence on the temperature conditions in the air heater. Uncontrolled entries of air into the boiler of an otherwise sealed air heater cause an increase in the flue gas outlet temperature at a reduced temperature difference ΔT_{min} between the flue gases and preheated air. Mixing in the hot part of the air heater causes a reduction of flue gas outlet temperature at unchanged or increased temperature difference ΔT_{min}. Mixing of air and flue gases in the cold part of the air heater causes a reduction of flue gas outlet temperature at unchanged temperature difference ΔT_{min}. It was shown that uncontrolled entries of air into the boiler have the greatest influence on the boiler's efficiency, while leakage in the air heater affects it only slightly. An example of real operation of an air heater at a thermal power plant showed that the quantity of air heated in the heater in the studied case decreased over time, which resulted in reduced boiler efficiency. At the same time, the leakage of the air heater increased from 3 to 6 %; this affected the magnitude of heat flux which occurs in the air heater, but did not have a significant influence on boiler efficiency.

8 OZNAČBE
8 SYMBOLS

specifična toplota	c_p	specific heat
entalpija	H	enthalpy
spodnja kurilnost goriva	H_i	lower calorific value of fuel
entalpijska razlika	ΔH	enthalpy difference
specifična entalpija	h	specific enthalpy
masni tok	$\dot{m}$	mass flow
najmanjša potrebna količina zgorevalnega zraka	$m_{z,\mathrm{min}}$	minimum required amount of combustion air
izgubljena toplota	Q_{iz}	heat loss
toplota segretega zraka	Q_{zr}	heat in heated air
temperatura	T	temperature
najmanjša temperaturna razlika v grelniku zraka	ΔT_{min}	lowest temperature difference in air heater
učinkovitost prenosnika toplote	ε	heat exchanger efficiency
razmernik zraka	λ	excess air ratio
delež toplote dimnih plinov, ki jo prenesemo na vodo in vodno paro	η_Q	share of heat of flue gases that is transferred to water and water vapour

Indeksi	**Indexes**	
dimni plini	dp	flue gases
gorivo	g	fuel
teoretični	th	theoretical
zrak	z	air
celotna količina zraka na vstopu v kotel	zc	total amount of air entering boiler
zgorevalni zrak, ki ne gre skozi grelnik zraka	zd	combustion air not passing through air heater

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9 REFERENCES

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Prejeto:
Received: 4.1.1999

Sprejeto:
Accepted: 26.2.1999

Drobnic-1.p65 84 22.3.99, 15:38