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Review scientific paper

Splošni model zgorevanja kosa premoga v cevi pri nadzorovanem dovodu zraka

General Model of the Combustion of a Single Coal Piece in Tubular Device with Controlled Air Flow

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Prispevek predstavlja eksperimentalno raziskavo zgorevanja posameznih kosov premoga velikosti 6,5 × 4,7 × 3,8 cm, mase 120 ± 7 g v zgorevalni cevi. Kosi premoga so zgorevali v znanih termodinamičnih razmerah v konvektivnem toku zraka kot oksidanta. Na podlagi eksperimentalnih podatkov zgorevanja kosa premoga smo hitrost zgorevanja, to je spremembo mase goriva v času, popisali z reduciranimi veličinami. Reducirana hitrost zgorevanja je podana v odvisnosti od reduciranega časa. Medsebojne veličine so podane v obliki polinomov z veliko stopnjo prilagajanja. Uvedena je analiza zgorevanja kosa premoga v tridimenzionalnem prostoru z uvedbo reducirane hitrosti zgorevalnega zraka. Ugotovili smo, da je reducirana hitrost zgorevanja kosa premoga neodvisna od reducirane hitrosti zgorevalnega zraka in njene reducirane temperature.

Ključne besede: zgorevanje premoga, hitrosti zgorevanja, analize zgorevanja, modeli zgorevanja

The paper presents experimental research into the combustion of individual coal pieces with dimensions of 6.5 × 4.7 × 3.8 cm and masses of 120 ± 7 g in a combustion pipe. The coal pieces were burned under known thermodynamic conditions in a convective air current, which served as an oxidant. Based on experimental data obtained from the combustion of single coal pieces, combustion rate (i.e. variation of fuel mass vs. time) was described using non-dimensional quantities. The non-dimensional combustion rate is given in correlation with non-dimensional time. Mutual factors are given in the form of polynomials with a large degree of adaption. The analysis of coal combustion in a three-dimensional space was made by the introduction of non-dimensional combustion air flow velocity. It was found that the non-dimensional combustion rate of the combustion of coal pieces does not depend on non-dimensional combustion air flow velocity or temperature.

Keywords: coal combustion, combustion velocity, analysis of combustion, combustion models

0 UVOD

V široki porabi kose premoga kurimo v malih kuriščih - štedilnikih, kotlih, itn., ki so namenjena za ogrevanje bivalnih prostorov ter kuhanje. Uporaba kurilnih naprav na premog v kosih sicer v razvitem svetu izginja, vendar pa bo premog tudi v prihodnjem stoletju pomembno gorivo v danes nerazvitem svetu, kjer živi dve tretjini svetovnega prebivalstva. Raziskovalno delo je na področju zgorevanja premoga v kosih, po zatonu uporabe običajnih štedilnikov, peči in kotlov na premog za centralno ogrevanje, praktično ugasnilo. Čeprav uporaba premoga pomeni največje onesnaževanje okolja med vsemi fosilnimi gorivi ter veliko prispeva k nastanku tople grede, bo tudi v naslednjem stoletju pomenil pomemben energetski vir.

Večina dosedanjih raziskav se je osredotočila na vžig in zgorevanje premogovega prahu in zrn premoga ([1] in [2]). Obnašanje večjih kosov premoga pri vžigu in zgorevanju v nadzorovanih razmerah do sedaj še ni bilo celovito raziskano. V literaturi ni rezultatov niti modelov, ki bi popisovali obnašanje kosa premoga pri gorenju v prisilnem toku zraka, ni raziskan učinek hitrosti toka zraka kot oksidanta na proces vžiga in hitrost zgorevanja ([3] in [4]). Slednje se nanaša na kurišča, kjer je razmerje prostornina goriva proti prostornini zgorevalnega prostora relativno majhno. Zgorevanje premoga na rešetki, predvsem v velikih kuriščih, kjer je razmerje

0 INTRODUCTION

In general use, coal is burnt in small ovens and boilers for heating and cooking. The use of coal furnaces is declining in developed countries, but in developing countries, which represent two-thirds of the world's population, coal will remain important fuel into the next century. Research work on the combustion of coal pieces almost ceased after the use of classic coal ovens and boilers was reduced. Despite the fact that coal is the greatest source of pollution of all fossil fuels and contributes most to the greenhouse effect, it will not be removed from consumption.

Most research work focused on the ignition and combustion of coal dust and coal pellets ([1] and [2]). The behavior of larger pieces on ignition under controlled conditions has not yet been thoroughly investigated. There are no data or models in literature that describe the behavior of coal pieces during combustion in forced air-flow. The effect of air velocity on the ignition process has also not been adequately researched ([3] and [4]). This refers to furnaces with a relatively small fuel-to-combustion-chamber-volume ratio. The combustion of coal on prostornine zgorevalnega prostora glede na protornino kosa premoga zelo veliko, pa je relativno dobro preučeno.

Zgorevalni proces kapljivih in plinastih goriv je v primerjavi z zgorevalnim procesom trdnih goriv, predvsem premogov, razmeroma dobro poznan. Prav tako je proces zgorevanja premoga v velikih napravah (prašne kurjave, fluidiziran sloj, uplinjanje) razmeroma dobro raziskan ([5] in [6]). Najmanj je raziskano zgorevanje oglatih kosov premoga v kurilnih napravah manjših toplotnih moči, ki pa se v gospodinjstvih največ uporabljajo.

Za zgorevanje večjih granulacij premoga je značilno:

- Zgorevanje premoga v kosih je proces z izrazito spremenljivim časom zgorevanja, saj gorivo ne zgori v trenutku. Čas zgorevanja je odvisen od robnih pogojev, med katerimi so masa, velikost in oblika kosa goriva pomemben robni pogoj.
- V procesu zgorevanja se hitrost oksidacije premoga s kisikom iz zraka nenehno spreminja, s tem pa količina odgorele mase goriva. Iz dosedanjih opazovanj in raziskav je znano, da je zgorevanje kosa premoga nelinearen in časovno izrazito spremenljiv proces. Čas zgorevanja je odvisen od številnih robnih pogojev: kurišča, kakovosti, količine, oblike in lastnosti goriva, hitrosti, temperature in vlažnosti zraka itn.
- V procesu zgorevanja kosov premoga se pojavljajo motnje - saj se okolje okoli kosa premoga s časom naključno spreminja (neenakomerna razporeditev zgorevalnega zraka, neenakomerna velikost in gladkost površine kosa premoga, neenakomerna oddaljenost kosov goriva drug od drugega, spreminjajoča in različna hitrost zraka med delci goriva itn.).
- Regulacija zgorevanja je otežena. Masa goriva, ki sodeluje v zgorevalnem procesu, se nenehno spreminja. Pri gruči kosov ali celo pri posameznem kosu premoga se dogaja, da je v neposredni bližini lahko kos premoga, ki je že izpostavljen reakciji zgorevanja, in kos, ki reakciji ni izpostavljen. Le procesi zgorevanja z nadzorovanim dovodom zraka in količino goriva so lahko energijsko učinkoviti in ekološko primerljivi.

grate in large furnaces, in which the ratio of combustion chamber volume to coal piece volume is very large, is relatively well researched.

The combustion process for liquid and gaseous fuels compared to solid fuels, such as coal, is well studied and known. This is also the case with coal combustion in large coal combustors of (coal dust furnace, fluidised bed, evaporation) different kinds ([5] and [6]). However, coal combustion of brick form coal piece in domestic-use sized furnaces is least researched.

This type of larger size coal combustion is distinguished by the following:

- The combustion of coal pieces is a process where combustion time varies heavily, as fuel does not burn out immediately; combustion time depends on boundary conditions, such as piece mass, size and shape as the primary ones.
- During the combustion process, the oxidation of a coal piece changes constantly and the combusted mass with it. From research results to date it is known that coal piece combustion is a non-linear time-variant process. Combustion time depends on numerous boundary conditions, such as furnace geometry, fuel quality, fuel shape and characteristics, air velocity, air temperature, air humidity etc.
- Interference occurs during the process of combustion of coal pieces as the immediate vicinity of a coal piece changes randomly due to non-uniform air distribution, non-uniform coal piece size and smoothness, shape, non-uniform distance between pieces, variable and non-uniform air velocity etc.
- The control of combustion is difficult, as piece mass constantly varies during combustion. In the case of several coal pieces, and even with a single one, the combustion process is non-homogeneous (while one piece may already be burning, another (or others) close to it is (are) not). Only combustion processes which take place under controlled air delivery and fuel quantity conditions can be energy efficient and environmentally friendly.

1 EKSPERIMENTALNA NAPRAVA IN POSTOPEK

Namen preskusa je bilo ugotoviti dinamiko zgorevanja rjavega premoga v kosu z velikim deležem hlapnih snovi in vlage (preglednica 1). Eksperimentalno napravo (sl.1) so sestavljali zgorevalna cev, naprava za pripravo vročega zraka in merilna oprema. Zgorevalna cev iz nerjavnega jekla, notranjega premera 108 mm, je imela dvojno steno in je bila toplotno izolirana. Kos premoga, oglate oblike je bil postavljen v tok vročega zraka

1 EXPERIMENTAL PROCEDURE AND EQUIPMENT

The aim of the experiment was to establish the combustion dynamics of brown coal pieces containing a large amount of volatiles and water (Table 1). The experimental device (Fig. 1) consisted of a combustion tube, a device for air heating and various instruments. A combustion tube made of stainless steel with a net diameter of 108 mm had a double wall and external thermal insulation. A square-shaped coal piece was placed in a hot air current 400 mm in

400 mm v zgorevalni cevi. Nosilni element premoga je bil izveden v obliki votlega stožca in priključen z elektronsko tehtnico. Proces zgorevanja smo opazovali skozi opazovalno okno. Vzorce produktov zgorevanja smo črpali tik nad gorečim kosom premoga s tremi, posebej prirejenimi priključki, 260 mm pod vrhom zgorevalne cevi. Koncentracije produktov zgorevanja bodo podane v drugem članku. Zgorevalni zrak smo z ventilatorjem vodili prek električnih grelnikov toplotne moči 6 kW. Pod kosom premoga je bil vgrajen stabilizator zračnega toka, ki je zagotavljal enakomeren hitrostni profil po prerezu zgorevalne cevi.

the combustion tube. The element carrying the coal piece was hollow-cone shaped and connected to an electronic scale. The combustion process was monitored through an opening for inspection. Combustion products were sampled immediately above the coal piece by use of three adapted connectors placed 260 mm below the combustion tube top. The concentrations of the flue gases will be done in another paper. Air was passed over electric heaters of 6 kW power using a fan. Below the coal piece, an air current stabilizing device was built in, ensuring uniform velocity profile over the entire combustion tube cross-section.

Preglednica 1. *Analiza rjavega premoga*
Table 1. *Analysis of brown coal*

gostota density	720 kg/m³
gorljive snovi combustibles content	66,51 %
koks coke content	45,01 %
hlapne snovi volatiles content	33,85 %
ogljik carbon	32,66 %
žveplo: celotno sulphur: total	3,89 %
žveplo: gorljivo sulphur: combustible	3,20 %
kurilnost heating value	17,403 MJ/kg

Elementna analiza premoga
Coal element analysis

ogljik carbon	45,46 %
vodik hydrogen	3,46 %
žveplo sulphur	3,20 %
kisik oxygen	13,68 %
dušik nitrogen	0,71 %
vlaga moisture	21,14 %
pepel ashes	12,14 %

V ustaljenem stanju smo, pri izbrani temperaturi in hitrosti zgorevalnega zraka v merilnem prerezu nosilnega elementa, vložili vzorec premoga, naključno odvzetega iz kupa rjavega premoga. Odbrani kos premoga je bil nepravilne oblike, njegove ploskve so bile različno špičaste. Ker imata oblika in hrapavost površine, poleg drugih dejavnikov, zelo pomembno vlogo pri vžigu premoga, še posebej večjih kosov, smo kos premoga pred postavitvijo v eksperimentalno napravo obdelali. Vsi preskušanci so imeli približno enake značilnosti: obliko, velikost in maso. Kosi premoga so bili naslednjih dimenzij: dolžine 6,5 ± 0,5 cm, širine 4,7 ± 0,3 cm in višine 3,8 ± 0,3 cm in začetne mase med 113 in 127 grami. Vse ploskve premoga so bile razmeroma enako gladke.

Under steady-state conditions, at chosen air temperature and velocity in a monitored cross-section of the element carrying the coal piece, a randomly chosen coal piece was placed in the experimental device. The coal piece was of irregular shape with a sharp surface with spikes of different sizes. The shape and surface sharpness are, among others, factors of primary importance for the ignition process, especially when using large coal pieces. Therefore coal pieces were first prepared for testing, so all coal pieces were of approximately the same geometry, size and mass. Coal pieces were 6.5 ± 0.5 cm in length, 4.7 ± 0.3 cm in width and 3.8 ± 0.3 cm in height. All surfaces of coal pieces were of similar smoothness and their initial masses ranged from 113 to 127 g.

Zgorevanje kosov premoga smo analizirali pri treh temperaturah zgorevalnega zraka. Glede na hitrost zgorevalnega zraka so preskusi potekali pri Reynoldsovih številih laminarnega in delno vmesnega področja (preglednica 2). Hitrost zraka se je v prerezu eksperimentalne naprave spremenila po vstavitvi preskušanca vanjo. Zato smo obravnavali dve hitrosti zraka oziroma dve Reynoldsovi števili. Reynoldsovo število, ki je podano v točki prereza pod preskušancem in je preračunano na premer preskuševalne cevi, je označeno z Re (enačba 1). Drugo Reynoldsovo število, označeno z Re_1 (enačba 2), pa je karakteristično število v prerezu, kjer preskušanec gori. Definirano je z realno povprečno hitrostjo zraka v prerezu in razliko med premeroma preizkuševalne cevi in hidravličnega premera preskušanca.

The combustion process of coal pieces was analyzed at three different air supply temperatures. In terms of air velocity, the experiments were run in laminar and intermediate domains of air flow with respect to Reynolds numbers (Table 2). The air velocity changes after a coal piece is inserted into the experimental device. Therefore two different air velocities, i.e. two Reynolds numbers, were considered. The Reynolds number at the cross-section below the coal piece was calculated for combustion tube net diameter (Re) using equation (1). The second Reynolds number (Re_1) calculated using equation (2) is the characteristic number for the cross-section in which the coal piece combustions take place, and is defined by the actual average air velocity in the cross-section and the difference between the combustion tube net diameter and the hydraulic diameter of the coal piece.

$$Re = \frac{v.d}{\upsilon} \qquad (1),$$

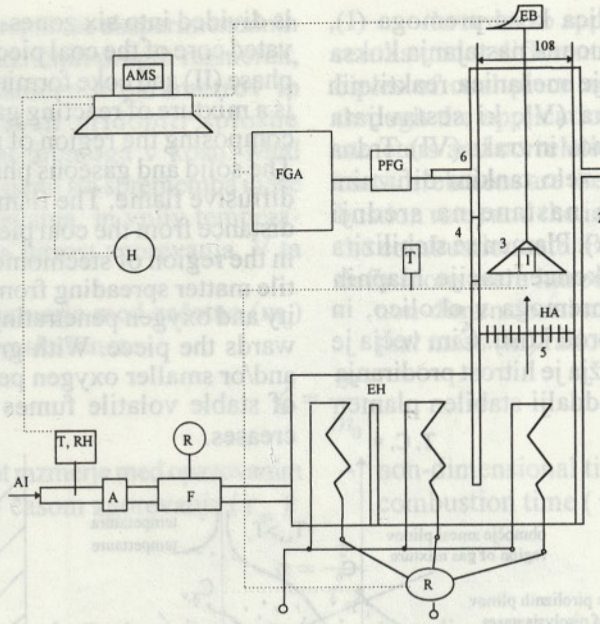
$$Re_1 = \frac{v_1}{\upsilon} \frac{1}{1 - \frac{4.a.b}{\pi.d^2}} .(d - \frac{2.a.b}{(a+b)}) \qquad (2).$$

Preglednica 2. *Temperature zgorevalnega zraka, hitrosti zraka v zgorevalni cevi in Reynoldsova števila*
Table 1. *Temperature of combustion air, air velocity in combustion tube and Reynolds numbers*

temperatura zraka air temperature (K)	Hitrost zraka (v) air velocity (v) (m/s)	Re	Re_1
623	0,17	331	395
	0,59	1151	1290
	0,71	1385	1553
	1,80	3513	3937
723	0,23	351	394
	0,74	1131	1268
	0,80	1223	1370
	1,54	2354	2638
823	0,30	370	430
	0,75	926	1074
	1,07	1321	1533
	1,73	2136	2479

Po privzeti razlagi o fizikalnih pojavih zgorevanja premogovih zrn in dosedanjih teorij o kemičnih reakcijah pri gorenju trdnih goriv ([7] do [12]), je bila postavljena hipoteza o procesu zgorevanja kosa premoga, ki upošteva, da pirolizni plini, ki nastajajo pri segrevanju kosa premoga, ne zgorevajo z enako hitrostjo. Ker je njihova sestava različna, koncentracija ob površini kosa pa odvisna od njihove oblike, temperature in hitrosti zgorevalnega zraka, ima čelo plamena nezvezno črto. Trenutna razdalja čela plamena od kosa premoga se stalno spreminja. S tem se spreminja tudi prenos toplote s plamena na goreči kos premoga [13].

Based on the assumed explanation of the physical phenomena of coal grain combustion and existing theories on the chemistry of solid fuel combustion ([7] to [12]), the following hypothesis on the process of coal piece combustion was formulated: The gases which are the product of coal pirolysis during combustion do not burn at the same rate. Their chemical composition is different and their concentration at the coal piece surface depends on the coal piece shape, temperature and combustion air velocity. Therefore the flame front line is not continuos. The distance of the flame from the coal piece changes permanently, and with it the heat transfer from the flame to the coal piece [13].



merilnik pretoka zraka,	*A*	*air flow meter,*
avtomatski merilni sistem,	*AMS*	*automatic measuring system,*
analizator produktov zgorevanja,	*FGA*	*flue gas analyzer,*
električni grelnik,	*EH*	*electric heater,*
štoparica,	*H*	*timer,*
elektronska tehtnica,	*EB*	*electronic balance,*
priprava produktov zgorevanja,	*PFG*	*preparation of flue gases,*
regulator,	*R*	*regulator,*
zaznavalo relativne vlažnosti zraka,	*RH*	*sensor of relative air humidity,*
temperaturno zaznavalo,	*T*	*temperature sensor,*
stabilizator toka vročega zraka,	*HA*	*direction of hot air flow,*
vstop zraka,	*AI*	*air inlet,*
kos premoga,	*1*	*coal,*
zgorevalna cev,	*2*	*combustion pipe,*
nosilni element premoga,	*3*	*crucible,*
opazovalno okno,	*4*	*optical window,*
stabilizator toka zraka,	*5*	*air flow stabilizer,*
zajem produktov zgorevanja;	*6*	*sampling of flue gases;*

Sl. 1. *Merilni stavek*

Fig. 1. *The experimental device*

Glede na izjemno zapletenost procesa ni bilo mogoče izdelati zadovoljivega matematičnega modela, ki bi ob upoštevanju vseh kemičnih reakcij hkrati popisal tudi prenos toplote in snovi ter hidrodinamične razmere v področju mejne plasti nad površino gorečega kosa in čelom plamena. Zato smo na podlagi eksperimentalnih podatkov procesa zgorevanja kosa premoga, z vodoravno postavljenimi plastnicami, proces zgorevanja popisali z reduciranimi veličinami.

3 MODEL ZGOREVANJA KOSA PREMOGA

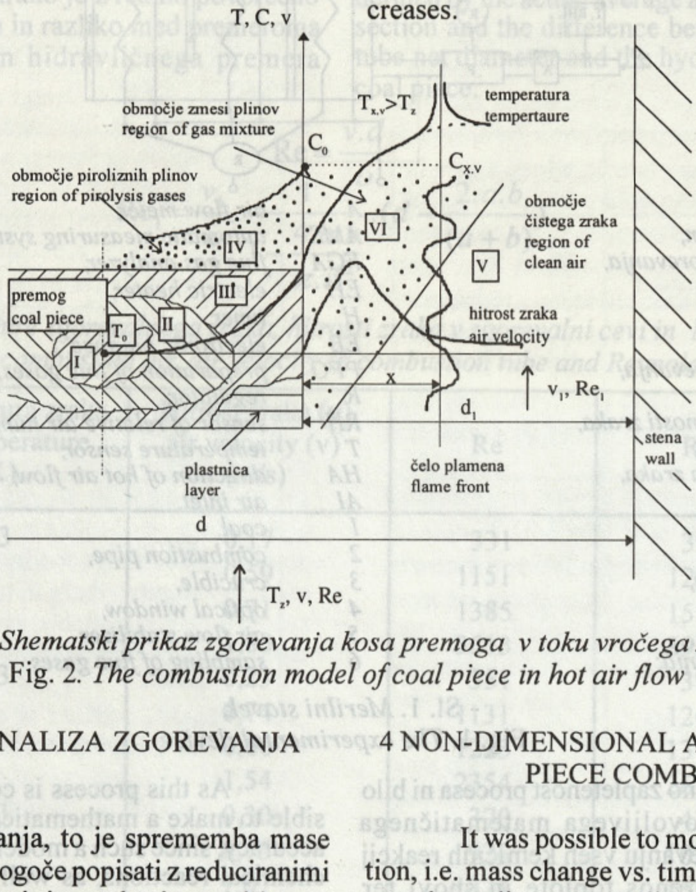
Ko je kos premoga vstavljen v okolje višje temperature, se prične segrevati, kar je shematsko prikazano na sliki 2. Ko so ustvarjeni pogoji za vžig, zagori. Ob posamezni površini ali okoli kosa goriva se razvije difuzni plamen. Pirolizne pare in plini, ki izhajajo iz premoga, se vžigajo pod vplivom sevanja plamena in vročega zraka, vse dokler izhajajo iz mase goriva. Model zgorevanja razdelimo v šest con. Trdna

As this process is complex, it was not possible to make a mathematical model of satisfactory accuracy, since such a model must encompass all the chemical reactions, as well as time heat and mass transfer and hydrodynamic conditions in the boundary layer area between the surface of a burning piece and the flame area at the same time. Instead, the combustion process was described in a non-dimensional way on the basis of experimental data on the coal piece combustion process. The shape of the coal piece was that of a recumbent square with horizontal layers.

3 COMBUSTION MODEL

Once the coal piece is introduced in elevated temperature ambient, it is heated, what is shown in Fig. 2. When the ignition conditions are created, it inflames. At individual surface or around the coal piece a diffusive flame develops. Pyrolysis vapours and gases exiting from the coal are ignited by the influence of flame radiation and hot air while they are coming from the fuel mass. Combustion model faza je še neaktivirana sredica kosa premoga (I), sledita ji cona pirolize (II) in cona nastajanja koksa (III). Območje plinske faze je mešanica reaktivnih plinov goriva (IV) in zraka (V), ki sestavljata območje zmesi reaktivnih plinov in zraka (VI). Trdna in plinasta faza sta ločeni z zelo tankim difuznim plamenom. Čelo plamena nastane na srednji oddaljenosti od kosa goriva (x). Plamen se stabilizira v področju stehiometrične koncentracije hlapnih snovi, ki se širijo od kosa premoga v okolico, in kisika, ki prodira iz okolice proti kosu. Čim večja je hitrost uplinjanja in/ali čim nižja je hitrost prodiranja kisika, tem dlje od kosa se oddalji stabilen plamen hlapnih snovi.

is divided into six zones. Solid phase is not yet activated core of the coal piece (I), followed by pyrolisys phase (II) and coke forming phase (III). The gas phase is a mixture of reacting gases of fuel (IV) and air (V) composing the region of reacting gases and air (VI). The solid and gaseous phases are separated by a thin diffusive flame. The flame front is formed at certain distance from the coal piece (x). The flame stabilises in the region of stechiometric concentration of volatile matter spreading from the coal piece to its vicinity and oxygen penetrating from the surroundings towards the piece. With greater gasification velocity and/or smaller oxygen penetration velocity, the size of stable volatile fumes out of the coal piece increases.



Sl. 2. *Shematski prikaz zgorevanja kosa premoga v toku vročega zraka*
Fig. 2. *The combustion model of coal piece in hot air flow*

4 REDUCIRANA ANALIZA ZGOREVANJA

Hitrost zgorevanja, to je sprememba mase goriva po času, je bilo mogoče popisati z reduciranimi veličinami, ki popisujejo reducirano hitrost zgorevanja v odvisnosti od reduciranega časa.

Ob analizi procesa zgorevanja kosa premoga smo ugotovili pojave nezveznosti, ki jih ni mogoče modelirati. Med zgorevanjem nastajajo, v določenih razmerah, tako velike notranje napetosti v kosu gorečega premoga, da se razsloji ali/in razpade na več delov. S tem se bistveno poveča njegova površina ter pospešijo procesi, ki so vezani na aktivnost površine (sušenje, uplinjanje, zgorevanje). Površina je v dosedanjem modeliranju, predvsem manjših granulacij premoga, pogosto uporabljen parameter ([3] in [14]). Ker pa v procesu zgorevanja kosa premoga lahko enoznačno definiramo le začetno površino, tega parametra zaradi njegove nestalnosti nismo vnesli v naš model. Zamenjali smo ga s spremembo mase po času.

4 NON-DIMENSIONAL ANALYSIS OF COAL PIECE COMBUSTION

It was possible to model the rate of combustion, i.e. mass change vs. time, in a non-dimensional way depending on non-dimensional time.

During the analysis of the process of coal piece combustion, non-continuos phenomena were observed, which could not be modelled. During the process of combustion under known conditions, stress is generated in the coal piece which cause the decomposition of the piece into several smaller pieces. This increases the surface area of the piece, and all processes associated with surface area (drying, gasification, combustion) are accelerated. The surface of the coal piece is a parameter frequently used in current models for small coal piece sizes ([3] and [14]). Since in the process of coal piece combustion, only the initial surface area of the piece can be uniformly defined due to its variability, that parameter was not used in the presented model; it was replaced by coal piece mass change vs. time.

Da bi bilo mogoče rezultate eksperimentalnih raziskav uporabiti tudi v različnih drugih razmerah, smo z normiranjem posameznih parametrov in korelacijsko analizo skušali pridobiti splošne zakonitosti pri zgorevanju premoga v kosu. Med najpomembnejšimi korelacijami sta sprememba mase po času, to je hitrost zgorevanja, in vpliv temperature zgorevalnega zraka na hitrost zgorevanja. V ta namen smo definirali:

- reducirano maso kot razmerje med začetno (m_o) in trenutno maso (m) preskušanca:

In order to apply the experimented research results under different conditions, the general principles of coal piece combustion were investigated through the application of certain standardized parameters and correlation analysis. The most important correlations are the mass-change over time (combustion rate) and the influence of air temperature on the combustion rate. For this purpose, the following definitions were introduced:

- non-dimensional mass as initial mass (m_o) to actual mass (m) ratio of coal piece:

$$\zeta = \frac{m}{m_0} \tag{3}$$

- reducirani čas procesa kot razmerje med opazovanim časom (τ) in celotnim časom zgorevanja (τ_∞):
- non-dimensional time as actual time (τ) to total combustion time (τ_∞) ratio:

$$\eta = \frac{\tau}{\tau_\infty} \tag{4}$$

- reducirano hitrost zraka kot razmerje realne hitrosti zraka (v_r) in normne hitrosti zraka (v_n), ki jo definiramo z 1 m/s:
- non-dimensional air velocity as real air velocity (v_r) to norm air velocity (v_n) ratio defined in 1 m/s:

$$v = \frac{v_r}{v_n} \tag{5}$$

- reducirano hitrost odgorevanja, ki vključuje vse faze procesa od sušenja, uplinjanja, zgorevanja s plamenom in dogorevanja koksnega ostanka, zapišemo kot razmerje reducirane mase (ζ) in reduciranega časa (η), oziroma med trenutno in povprečno hitrostjo odgorevanja kosa premoga:
- non-dimensional combustion rate incorporating all phases (drying, gasification, combustion by flame, final combustion of coke remnants), which can be written as non-dimensional mass (ζ) to non-dimensional time (η) ratio or actual to average combustion rate ratio:

$$\psi = \frac{\zeta}{\eta} = \frac{m}{m_o} \cdot \frac{\tau_\infty}{\tau} = \frac{m}{\tau} / \frac{m_o}{\tau_\infty} \tag{6}$$

- reducirano temperaturo kot razmerje temperature zgorevalnega zraka (T_z) in temperature okolice (T_o):
- non-dimensional temperature defined as combustion air temperature (T_z) to ambient temperature (T_o) ratio:

$$\Theta = \frac{T_z}{T_o} \tag{7}$$

Za naše preskuse dobimo pri temperaturi okolice 293 K:

For experiments described in this article, for ambient temperature of 293 K, it is obtained:

T = 623 K $\Theta = 2.13$
T = 723 K $\Theta = 2.47$
T = 823 K $\Theta = 2.81$

Ker so posamezni parametri odvisni medsebojno ter od temperature (T) in hitrosti zraka (v), lahko zapišemo:

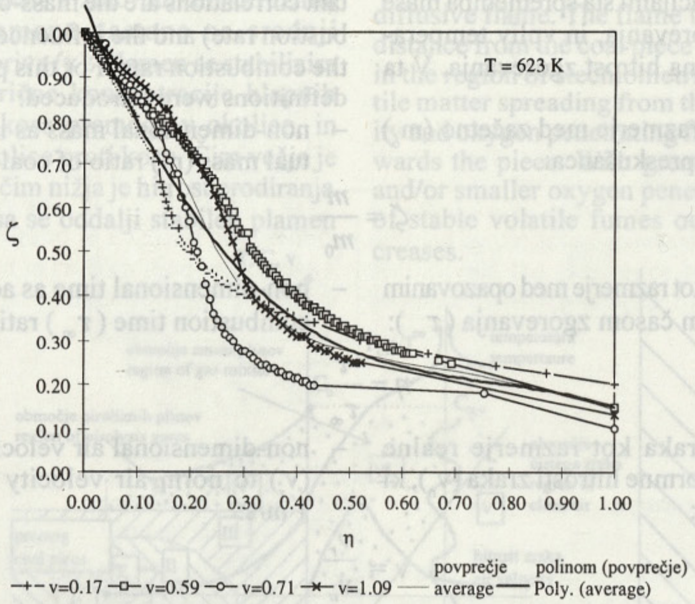
As particular parameters are interdependent and depend in addition on air temperature (T) and air velocity (v), it can be written:

$$\zeta = \zeta\,(T, v) \tag{8}$$
$$\eta = \eta\,(T, v) \tag{9}$$
$$\psi = \psi\,(T, v) \tag{10}$$
$$\tau_\infty = \tau_\infty(T, v) \tag{11}$$

Na sliki 3 in 4 so prikazani rezultati preskusov zgorevanja kosov premoga pri zgorevalni temperaturi zraka 623 K in 823 K v reduciranih

Figures 3 and 4 show the results of experiments of coal pieces combustion at temperatures of 623 K and 823 K in non-dimensional coordinates koordinatah ζ, η s parametrom reducirane hitrosti zraka. Pri različnih reduciranih hitrostih poteka proces zgorevanja z majhnimi odstopanji. Delno izstopa predvsem potek procesa zgorevanja kosa premoga pri reducirani hitrosti 0,71.

ζ, η, with non-dimensional air velocity serving as the parameter. The combustion process takes place at different non-dimensional rates with small deviations. The combustion of a coal piece at a non-dimensional rate of 0.71 is markedly different.



Sl. 3. *Odvisnost reducirane mase kosa premoga v odvisnosti od reduciranega časa pri temperaturi zraka 623 K*

Fig. 3. *Non-dimensional coal piece mass against non-dimensional time at an air temperature of 623 K*

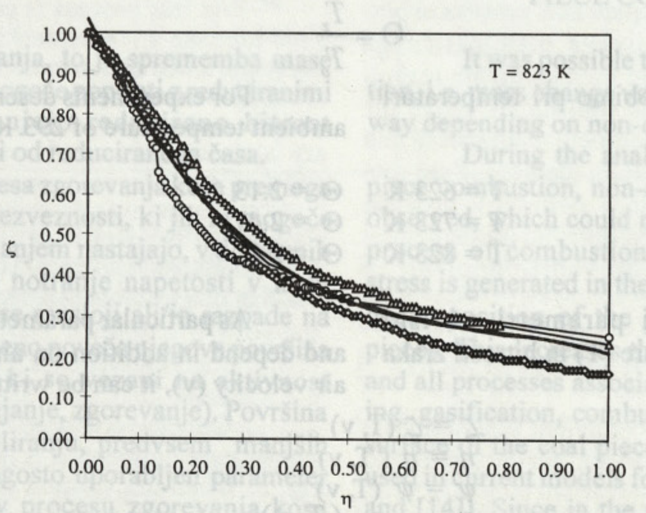
Medsebojno odvisnost reducirane mase in reduciranega časa za eksperimente temperature izrazimo s polinomom 3. stopnje. Koeficienti korelacije, podani ob koncu enačb, izkazujejo veliko stopnjo prilagajanja:

The interdependence of non-dimensional mass and non-dimensional time is expressed by a third order polynomial. The correlation coefficients given at the end of the equations show a large degree of accuracy:

$$T = 623\ \mathrm{K} \qquad \zeta = -1{,}56 .\ \eta^3 + 3{,}65 .\ \eta^2 - 3{,}00\ \eta + 1{,}06 \qquad R^2 = 0{,}991 \tag{12}$$

$$T = 723\ \mathrm{K} \qquad \zeta = 0{,}51 .\ \eta^3 - 0{,}30 .\ \eta^2 - 1{,}05\ \eta + 1{,}04 \qquad R^2 = 0{,}998 \tag{13}$$

$$T = 823\ \mathrm{K} \qquad \zeta = -1{,}39 .\ \eta^3 + 3{,}23 .\ \eta^2 - 2{,}66\ \eta + 1{,}03 \qquad R^2 = 0{,}997 \tag{14}$$

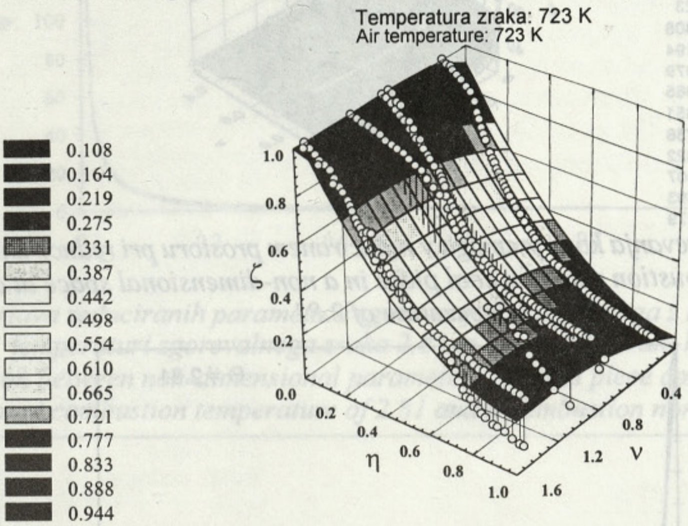


Sl. 4. *Odvisnost reducirane mase kosa premoga v odvisnosti od reduciranega časa pri temperaturi zraka 823 K*

Fig. 4. *Non-dimensional coal piece mass against non-dimensional time at an air temperature of 823 K*

Za nazornejši prikaz prikažemo zgorevanje kosa premoga v tridimenzionalnem diagramu z upoštevanjem reducirane hitrosti zraka kot tretje dimenzije. Na sliki 5 je prikazana reducirana masa zgorevanja kosa premoga pri temperaturi zgorevalnega zraka 723 K v odvisnosti od reduciranega časa in reducirane hitrosti zgorevalnega zraka.

To help provide a better understanding, the combustion of coal pieces in a three-dimensional diagram can be expressed by non-dimensional air velocity. Fig. 5 shows non-dimensional coal piece mass during its combustion at an air temperature of 723 K against non-dimensional time and non-dimensional air velocity.



Sl. 5. *Reducirana masa zgorevanja kosa premoga v odvisnosti od reduciranega časa pri temperaturi zgorevalnega zraka 723 K*

Fig. 5. *Non-dimensional coal piece mass vs. non-dimensional time during combustion at air temperature of 723 K*

Upoštevaje vse tri parametre dobimo z reducirano maso odgorelega premoga naslednje odvisnosti:

Bearing in mind all three parameters the following expressions of non-dimensional burnt coal mass are obtained:

$$T = 623\ K \qquad \zeta = 1,60\,\eta^2 - 2,18.\,\eta - 0,14\,v^2 + 0,31\,v - 0,31\,v.\,\eta + 0,91 \qquad (15),$$

$$T = 723\ K \qquad \zeta = 0,76\,\eta^2 - 1,63.\,\eta - 0,11\,v^2 + 0,28\,v + 0,02\,v.\,\eta + 0,93 \qquad (16),$$

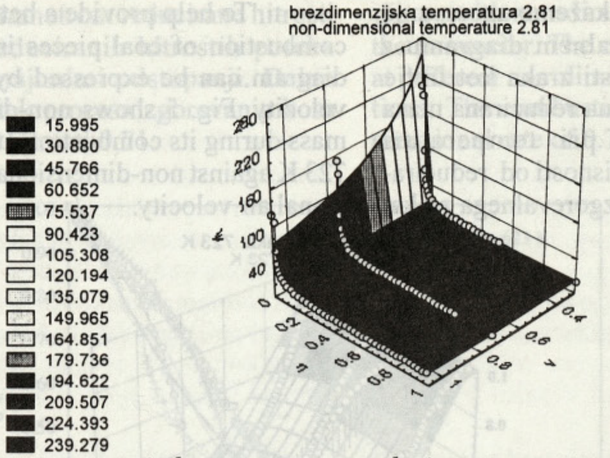
$$T = 823\ K \qquad \zeta = 1,28\,\eta^2 - 1,87.\,\eta - 0,49\,v^2 + 0,75\,v - 0,15\,v.\,\eta + 0,75 \qquad (17).$$

Iz podanih enačb je razvidno, kako se temperatura kaže v koeficientih polinoma. Ker ima temperatura zgorevalnega zraka velik vpliv na spremembo koeficientov reduciranih veličin, v nadaljnem koraku vpeljemo tudi za temperaturo zgorevalnega zraka reducirano veličino (7). Reducirano hitrost odgorevanja kosa premoga podajamo v reduciranem prostoru (sl. 6) v odvisnosti od reduciranih parametrov hitrosti zgorevanja, časa, hitrosti zgorevalnega zraka in z upoštevanjem reducirane temperature. Na sliki 7 je reducirana hitrost, prikazana v ravnini v odvisnosti od reduciranega časa za primer reducirane temperature 2,81 in različnih reduciranih hitrostih zgorevalnega zraka.

Razvidno je, da se reducirane hitrosti zgorevanja kosa premoga pri različnih reduciranih hitrostih zgorevalnega zraka prekrivajo. Tudi reducirana temperatura nima izrazitega vpliva na reducirano hitrost odgorevanja. To pa pomeni pomembno ugotovitev, da je reducirana hitrost odgorevanja kosa premoga neodvisna od reducirane hitrosti zgorevalnega zraka in njene reducirane temperature. V reduciranem prostoru se celotni proces zgorevanja kosa premoga praktično konča že v začetnih 15 % reduciranega časa.

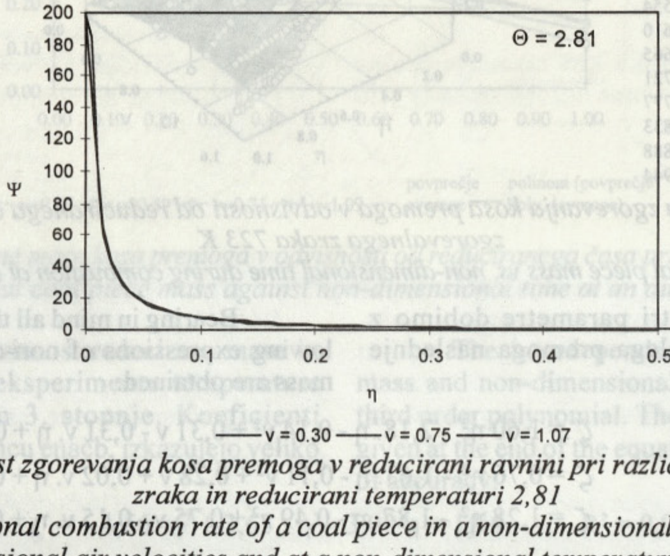
It is evident from the above equations that the temperature is embedded within the polynomial coefficients. It is evident that the air temperature influences the coefficients of non-dimensional values. For this reason, the combustion air temperature had to be treated as non-dimensional as well (7). Non-dimensional combustion rate of a coal piece is given in non-dimensional space (Fig. 6) against non-dimensional parameters of combustion rate, time, air velocity and non-dimensional temperature. Figure 7 shows non-dimensional rate in a layer against non-dimensional time at a non-dimensional temperature of 2.81 for different non-dimensional air velocities.

It is evident that non-dimensional combustion rates for different non-dimensional air velocities overlap. The non-dimensional temperature also does not have a significant effect on the non-dimensional combustion rate, which means that the non-dimensional combustion rate of a coal piece does not depend on the non-dimensional air velocity and non-dimensional air temperature. In the non-dimensional space the combustion process ends within the initial 15% of the non-dimensional time.



Sl. 6. *Reducirana hitrost zgorevanja kosa premoga v reduciranem prostoru pri reducirani temperaturi 2,81*

Fig.6. *Non-dimensional combustion rate of a coal piece in a non-dimensional space at a non-dimensional temperature of 2.81*



Sl. 7. *Reducirana hitrost zgorevanja kosa premoga v reducirani ravnini pri različnih reduciranih hitrostih zraka in reducirani temperaturi 2,81*

Fig. 7. *Non-dimensional combustion rate of a coal piece in a non-dimensional layer at different non-dimensional air velocities and at a non-dimensional temperature of 2.81*

Po analizi potekov eksperimentalnih podatkov oblikujemo splošni model (sl. 8) odgorevanja kosa premoga v reduciranih veličinah. Za razmerje $\psi = \psi(\eta)$ dobimo izraz:

Based on experimental data analysis, a general model of coal piece combustion is given in terms of non-dimensional values (Fig. 8). For the relation $\psi = \psi(\eta)$, the following expression is obtained:

$$\psi = \frac{1}{\eta} - 1 \qquad (18).$$

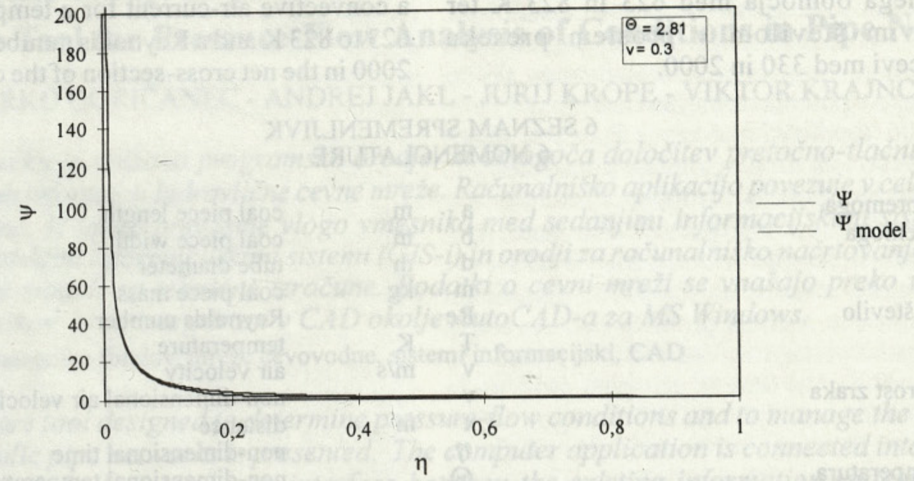
Z eksplicitnim upoštevanjem mase premoga (3), zgorevalnega časa (4) in enačbe (6) dobimo:

Taking into account coal piece mass (3), combustion time (4) and equation (6) explicitly:

$$\frac{m}{m_0} = 1 - \frac{\tau}{\tau_\infty} \qquad (19).$$

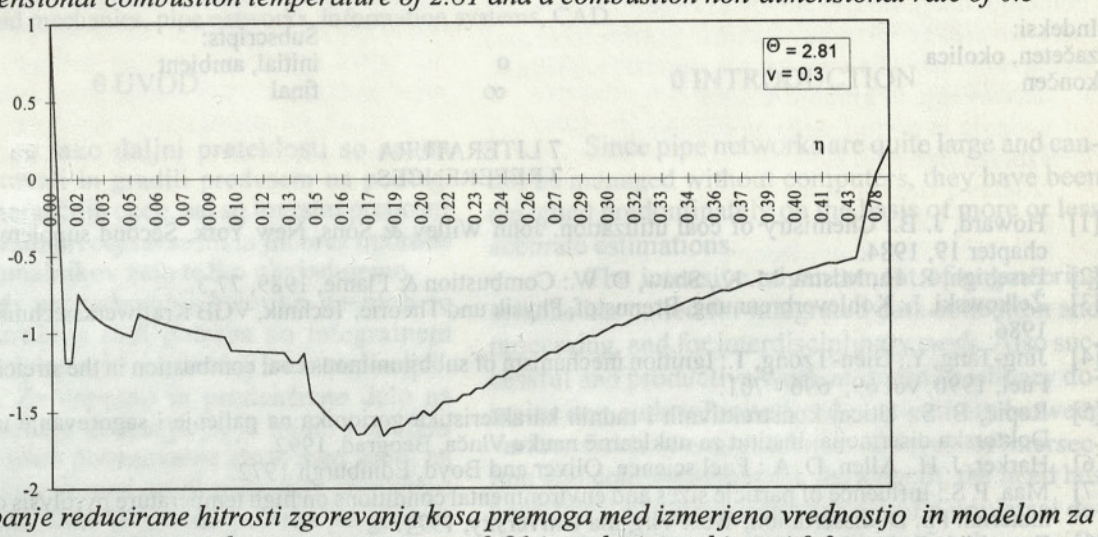
S tem smo popisali proces zgorevanja v splošni obliki, ki je praktično neodvisen od hitrosti in temperature zgorevalnega zraka. Oba parametra sta namreč implicitno skrita v spremembi mase kosa premoga (m), trenutnega (τ) in končnega (τ_∞) časa. Odstopanje modela od izmerjenih (praktičnih) vrednosti, za primer reducirane temperature 2,81 in reducirane hitrosti zgorevalnega zraka 0,3, je razvidno s slike 9. Odstopanje reducirane hitrosti zgorevanja kosa premoga med izmerjeno vrednostjo in modelom je zanemarljivo.

This expression describes the combustion process of a coal piece in general, which is virtually independent of air velocity and air temperature, since both parameters are implicitly hidden in the changes of coal piece mass (m), the actual (τ) and final time (τ_∞). The discrepancies of the model from the measured data values in the case of a non-dimensional temperature of 2.81 and a non-dimensional air velocity of 0.3 are shown in Fig. 8. The discrepancy between the measured and computed values of the non-dimensional combustion rate of coal piece is negligible.



Sl. 8. *Primerjava reduciranih parametrov zgorevanja kosa premoga z modelom pri reducirani temperaturi zgorevalnega zraka 2,81 in njeni reducirani hitrosti 0,3*

Fig. 8. *Comparison between non-dimensional parameters for coal piece combustion and the model at a non-dimensional combustion temperature of 2.81 and a combustion non-dimensional rate of 0.3*



Sl. 9. *Odstopanje reducirane hitrosti zgorevanja kosa premoga med izmerjeno vrednostjo in modelom za primer reducirane temperature 2,81 in reducirane hitrosti 0,3*

Fig. 9. *Differences between non-dimensional combustion rate of a coal piece and the model for a non-dimensional temperature of 2.81 and a non-dimensional rate of 0.3*

Ker so bile opravljene raziskave le na eni vrsti premoga in v relativno ozkih mejah, je potrebno model po enačbi (19) preveriti z nadaljnjimi raziskavami drugih vrst premogov in biomase.

Since the experiments were carried out with one coal and in relativly narrow bound only, the model of eq. (19) has to be verified by further research on various coals and biomass.

5 SKLEP

Raziskovali smo odgorevanje kosa rjavega premoga, vstavljenega v preskuševalno napravo z vodoravno ležečimi plastnicami, oziroma s pravokotno ležečimi plastnicami glede na smer zgorevalnega zraka. Na podlagi eksperimentalnih rezultatov zgorevanja kosov premoga in uvedbe reduciranih veličin za hitrost in čas zgorevanja kosa premoga ter reduciranih veličin za temperaturo in hitrost oksidanta - zraka smo izdelali splošni model, s katerim popišemo zmanjševanje njegove mase. Model omogoča s poznavanjem začetne mase goriva in končnega časa popis nezgorele mase zgorevanja

5 CONCLUSION

Research was conducted into combustion of brown coal piece. Combustion took place in an experimental device with horizontal layers lying perpendicular to the direction of combustion air flow. On the basis of experimental data and the introduction of non-dimensional values for combustion time, combustion rate and temperature, and air velocity, a general model was made for the calculation of coal piece mass reduction during the combustion process. If the initial mass and total combustion of unburned coal piece mass are known, the model allows a math-rjavega kosa premoga v konvektivnem toku zraka, temperaturnega območja med 623 in 823 K ter Reynoldsovim številom v prostem preseku zgorevalne cevi med 330 in 2000.

ematical description of unburned coal piece mass in a convective air-current for a temperature range of 623 to 823 K and a Reynolds number range of 330 to 2000 in the net cross-section of the combustion tube.

6 SEZNAM SPREMENLJIVK
6 NOMENCLATURE

dolžina kosa premoga	a	m	coal piece length
širina kosa premoga	b	m	coal piece width
premer cevi	d	m	tube diameter
masa	m	kg	coal piece mass
Reynoldsovo število	Re		Reynolds number
temperatura	T	K	temperature
hitrost	v	m/s	air velocity
reducirana hitrost zraka	v		non-dimensional air velocity
razdalja	x	m	distance
reducirani čas	η		non-dimensional time
reducirana temperatura	Θ		non-dimensional temperature
čas	τ	s	time
kinematična viskoznost	υ	m^2/s	kinematic viscosity
reducirana hitrost zgorevanja	ψ		non-dimensional combustion rate
reducirana masa	ζ		non-dimensional mass

Indeksi:		Subscripts:
začeten, okolica	o	initial, ambient
končen	∞	final

7 LITERATURA
7 REFERENCES

[1] Howard, J. B.: Chemistry of coal utilization. John Willey & Sons, New York, Second supplementary volume, chapter 19, 1984.

[2] Essehigh, R. H., Mistra, M. K., Shaw, D. W.: Combustion & Flame, 1989, 77,3.

[3] Želkowski, J.: Kohleverbrennung, Brennstof, Physik und Theorie, Technik, VGB Kraftwerkstechnik GMBH, Essen 1986.

[4] Jing-Tang, Y., Gien-Tzong, T.: Ignition mechanism of subbituminous coal combustion in the stretched - flow field. Fuel, 1990, vol 69, 696 - 701.

[5] Repič, B. S.: Uticaj konstruktivnih i radnih karakteristika gorionika na paljenje i sagorevanje ugljenog praha. Doktorska disertacija, Institut za nuklearne nauke Vinča, Beograd, 1992.

[6] Harker, J. H., Allen, D. A.: Fuel science. Oliver and Boyd, Edinburgh 1972.

[7] Maa, P. S.: Influence of particle sizes and environmental conditions on high temperature pyrolysis of the cellulosic material. Ph. D. dissertation, West Virginia University, 1971.

[8] Essenhigh, R. H.: Combustion and flame propagation in coal systems: A review, 16th International Symposium of Combustion, Pittsburg, ZDA, 1977, 353-372.

[9] Reznjakov, A. B., Basina, I. P.: Gorenie natural'nogo tverdogo topliva. Nauka, Alma Ata, 1968.

[10] Di Blasi, C.: Ignition and flame spread across solid fuels. Oran E.S., Boris J.P.: Numerical Aproaches to Combustion Modeling, vol. 138, Progress in Astonautics and Aeronautics, AIAA, 1991.

[11] Chomaik, J.: Combustion, a study in theory, fact and application. Gordon and Breach Science Publishers, New York 1990.

[12] Fu, W., Zhang, Y., Han, H., Duan, Y.: A study on devolatization of large coal particle. Combustion and Flame 70, 1987, 253 - 266.

[13] Butala, V.: Zgorevanje rjavega premoga v kosih. Doktorska disertacija. Univerza v Ljubljani, Fakulteta za strojništvo, Ljubljana 1997.

[14] Joksimovič - Tjapkin, S.: Procesi sagorevanja. Univerza v Beogradu, Tehnološko metalurški fakultet, Beograd 1987.

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