

Primernost optičnih lastnosti slovenskih premogov za uplinjanje s koncentriranim sončnim sevanjem

The Radiative Properties of Slovenian Coals as an Absorptive Substance for Gasification by Concentrated Solar Radiation

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V prispevku je predstavljena zamisel o uplinjanju premoga s koncentriranim sončnim sevanjem. Izračuni so opravljeni na podlagi Mieove teorije sipanja elektromagnetnega valovanja z okroglimi delci poljubnih velikosti. Obravnavane so nekatere posebnosti računanja po Mieovi metodi, predstavljen je nov kriterij za zadostno konvergenco vrst pri računanju amplitudnih funkcij, predstavljen pa je tudi nov faktor učinkovitosti, s katerim je mogoče računati odbiti del vpadnega sevanja. Optične lastnosti delcev izbranih premogov, ki določajo zmožnosti absorbiranja in odbijanja sevanja, so izračunane po njihovi kemični sestavi. Lastnosti izbranih premogov so primerjane z lastnostmi drugih snovi iz ogljika, to so pirolitični ogljik, koks, antracit in črni premog. Izračunane vrednosti spektralnih količin so na podlagi standardiziranih spektralnih gostot sončnega sevanja preračunane v globalne vrednosti. Izbira primernih velikosti in snovi delcev temelji na količini odbitega in absorbiranega energijskega toka vpadnega sončnega sevanja. Določene so najbolj primerne velikosti delcev rjavega premoga za plinsko suspenzijo, pri katerih dosega postopek uplinjanja rjavega premoga s koncentriranim sončnim sevanjem velike izkoristke.

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(Ključne besede: premogi slovenski, lastnosti optične, uplinjanje premoga, sevanje sončno)

In this paper the idea of coal gasification by concentrated solar radiation is described. The calculations are performed on the basis of Mie's scattering theory for spheres of arbitrary sizes. Some aspects of the Mie calculations are discussed, a new criterion for the sufficient condition for the convergence of the amplitude functions is presented and a new efficiency factor for reflection is introduced. The optical properties of selected coals are determined on the basis of their chemical composition. The absorption and reflection properties of the coals and carbonaceous materials, such as carbon black, coke, anthracite and black coal, are determined. The results of the spectral properties' calculations are extended to the global properties on the basis of the spectral intensities of the solar radiation. The conditions for a high-efficiency process involving brown-coal gasification are defined by a determination of the most suitable sizes of brown coal particles for the particle-gas suspension.

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(Keywords: Slovenian coals, optical properties, coal gasification, solar radiation)

0 UVOD

Spreminjanje energije koncentriranega sončnega sevanja v toploto plinov je mogoče posredno prek segrelih sten absorberja ali neposredno s prostorninskim absorbiranjem sončnega sevanja, pri katerem se energija prenaša med širjenjem skozi plast plina v absorberju. Prozorne, optično neaktivne pline naredimo absorptivne z dodajanjem trdnih, absorptivnih delcev v plin. Ta postopek je prvi opisal Hunt [1]. Take suspenzije je v absorberjih mogoče segreti s koncentriranim sončnim sevanjem do temperatur nad 700 °C. Zamisel uspešnega prostorninskega absorbiranja

0 INTRODUCTION

Heating gases to high temperatures by concentrating solar energy can be performed indirectly from hot receiver walls or directly in the gas itself by volumetric absorption. In the case of transparent gases, the absorption of the solar radiation can be achieved by adding solid, absorptive particles to the gas. This process was first described by Hunt [1]. In such absorbers the suspension can be heated to temperatures over 700 °C. The idea is based on the fact that a black fluid can act like a black body, and therefore be an

temelji na predpostavki, da vlogo črnega telesa prevzame prostornina črnega plina, ki naj tako postane idealni absorber sevanja. Lastnostim črnega telesa se približamo, če telo ni prozorno in odbija zanemarljivo majhen del vpadnega sevanja. Iz teh pogojev izhaja, da morajo imeti v plin dodani delci poudarjeno lastnost absorptivnosti in tudi kolikor je le mogoče šibko zmožnost odbijanja sončnega sevanja. Takšne lastnosti so tudi pogoj za velik izkoristek postopka v absorberju. Ker je specifična površina delcev prahu zelo velika, tudi več ko 50 kvadratnih metrov na gram snovi, se toplotni tok, ki ga delci absorbirajo, hitro prenaša v okoliški plin pri zelo majhnih temperaturnih razlikah. Plinu torej temperatura narašča praktično sočasno s temperaturo delcev.

Preizkusi absorbiranja sončnega sevanja v plinskih suspenzijah so pokazali ([2] in [3]), da so delci iz ogljika, ki nastanejo pri pirolitičnem razpadu acetilena, po svojih optičnih lastnostih zelo primerni za uporabo v absorptivni suspenziji. Problematični pa so zaradi visokih stroškov izdelovanja. Zaradi takih okoliščin postanejo kot snov delcev zanimivi tudi drugi naravni materiali iz črnega ogljika, posebno še premogi. Pri uporabi premogovih delcev za absorptivne suspenzije pa se hitro pojavi zamisel o uplinjanju premoga z uporabo zelo koncentriranega sončnega sevanja. Energija, potrebna za postopek uplinjanja premoga, se v takem postopku dobi iz koncentriranega sončnega sevanja in ne iz zgorevalne toplote premoga. Postopek vplinjania poteka v globokem absorberju, kjer je mogoča prostorska absorpcija sevanja skozi dano debelino plasti suspenzije [4]. Nosilni plin je zmes zraka in vodne pare. Namen prispevka je raziskati lastnosti domačih premogov in oceniti njihovo primernost za opisani postopek.

V začetnem delu prispevka je nekaj pozornosti namenjeno tehniki računanja Mieove teorije sipanja. Razvijanje numeričnih modelov za računanje Mieovih algoritmov kljub razvoju računalništva ne spada med trivialne numerične probleme, temveč je tematika s katero se avtorji še danes resno ukvarjajo ([5] in [6]). Predstavljene so nekatere posebnosti in specifične rešitve pri računanju Mieovih algoritmov. Rezultati matematičnih modelov izdelanih v skladu z Mieovo teorijo sipanja, na osnovi katerih so narejeni uporabljeni računalniški programi, so splošno veljavni pri računanju sipanja elektromagnetnega sevanja. Osrednji del prispevka je namenjen sestavi različnih snovi iz ogljika, raziskovanju povezave med zgradbo snovi in lomnimi količniki ter metodam določevanja optičnih lastnosti materialov iz ogljika. Pozornost je predvsem usmerjena na domače rjave premoge. Raziskave optičnih lastnosti, absorbiranja in odbijanja sončnega sevanja so omogočile določitev najbolj primerne vrste snovi in velikost delcev iz teh snovi. Izračunani so absorbirani in odbiti tokovi vpadne energije sončnega sevanja. Za oceno primernosti domačih rjavih premogov kot materiala za absorbiranje koncentriranega sončnega sevanja so uporabljeni podatki, ki so bili dobljeni z predhodno izvedenimi eksperimenti s pirolitičnim ogljikom.

ideal absorber of solar energy. The properties of a black body can be approached if two conditions are satisfied: a negligible fraction of the incident radiation is reflected, and the body must not be transparent. From this it follows that the added particles must have a high absorption ability and the lowest possible ability to reflect solar radiation. Such properties will ensure a highly efficient gas-particle absorber. The surface area per unit mass of the very small particles can be up to $50 \text{ m}^2/\text{g}$, and more in some cases. Which means that the power absorbed by the particles is quickly converted into a thermal energy flux and transferred to the surrounding gas. As a result, the gas temperature increases almost as quickly as the temperature of the particles.

Experiments on the absorption of solar radiation applied to particle-gas suspensions ([2] and [3]) have indicated that acetylene carbon-black particles produced by the pyrolytic decomposition of hydrocarbons are very suitable in terms of their optical properties. Unfortunately, however, the production of carbon-black particles is expensive. For this reason other natural carbonaceous materials are of interest, e.g., coals with the appropriate composition. This realisation led to an idea. The process of coal gasification can be performed with the heat flux from highly concentrated solar radiation in the depth absorber of solar energy by volumetric absorption in a coal-particle-gas solar receiver. In this process the energy needed for volatilisation is obtained from the solar radiation instead of from burning the coal [4]. Carrier gas is the mixture of air and steam. The aim of this paper is to examine the properties of coals, especially domestic coals, and determine their suitability for the described process.

The paper begins with a discussion of some computational aspects of the Mie theory of light scattering by particles. The development of calculation methods for Mie scattering algorithms is not a trivial problem, see, for example, ([5] and [6]). In this paper some useful and interesting features of the Mie scattering-theory calculations are presented. The methods and models from which the programs used for the calculations are derived are applicable to electromagnetic-wave scattering in general. The central sections deal with the composition and optical properties of carbonaceous materials, especially the optical properties of domestic brown coals. The appropriate composition and the sizes of the coal particles are determined, and the absorbed and reflected energy fluxes are calculated. On the basis of the acquired data from experiments on carbon-black particles an estimation of the optical properties of some domestic coals and their suitability as absorptive matter are presented.

1 POSTOPKI RAČUNANJA IN IZHODIŠČA

1.1 Definiranje spektralnih veličin

Majhni, trdni delci sipanjo elektromagnetno valovanje sorazmerno z $\lambda^4 V^2$, in ga absorbirajo sorazmerno z $\lambda^{-1} V$, kjer je λ valovna dolžina vpadnega sevanja in V prostornina delca [5]. Če so torej delci zelo majhni, lahko postane absorpcija prevladujoči pojav. Spekter sončnega sevanja, kjer so gostote spektralnega svetlobnega toka velike, je v območju valovnih dolžin med $0,3 \mu\text{m} \leq \lambda \leq 2,5 \mu\text{m}$.

V tem intervalu je približno 95% energijskega toka sončnega sevanja. Iz navedenega je razvidno, da pomeni pojem "zelo majhni delci" velikosti delcev s premerom enakim in manjšim od valovnih dolžin v navedenem intervalu sončnega sevanja.

Raziskovanje pojavov interakcije delcev in elektromagnetnega valovanja teh velikosti je mogoče z uporabo tako imenovane splošne teorije sipanja oziroma Mieove teorije sipanja z okroglimi delci. Optične lastnosti naključno razporejenih delcev so malo odvisne od oblike teh delcev, zato storimo majhno napako, če delcem premoga, čeprav ni nujno da so okrogli, pripišemo okroglo obliko. Ta predpostavka omogoča, da za računanje optičnih lastnosti premogovih delcev uporabimo Mieovo teorijo sipanja elektromagnetnega valovanja za okrogle delce poljubnih velikosti.

Teorija omogoča opis pojavov sipanja, prostorske porazdelitve sipanja, slabljenja gostote sevanja in absorbiranja elektromagnetnega sevanja z delci. Nazorno je predstavljena v delu Van de Hulst [5], izdelani matematični algoritmi, postopki računanja in računalniški modeli pa so predstavljeni v [6] in [8]. Pri izračunih je upoštevano, da delci lebdijo v prozornem, optično neaktivnem plinu. Rezultate teorije sipanja smo razširili s faktorjem učinkovitosti odboja s katerim lahko izračunamo energijski tok sevanja, ki ga delec odbija v polprostor (2π), to je v smeri proti viru sevanja [7].

Predstavili bomo le nekaj, za razumevanje najbolj potrebnih izrazov in definicij, ki jih nujno potrebujemo pri opisih in utemeljitvah. Najbolj pomembni in uporabni rezultati teorije sipanja so faktorji učinkovitosti, K_{sc} za sipanje, K_{ex} za slabljenje in K_{ab} za absorpcijo, za posamezni delec in za posamezno valovno dolžino svetlobe. S temi faktorji določamo sipani, oslabljeni in absorbirani spektralni energijski tok vpadnega sevanja. Faktor učinkovitosti sipanja je izražen:

$$K_{sc,\lambda} = \frac{1}{x^2} \int_0^\pi [|S_1(m, x, \theta)|^2 + |S_2(m, x, \theta)|^2] \sin \theta d\theta \quad (1),$$

faktor učinkovitosti slabljenja kot:

1 CALCULATION PROCEDURE AND SUBJECT LIMITATIONS

1.1 Definition of the spectral quantities

The scattering of electromagnetic radiation by small spherical solid particles is proportional to $\lambda^4 V^2$ whereas the absorption is proportional to $\lambda^{-1} V$, where λ is the wavelength of the incident radiation and V is the volume of the particle [5]. Thus, for very small particles, absorption becomes the predominant property. The spectrum of solar radiation under consideration is in the wavelength interval $0,3 \mu\text{m} \leq \lambda \leq 2,5 \mu\text{m}$.

This interval includes about 95% of the energy flux of solar radiation. It is clear that that "very small particles" means particles with diameters in the same range as, or smaller than, the wavelength of the spectral solar radiation. When researching the optical properties of such particles, the light-scattering theory introduced by Mie should be applied.

The radiative properties of randomly oriented small particles are not very sensitive to their shape and therefore although the particles of pulverized coal cannot be spherical, the particles discussed in this paper will be considered as homogeneous spheres. This assumption makes it possible to predict the spectral properties of the particles by using the Mie scattering theory for spheres of arbitrary size.

The interpretation of the Mie theory as it applies to the scattering and absorption of electromagnetic radiation by small particles is comprehensively covered by Van de Hulst [5], while the mathematical models and calculation procedures are presented in [6] and [8]. For calculations it was assumed that the particles float in an optically inactive, transparent gas. The final results of the scattering theory were expanded, and an efficiency factor for reflection, K_{re} , which makes it possible to calculate the power reflected by the particle into the hemispherical angle (2π), was introduced [7].

For reasons of brevity, only a few extracts and the definitions of certain quantities applied when solving the given problem will be presented. The most important results of the scattering theory are the efficiency factors for scattering K_{sc} , extinction K_{ex} , and absorption K_{ab} , for individual particles. These factors make it possible to determine the scattered, the extincted and the absorbed parts of the incident power of the spectral radiation. The efficiency factor for scattering is expressed as:

the efficiency factor for extinction as:

$$K_{ex,\lambda} = \frac{4}{x^2} \operatorname{Re}\{S(m, x, 0)\}. \quad (2).$$

Faktor učinkovitosti absorpcije se računa posredno z izrazom:

The efficiency factor for the absorption is calculated indirectly from the equation:

$$K_{ab,\lambda} = K_{ex,\lambda} - K_{sc,\lambda} \quad (3).$$

Faktorji učinkovitosti se nanašajo na spektralne gostote energijskega toka. Računajo se, glede na nihanje električne poljske jakosti, z uporabo dveh komponent amplitudnih funkcij, ki sta kompleksni števili in izraženi s konvergenčnima vrstama:

The resulting efficiency factors, which refer to the spectral intensity, are expressed by the amplitude functions, which are in the form of complex numbers given by a converging series:

$$S_1(m, x, \theta) = \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} (a_n \pi_n + b_n \tau_n) \quad (4)$$

$$S_2(m, x, \theta) = \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} (b_n \pi_n + a_n \tau_n) \quad (5).$$

Funkciji kotne odvisnosti τ_n in π_n v enačbah (4) in (5) sta izraženi z Legendrovimi polinomi in njihovimi odvodi. Kot sipanja θ je določen s smerjo širjenja vala in smerjo opazovanja.

The angular coefficients τ_n and π_n in equations (4) and (5) are defined in terms of Legendre polynomials and their derivatives. The scattering angle θ is determined by the forward direction of the incident wave and the direction of observation.

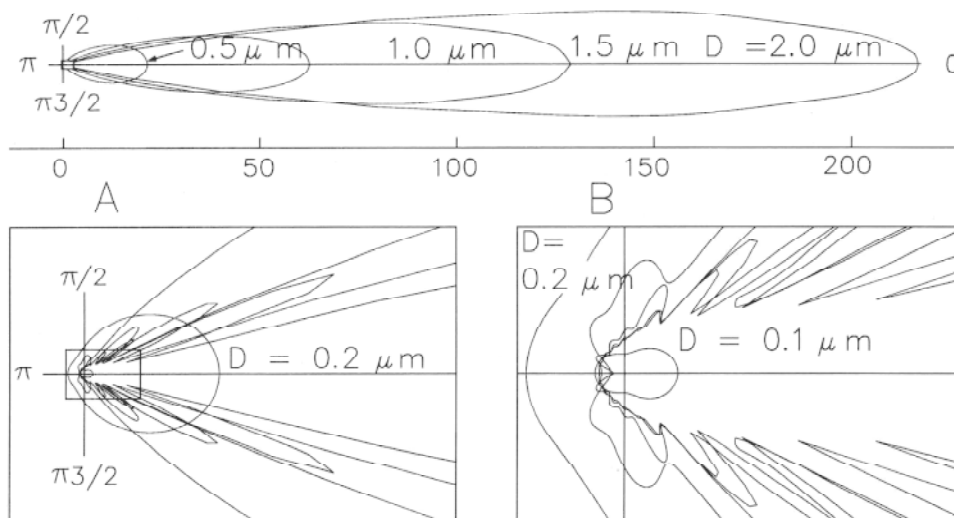
Optične lastnosti absorptivnih snovi določa kompleksni lomni količnik m , ki je tudi spektralna veličina:

The optical properties of the absorbing materials are characterized by the complex refractive index m , which is a spectral quantity:

$$m = n - i\kappa \quad (6)$$

za $n = \operatorname{Re}m$ in $\kappa = \operatorname{Im}m$. Vrednosti realne in imaginarne komponente lomnega količnika so odvisne od snovi in valovne dolžine vpadnega sevanja.

with $n = \operatorname{Re}m$, $\kappa = \operatorname{Im}m$. The values of the real and imaginary parts of the refractive index are functions of the substances and of the wavelengths of the incident radiation.



Sl. 1. Potek funkcije kotne porazdelitve sipanja pri valovni dolžini $\lambda = 0,5 \mu\text{m}$ za trboveljski rjavi premog in za delce premerov $D = 0,1; 0,2; 0,5; 1,0; 1,5; 2,0 \mu\text{m}$. Izsek A je povečani segment iz osnovne slike, izsek B pa je povečan segment iz izseka A.

Fig. 1. Plot of the angular-efficiency function at wavelength $\lambda = 0,5 \mu\text{m}$ for Trbovlje brown coal particles of diameters $D = 0,1, 0,2, 0,5, 1,0, 1,5, 2,0 \mu\text{m}$. The enlargement segment A is abstracted from the basic figure, the segment B is an enlargement of the segment denoted in segment A.

Brezrazsežni parameter velikosti x je izražen z razmerjem premera delca D in valovno dolžino λ vpadnega elektromagnetnega vala:

$$x = \frac{\pi D}{\lambda} \quad (7).$$

Koeficienta sipanja $a_n(x)$ in $b_n(x)$ v enačbah (4) in (5) sta izražena z cilindričnimi funkcijami, $\psi_n(x)$, $\zeta_n(x)$ in $\psi_n(y)$, pri realnem argumentu s polcelim pozitivnim in negativnim indeksom ter z odvodi teh funkcij:

$$a_n(x) = \frac{A_n(y)\psi_n(x) - m\psi_n'(x)}{A_n(y)\zeta_n(x) - m\zeta_n'(x)} \quad (8)$$

$$b_n(x) = \frac{mA_n(y)\psi_n(x) - \psi_n'(x)}{mA_n(y)\zeta_n(x) - \zeta_n'(x)} \quad (9),$$

tu je x realen, in $y = mx$, torej kompleksen. Funkcija $A_n(y)$ v (8) in (9) s kompleksnim argumentom je izražena kot:

$$A_n(y) = \frac{\psi_n'(y)}{\psi_n(y)} \quad (10).$$

Matematični modeli za računanje funkcij sipanja in amplitudnih funkcij ter njihova zgradba so prikazani v literaturi [6] do [8] in jih tu ne bomo obravnavali.

1.2 Faktor učinkovitosti odboja

Izkoristek absorberjev sončne energije je močno odvisen od odbitega toka energije vpadnega sevanja. Ta se iz energijskega toka vpadnega sevanja, ki vstopa v absorber, odbija nazaj proti viru sevanja. Da bi lahko določili odbiti tok energije vpadnega sevanja, smo vpeljali nov faktor, ki smo ga imenovali faktor učinkovitosti odboja [7].

Za ponazoritev pomena tega faktorja lahko uporabimo sliko 1, na kateri so prikazane lastnosti sipanja okoli delcev premoga. Sipanje v prostor okoli delca je prikazano z vrednostmi funkcije kotne porazdelitve sipanja. Središče delca je v prerezu križa, vpadno sevanje se širi od leve proti desni. Za odbito sevanje štejemo tisti del sipanega sevanja, ki se sipa v kot $\Theta: \pi/2, \pi, 3\pi/2$. Polni prostorski kot smo razdelili z ravnino skozi središče delca in pravokotno na vpadno sevanje, na prostorska kota $(2\pi)^+$ v smeri širjenja vpadnega sevanja (naprej) in prostorski kot $(2\pi)^-$ v smeri proti viru vpadnega sevanja (nazaj). Enako smo razdelili izraz (1), s katerim računamo sipanje delca, na faktor za sipanje nazaj in faktor za sipanje naprej [7]:

$$K_{sc,\lambda} = K_{re,\lambda} + K_{for,\lambda} \quad (11).$$

Prvi člen na desni strani enačbe (11) je faktor učinkovitosti odboja:

The dimensionless size parameter x denotes the relation between the particle diameter D and the wavelength of the incident radiation λ :

The scattering coefficients $a_n(x)$ and $b_n(x)$ in equations (4) and (5) are expressed by Ricatti-Bessel functions of half integral order with real and complex arguments $\psi_n(x)$, $\zeta_n(x)$ and $\psi_n(y)$ and their derivatives:

where x is real, and $y = mx$ and is, therefore, complex. The function $A_n(y)$ in (8) and (9) with the complex argument is expressed as:

The structure of the computational schemes for calculating the scattering and amplitude functions are presented in [6] to [8] and will not be discussed in this paper.

1.2 The efficiency factor for reflection

When considering the efficiency of solar-energy absorbers it is very important to know the power that is reflected from the incident radiation power that enters the absorber. In order to determine this energy flux we upgraded the scattering theory by introducing a new efficiency factor for the reflection [7].

As an illustration we can use Fig.1, where the angular-efficiency values are used to present the scattering abilities of the coal particles. The center of the particle is located at the center of the cross, and the incident radiation enters from the left-hand side. The backwards-reflected intensity is determined in terms of the angle $\Theta: \pi/2, \pi, 3\pi/2$. The plane through the center of the particle, perpendicular to the incident radiation, divides the total space around the particle into a hemispherical angle $(2\pi)^+$ in the direction of propagation of the incident radiation (forward), and a hemispherical angle $(2\pi)^-$ in the direction toward the source of the incident radiation (backward). Similarly, the integration in equation (1), which represents the scattering around the particle, is divided into backward scattering and forward scattering [7]:

The first term on the right-hand side of Equation (11) is the efficiency factor for reflection:

$$K_{re,\lambda} = \frac{1}{x^2} \int_{\frac{\pi}{2}}^{\pi} [|S_1(m, x, \theta)|^2 + |S_2(m, x, \theta)|^2] \sin \theta d\theta \quad (12).$$

S tem faktorjem je mogoče računati tok energije, ki se odbija v prostorski kot (2π):

From which the spectral power reflected by the particle into the hemispherical angle (2π) can be calculated:

$$P_{re,\lambda} = K_{re,\lambda} A_c I_{0,\lambda} \quad (13).$$

1.3 Novi kriterij za zadostno konvergenco pri računanju $S_1(\Theta)$ in $S_2(\Theta)$

Zanesljivost računanja amplitudnih funkcij ni odvisna le od zanesljivega izračunavanja posameznih koeficientov $a_n(x)$ in $b_n(x)$. Pomembno odvisna je tudi od tega, koliko členov n koeficientov $a_n(x)$ in $b_n(x)$ bomo v enačbah (4) in (5) pri seštevanju določiti kot zadostno število členov, s katerimi je dosežena zelena točnost rezultata. V literaturi je splošno vzeto, da je potrebno število členov pod znakom seštevanja, s katerimi je zagotovljena zadostna konvergenca, nekaj večje od vrednosti parametra x . Opis problema zadostnega števila seštetih členov je Bohren (1998) [8] opisal dobesedno takole: "Opozoriti moramo bralca, ki ima računalnik velikih zmogljivosti, naj se ne pusti zapeljati razmišljanju, da lahko dosežemo večjo natančnost, če pač seštejemo večje število členov. Računanje funkcij ψ_n po rekurzijskih formulah za naraščajoči n je nestabilno, računati je treba v dvojni natančnosti, zato moramo poskrbeti, da ne generiramo več členov, kakor je nujno potrebno za razumno konvergenco." Rešitev tega problema je za primer kompleksnih lomnih količnikov z $\text{Imm} > 0$ grafično prikazana na sliki 2 v kompleksni ravnini. Prikazan je potek vrednosti členov $a_n(x)$ in $b_n(x)$ v območju $0,1 \leq x \leq 12$ pri $n = 1, 6, 12$ in 14 . Pri vse večjih vrednostih reda n vse več vrednosti funkcij $a_n(x)$ in $b_n(x)$ "izginja" v točki $(0, 0i)$. To je posebno dobro razvidno za vrednosti funkcij pri $\chi = 12$. Ko se n zvečuje in ostaja x nespremenjen, lahko imaginarne komponente izračunanih vrednosti funkcij večkrat dosežejo vrednost nič, kar pa ne drži za realni del. Ta se približa vrednosti nič le enkrat, in to takrat, ko je vrednost n zadosti velika. Očitno je torej, da je edini kriterij za zadostno število členov pod znakom seštevanja v enačbah (4), (5) le zadosti majhna vrednost realne komponente funkcije, torej $\text{Re}\{a_n(x)\} \leq \varepsilon_1$ in $\text{Re}\{b_n(x)\} \leq \varepsilon_2$. Natančnost izračunanih vrednosti $S_1(\Theta)$ in $S_2(\Theta)$ je potem odvisna le od izbrane majhnosti za ε_1 in ε_2 .

1.4 Obnašanje funkcije $A_n(y)$ pri približevanju limitnih vrednosti

Obnašanje funkcije $A_n(y)$ postane zelo zanimivo, ko se zaradi večanja parametra velikosti x povečuje argument y , vrednost m pa ostaja

1.3 The new criterion of sufficient convergence for series $S_1(\Theta)$ and $S_2(\Theta)$

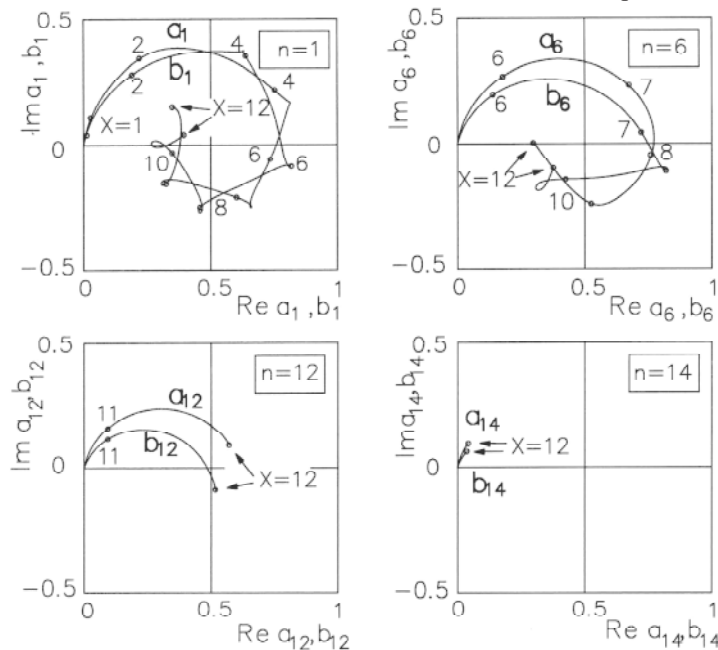
The accuracy of the calculation of amplitude functions does not depend only on the accuracy of the calculation of the scattering coefficients $a_n(x)$ and $b_n(x)$. When the summation in Equations (4), (5) is carried out, the main problem that influences the accuracy appears in determining the sufficient number n of terms $a_n(x)$ and $b_n(x)$ under the symbol for summation in order to achieve the desired precision of the result. In the literature it is generally accepted that the sufficient number of terms required for convergence is slightly more than the value of x . In connection with the problem of the sufficient number of terms, Bohren (1998)[8] pointed out literally: "But lest the reader with a large computer budget be seduced by the idea that if a certain number of terms is good then even more are better, we must issue a warning. Computation of ψ_n by forward recurrence is unstable, and it should be provided, that n is a double-precision variable and that one does not generate more orders of ψ_n than are needed for reasonable convergence." The way to solve this problem for a complex refractive index with $\text{Imm} > 0$ is graphically presented in Fig. 2 on a complex plane. Let us examine the changes to the terms of $a_n(x)$ and $b_n(x)$ in the interval $0,1 \leq x \leq 12$ for $n = 1, 6, 12$ and 14 . For each higher value of n more lower-order values of the functions $a_n(x)$ and $b_n(x)$ "vanish" at the point $(0, 0i)$. This is clearly shown in the picture for the functions values at $\chi = 12$. When n increases and x is constant, the values of the imaginary part of the function can frequently be zero, but this does not hold true for the real part, which approaches zero only once when the value of n increases sufficiently. It is evident that, at given conditions, only the sufficient small real part $a_n(x)$ and $b_n(x)$ value $\text{Re}\{a_n(x)\} \leq \varepsilon_1$ in $\text{Re}\{b_n(x)\} \leq \varepsilon_2$ is the criterion for the sufficient condition for cutting the summation in Equations (4), (5). The precision of the calculated values of $S_1(\Theta)$ and $S_2(\Theta)$ then depends on how small are the selected values of ε_1 and ε_2 .

1.4 Approaching the limit of the function $A_n(y)$

The behaviour of the function $A_n(y)$ when increasing the argument y by the size parameter x at constant m is very interesting. It is worth making a

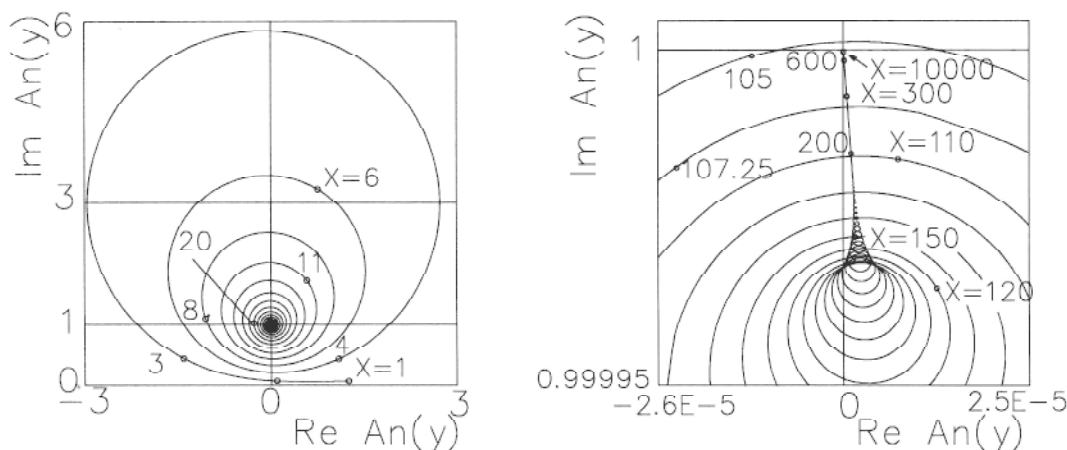
nespremenljiva. Na sliki 3 je graf funkcije $A_n(y)$ ko se njene vrednosti približujejo limiti funkcije $(0,+1i)$. V levem kvadratu potekajo vrednosti funkcije spiralno v širokem območju x -ov. V desnem kvadratu je narisano področje okoli limite, kjer postanejo argumenti veliki. Tu se obnašanje funkcije spremeni iz spiralne oblike v premočrtno, ko se vrednosti funkcije nekoliko asimetrično pomikajo proti limitni točki.

graphical presentation of the function $A_n(y)$ when it approaches its limit value $(0,+1i)$, (Fig. 3). In the left square the values of the function $A_n(y)$ spiral inward regularly within a wide interval of x . In the right square the area is enlarged around the limit, where the arguments of the function become big. The character of the curve changes and the values of the function become slightly unsymmetrical but form a straight line towards the limit point.



Sl. 2. Primeri vrednosti koeficientov sipanja $a_n(x)$ in $b_n(x)$ v območju $0,1 \leq x \leq 12$, za krogle $m = 1,29-0,0472i$ pri štirih različnih vrednostih n . Pri zadosti velikem n , vrednosti koeficientov $a_n(x)$ in $b_n(x)$ povsem "izginejo" v točki $(0,0i)$

Fig. 2. Examples of the values of the scattering coefficients $a_n(x)$ and $b_n(x)$, in the interval $0,1 \leq x \leq 12$, for spheres with $m = 1,29-0,0472i$, for four different values of n . For a sufficient number of terms n , the values of the coefficients $a_n(x)$ and $b_n(x)$, "vanish" fully at the point $(0,0i)$



Sl. 3. Vrednosti funkcije $A_n(y)$, $n = 1$, $m = 1,3-0,05i$, ko se v območju $1 \leq x \leq 10000$ približujejo limitni točki $(0,+1i)$. V kvadratu na desni strani je z veliko povečavo prikazano območje okoli limitne točke in obnašanje funkcije pri približevanju limitni točki.

Fig. 3. The values of function $A_n(y)$, $y = mx$, approaching the limit $(0,+1i)$ for $1 \leq x \leq 10000$, $m = 1,3-0,05i$ and $n = 1$. In the square on the right side is the segment of enlarged area around limit point.

1.5 Računanje globalnih vrednosti

Faktorji učinkovitosti določajo sipane in absorbirane tokove energij, ki jih delci z geometrijskim prerezom A_c prestrežejo iz energijskega toka spektralne gostote sevanja $I_{0,\lambda}$. Za določevanje absorbiranega in sipanega energijskega toka globalnega sevanja moramo z integracijo zbrati vse energijske tokove posameznih spektralnih gostot. Pri določanju gostot globalnega sevanja smo uporabili standardizirane vrednosti gostot spektralnih energijskih tokov sončnega sevanja na zemeljskem površju, v območju valovnih dolžin $0,3 \mu\text{m} \leq \lambda \leq 2,5 \mu\text{m}$, po ISO [9]. Po integriranju spektralnih vrednosti prek območja valovnih dolžin sončnega sevanja dobimo izraze za globalne vrednosti:

$$P_{ab} = A_c \int_{\lambda_1}^{\lambda_2} I_{0,\lambda} K_{ab,\lambda} d\lambda, \quad P_{re} = A_c \int_{\lambda_1}^{\lambda_2} I_{0,\lambda} K_{re,\lambda} d\lambda, \quad P_{in} = A_c \int_{\lambda_1}^{\lambda_2} I_{0,\lambda} d\lambda \quad (14).$$

Izraza P_{ab} in P_{re} določata za posamezni delec energijski tok, ki se je iz vpadnega sončnega sevanja absorbiral v delcu in energijski tok, ki se je iz vpadnega sončnega sevanja odbil v prostorski kot (2π) . Tu so $I_{0,\lambda}$ spektralne gostote sončnega sevanja. Absorbirani tok energije se v delcu spremeni v toploto. Integriranje prek območja valovnih dolžin sončnega sevanja od $\lambda_1 = 0,3 \mu\text{m}$ do $\lambda_2 = 2,5 \mu\text{m}$, s podintervali integriranja $\Delta\lambda = 0,5 \mu\text{m}$, smo izvajali z uporabo Simpsonovega pravila, posebej za vsako velikost delca. Ko izračunane energijske tokove podelimo z energijskim tokom, ki ga posamezni delec fizično prestreže, dobimo izraze P_{ab}/P_{in} in P_{re}/P_{in} , ki pomenijo absorbirani in odbiti energijski tok sončnega sevanja na enoto geometrijskega prereza delca.

2 ŽELENE OPTIČNE LASTNOSTI SNOVIDELCEV

Izgube energije koncentriranega sončnega sevanja, ki vstopa v absorber, so majhne, kadar imajo delci, razen poudarjene zmožnosti absorbiranja tudi kolikor je le mogoče majhno zmožnost odbijanja sončnega sevanja. Ti dve lastnosti sta odvisni od snovi delcev in od njihovih velikosti.

Obstaja široka paleta snovi s poudarjeno lastnostjo absorbiranja. Vsaki od teh snovi je lasten določen tip kompleksnega lomnega količnika. Posebnost za izbrano snov v našem primeru je, da mora imeti šibko zmožnost odbijanja in poudarjeno zmožnost absorbiranja predvsem v območju valovnih dolžin, pri katerih ima sončno sevanje največjo gostoto energijskega toka. Na sliki 4 so prikazane vrednosti faktorjev učinkovitosti za nekatere značilne tipe kompleksnih lomnih količnikov. Vrednosti teh faktorjev določajo, v kombinaciji z velikostjo, tudi optične lastnosti delcev. Senčeno področje v okviru na desni strani slike, ki pripada lomnemu količniku $m = 1,0 - i0,5$, pomeni območje, kjer kombinacija snovi in velikosti delcev daje zaželene lastnosti. V širokem območju valovnih dolžin in velikosti

1.5 Calculation of global quantities

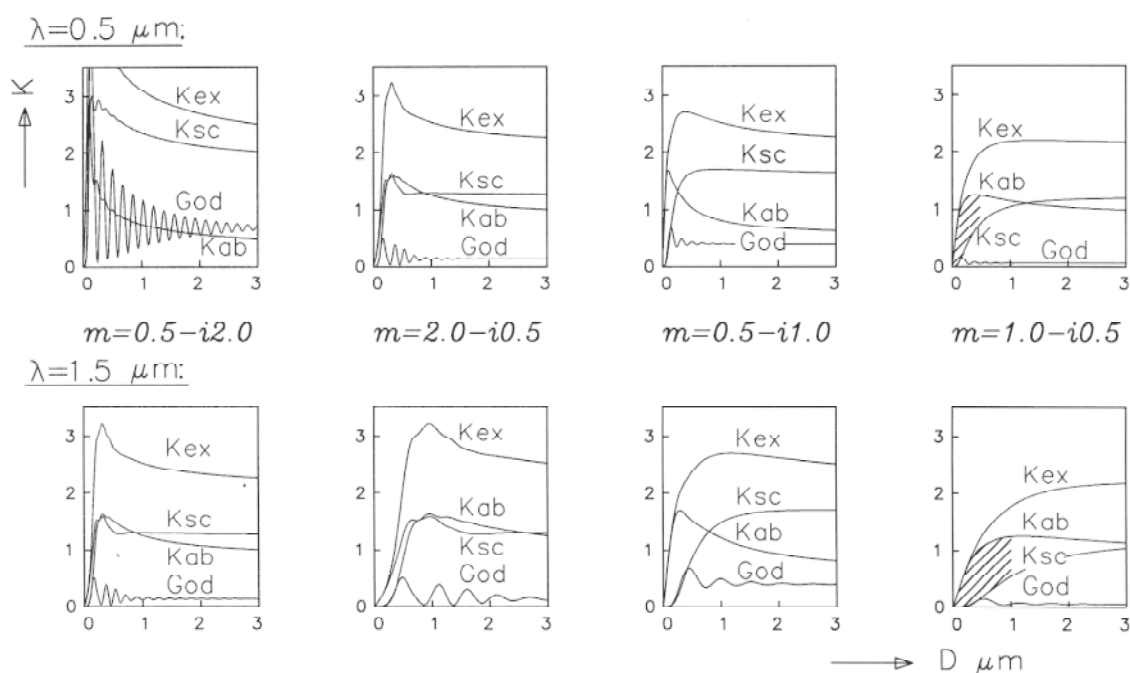
The efficiency factors make it possible to determine the power that a particle with a geometrical cross-section A_c intercepts from the incident radiation with spectral intensity $I_{0,\lambda}$ in the form of scattered and absorbed energy flux. To determine the global absorbed and scattered energy fluxes the energy fluxes of all the spectral intensities should be added together using integration. We determined the global radiative fluxes using the data for solar spectral irradiance on the earth's surface in the wavelength interval $0,3 \mu\text{m} \leq \lambda \leq 2,5 \mu\text{m}$, taken from ISO [9]. The global quantities given by the integration of the spectral quantities over global solar irradiance are:

The expressions P_{ab} and P_{re} determine for each individual particle size, the power absorbed and the power reflected into the hemispherical solid angle (2π) from the incident solar radiation. $I_{0,\lambda}$ are the spectral intensities of solar radiation. The absorbed power P_{ab} is converted into thermal energy flux in the particle. The integrals over the wavelength interval of the solar spectral irradiance from $\lambda_1 = 0.3 \mu\text{m}$ to $\lambda_2 = 2.5 \mu\text{m}$ are calculated by applying the composite Simpson's rule for each particle size, with an integration subinterval $\Delta\lambda = 0.5 \mu\text{m}$. By normalizing with the power that each individual particle physically intercepts we get the expressions P_{ab}/P_{in} and P_{re}/P_{in} , which represent the power of the incident solar radiation absorbed and the power reflected per unit of particle cross-sectional area.

2 THE REQUIRED PROPERTIES OF THE PARTICLES' SUBSTANCE

To achieve the minimum energy losses of energy flux for the concentrated solar radiation that enters the absorber, the particle-gas suspension must have, in addition to high absorption, as low as possible a tendency to reflect the solar radiation. These properties depend on the size and the material of the particles.

There is a wide variety of absorbing materials and a corresponding variety of types of refractive indices. In terms of low reflection and high absorption, the optical properties of materials must match these requirements, especially in the wavelength intervals where the intensity of the solar radiation is the highest. Fig.4 shows plots of efficiency factors, which represent the optical properties of individual particles, for some types of complex refractive indices that depend on the particle's material. The hatched area at $m = 1.0 - i0.5$ on the right-hand side of the figure represents the intervals where the optical properties of the particles correspond to the desired values, i.e., for



Sl. 4. Vrednosti faktorjev učinkovitosti za nekatere značilne tipe lomnih količnikov v območju velikosti delcev do $3 \mu\text{m}$ za valovni dolžini $0,5 \mu\text{m}$ in $1,5 \mu\text{m}$

Fig. 4. Plot of the values of the efficiency factors for some different types of refractive indices in an interval of particle diameters up to $3 \mu\text{m}$ for wavelengths $0.5 \mu\text{m}$ and $1.5 \mu\text{m}$.

delcev je njihova absorptivnost velika, zmožnost odboja pa izredno šibka. Zmožnost odbijanja sevanja je na teh slikah predstavljena z vrednostmi faktorja neposrednega (radarskega) odboja G_{od} . Iz predstavitve lahko ugotovimo, da je med vsemi variantami tipov lomnih količnikov najprimernejši tip $m = 1,0 - i0,5$, ki pripada snovem iz črnega ogljika, to so pirolitični ogljik, koks, premogi in saje.

a large interval of wavelength and particle diameters the absorption is high and the amount of direct reflection is low. Reflection is represented by the radar efficiency G_{od} . It is clear that the desired type of complex refractive index is $m = 1.0 - i0.5$, which corresponds to black carbonaceous materials, such as carbon blacks, coke, coals and soot.

3 OPTIČNE LASTNOSTI SLOVENSКИH PREMOGOV

3 THE OPTICAL PROPERTIES OF SLOVENIAN COALS

3.1 Lomni količniki

3.1 Refractive index

V Sloveniji imamo dve glavni vrsti premoga: lignit iz Velenja in rjavi premog iz Trbovelj. Premog iz Velenja ima lesnato strukturo, je svetlorjav, vsebuje prek 35 % vlage, veliko ksilita in je zelo neprimeren za fino mletje. Tudi njegova kemična sestava ne obeta izrazitih zmožnosti absorpcije.

There are two main types of coal deposits in Slovenia: lignite from Velenje, and brown coal from Trbovlje. The coal from Velenje has a wooden structure; it is yellowish brown, contains over 35 % of water, a lot of ksilit and it is very unsuitable for fine pulverizing. Its chemical structure is also not promising in terms of being a strongly absorbing substance.

Premog iz Trbovelj ima drugačne značilnosti. Je iz skupine temnejših rjavih premogov: po nemški klasifikaciji spada v skupino motno rjavih premogov, po mednarodni klasifikaciji v skupino SUBB B, oz. SUBB C in po ASTM klasifikaciji v skupino subbituminoznih premogov. Kot še uporabni premog lahko štejemo le frakcije, lažje od $1,4 \text{ t/m}^3$. Težje frakcije spadajo v razred karbomineralov in vsebujejo velik delež mineralnih snovi. Premogi z lastnostmi, prikazanimi v preglednici 1. so po ASTM D 385 standardni

On the other hand, the coal from the Trbovlje mine has very different properties. It belongs to the group of dull brown coals: according to the German Classification it belongs to Mattbraunkohle (opaque brown coal), according to the International Classification it belongs to the group SUBB B or SUBB C, and according to ASTM it belongs to the subbituminous class. For our purposes only coal fractions with a volume mass lower than 1.4 t/m^3 can be considered suitable. Heavier fractions contain too large amounts of minerals and belong to the group of carbominerits. Coals with the properties listed in Table 1.

Preglednica 1. Trboveljski premog, analiza na suhi osnovi

Table 1. Coal from Trbovlje - Proximate Analysis (Moisture Free Basis)

Specifična masa Specific weight	t/m ³	≤ 1,05	1,3 – 1,4
pepel ash	%	8	14
neizparljiv ogljik, C^{MAF} fixed carbon, C^{MAF}	%	44	42
izparljive snovi, V^{MAF} volatile matter, V^{MAF}	%	48	44

klasifikaciji najbliže skupini subbituminoznih premogov SUB C. Vrednosti realne in imaginarne komponente kompleksnega lomnega količnika takih premogov zadovoljivo popiše izraza [13]:

$$\left. \begin{aligned} n(\lambda) &= A + 0.005\lambda + 0.004 \left[\frac{1}{1-(\lambda-3.5)^2} - \frac{1}{1+(\lambda-2.5)^2} \right] \\ \kappa(\lambda) &= 0.35 - 0.05 \frac{\lambda}{1+(\lambda-3)^2} + 0.1 \frac{\lambda-1}{1+(9\lambda-1)^2} \end{aligned} \right\} \quad (15).$$

Vrednosti lomnih količnikov, ki opisujejo obnašanje spektralnega sevanja na snoveh, so pridobljene z meritvami na vzorcih dejanskih snovi. To pomeni, da podatki izmerjenih optičnih stalnic upoštevajo tudi dejanske vsebnosti pepela, vode in drugih snovi v premogu. Iz enačbe (15) je razvidno, da ima elementna sestava premoga močan vpliv na imaginarno komponento lomnega količnika. To odvisnost popisuje izraz:

$$A = 1.1 + 0.01V^{MAF} \quad (16),$$

kjer pomeni V^{MAF} delež lebdečih delcev in C^{MAF} delež neizparljivega ogljika v masi premoga brez vode in pepela.

Spreminjanje deleža neizparljivega ogljika C^{MAF} ima močan vpliv na vrednosti n in κ , pri premogih z $C^{MAF} \geq 85\%$, zelo majhen pa je vpliv pri premogih z $C^{MAF} \leq 85\%$. V našem primeru je delež neizparljivega ogljika, C^{MAF} okoli 50%, zato spreminjanje vrednosti C^{MAF} malo vpliva na vrednosti kompleksnega lomnega količnika trboveljskega premoga.

Za te vrste premoga še velja, da je realni del lomnega količnika n odvisen od valovne dolžine vpadnega sevanja in tudi od deleža izparljive snovi, medtem ko je vrednost imaginarnega dela κ odvisna le od valovne dolžine vpadnega sevanja. Vrednosti realnega in imaginarnega dela lomnega količnika za trboveljski premog so v odvisnosti od valovnih dolžin v območju $0,3 \mu\text{m} \leq \lambda \leq 2,5 \mu\text{m}$, narisane na sliki 5 v levem bloku prikaza. Za primerjavo so vrisane tudi vrednosti komponent lomnih količnikov za nekatere druge vrste premogov ([10] do [12]).

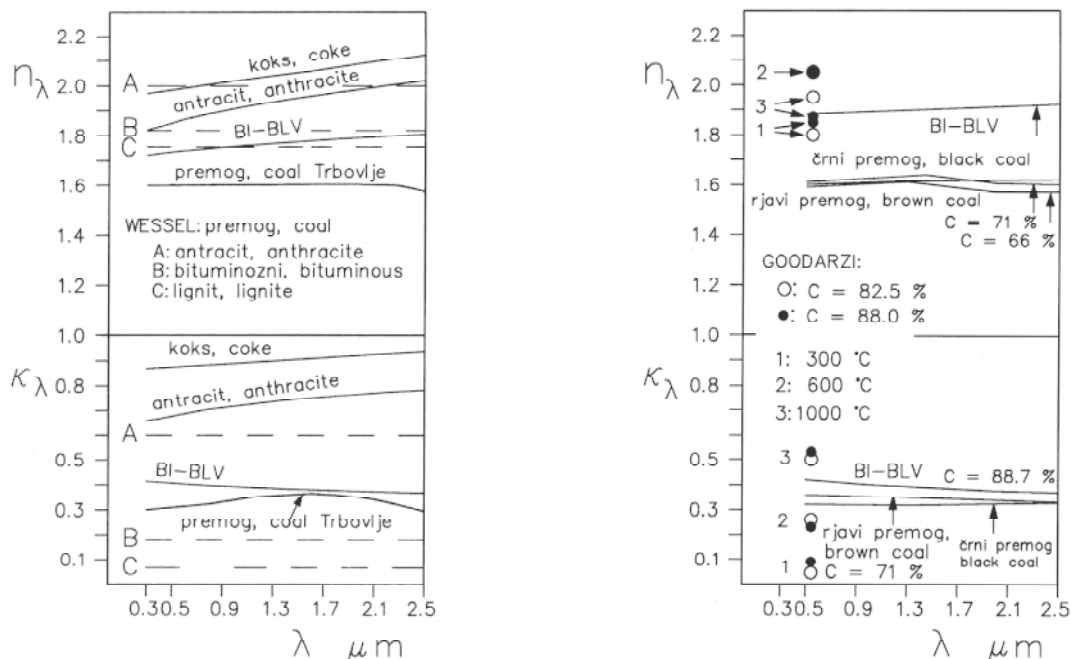
correspond closely to the subbituminous, highly volatile coals of group C, i.e., sub C, in accordance with the ASTM D 385 Standard Classification of coals. For the coals in this group the variations in the optical constants n and κ are described by the equations [13]:

The data for the refractive indices, which describe the interaction of the spectral electromagnetic radiation with the substance are determined by measurements on samples of real materials. This means that the values of the optical constants of the coals also depend on the actual ash and water contents of the coal. It is significant that the elemental composition of the coals only has a strong effect on the imaginary part of the refractive index. This influence is taken into account by the term:

where V^{MAF} represents the volatiles and C^{MAF} represents the fixed carbon content in a moisture-and-ash free mass of coal.

A change of C^{MAF} has a large influence on n and κ when $C^{MAF} \geq 85\%$, while for coals with values of $C^{MAF} \leq 85\%$ the optical constants n and κ depend little on the value C^{MAF} . In our case the value of C^{MAF} is a little less than 40% and so the influence of any variation in the fixed carbon content on the refractive index is negligible.

For the refractive indices of coal from Trbovlje is significant that the variation of the real part n depends on the wavelength of the incident radiation and also on the content of volatile matter, while the variation of the imaginary part κ is only a function of the wavelength of the incident radiation. The spectral values of the quantities n and κ for the coal from Trbovlje in the wavelength interval $0.3 \mu\text{m} \leq \lambda \leq 2.5 \mu\text{m}$ are presented in the left-hand part of Fig.5. For a comparison the values of the optical constants of several other coals of different types, ([10] to [12]) are also presented in Fig.5.



Sl. 5. Vrednosti realne in imaginarne komponente kompleksnega lomnega količnika za premoge in nekatere snovi iz ogljika v območju valovnih dolžin sončnega sevanja
 Fig. 5. Plot of the values of the real and imaginary parts of the complex refractive index for some coals and carbonaceous materials in the wavelength interval of solar radiation

3.2 Zmožnost premogovih delcev za absorpcijo in za odboj

Iz podatkov, prikazanih na sliki 7 in sliki 8, je razvidno, da so v območju istih velikosti izračunane vrednosti optičnih lastnosti rjavega premoga in pirolitičnega ogljika zelo podobne. Razlika je predvsem v tem, da so delci premoga optično mehkejši, kar pomeni, da sončno sevanje nekoliko manj intenzivno absorbirajo in nekoliko manj intenzivno odbijajo. Preizkusi slabljenja gostote energijskega toka sončnega sevanja, ki smo jih izvajali na suspenziji pirolitičnega ogljika iz acetilena, so potrdili veljavnost optičnih konstant pirolitičnega ogljika, ki smo jih izračunali po opisanih računskih postopkih ([2] in [3]). Rezultati teh preizkusov tudi potrjujejo zaupanje v vrednosti izračunanih optičnih značilnosti, ki smo jih za premoge predstavili v tem prispevku.

Raziskave sovplivanja majhnih delcev in sončnega sevanja so pokazale, da obstaja za vsako absorptivno snov neko specifično območje velikosti delcev, v katerem je zmožnost spektralnega odboja največja [2]. Na sliki 6 so predstavljene vrednosti spektralne absorptivnosti in reflektivnosti v izbranem območju velikosti delcev. Jasno so razvidna območja velikosti delcev z največjimi spektralnimi odboji.

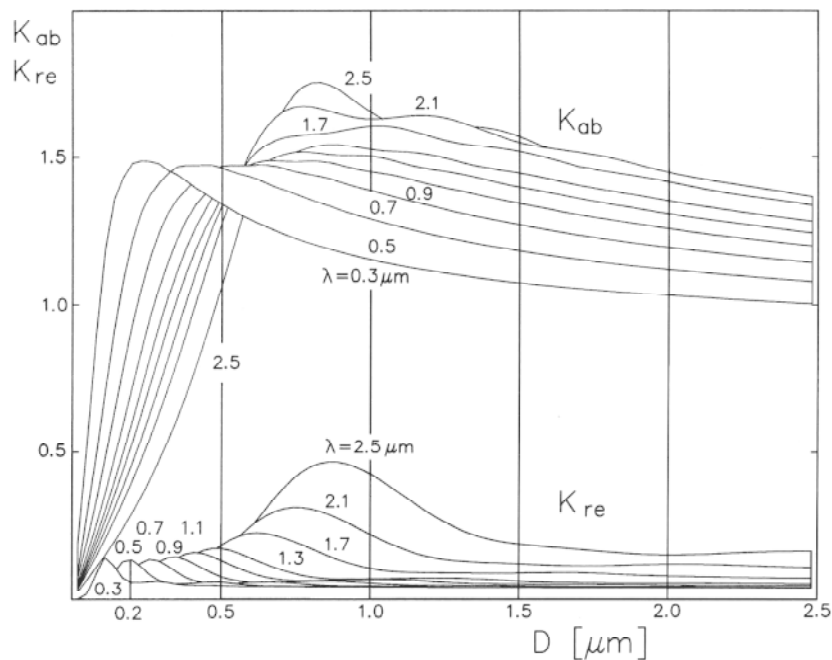
Globalne optične značilnosti ogljikovih snovi računamo po izrazih P_{ab}/P_{in} in P_{re}/P_{in} iz enačbe (14). Rezultat so vrednosti za specifično absorptivnost in specifično odbojnost za sončno sevanje, ki so prikazane v sliki 7 in sliki 8. Vrednosti za premog iz

3.2 The ability of the coal to absorb and reflect

From the data presented in Fig.7 and Fig.8 it is clear that within the interval of equal diameters the calculated optical properties of brown coal particles are very similar to the properties of carbon-black particles. The difference is only that brown coal particles are optically slightly softer, which means that they are less able to reflect and absorb. The experiments on the extinction of solar radiation intensity, which were performed with a suspension of acetylene carbon-black particles, confirmed the calculated optical properties of the carbon-black particles, which were calculated according described calculations ([2] and [3]). This means that we also can have confidence in the calculated values of the optical properties of the brown coal particles presented in this paper.

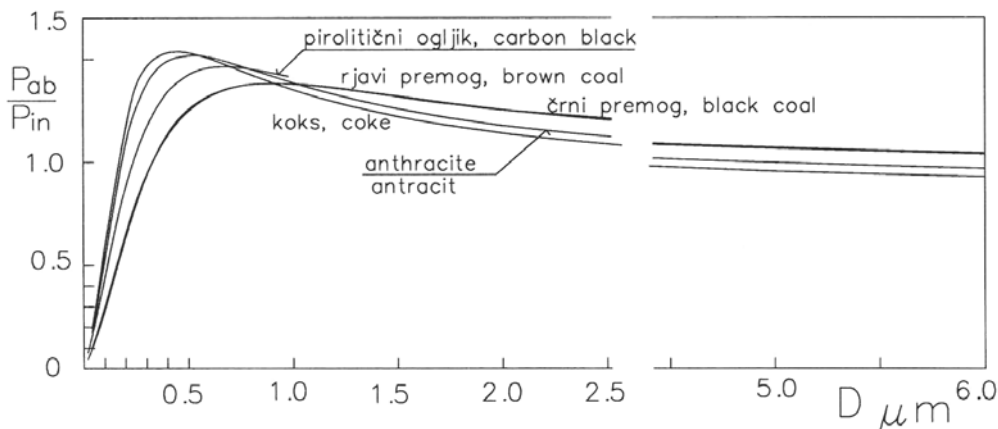
Previous research on the problems of the interaction of small particles with solar radiation has shown that the maximum level of reflection exists for each individual absorptive material in a specific interval of particle diameter [2]. Fig.6 presents the spectral absorption and reflection for a range of diameters. The region of maximum spectral reflectivity is clearly evident.

On the basis of Equations (14) and after normalisation with the power P_{in} we calculated the global optical properties of the carbonaceous materials. The results are the specific absorptivity and reflectivity of solar radiation, see Fig.7 and Fig.8.



Sl. 6. Vrednosti faktorjev učinkovitosti K_{ab} in K_{re} za delce rjavega premoga, ki ponazarjajo velikost absorbiranega in odbitega energijskega toka vpadnega sevanja enotnih spektralnih gostot pri nekaterih valovnih dolžinah v območju $0,025 \mu\text{m} \leq \lambda \leq 2,5 \mu\text{m}$.

Fig. 6. The values of the efficiency factors K_{ab} in K_{re} of brown coal particles which illustrate the absorbed and reflected uniform spectral intensities at different wavelengths in the interval $0.025 \mu\text{m} \leq \lambda \leq 2.5 \mu\text{m}$.



Sl. 7. Delež absorbiranega energijskega toka, ki ga delec absorbira iz vpadnega sončnega sevanja, ki pade na enoto njegovega geometrijskega prereza.

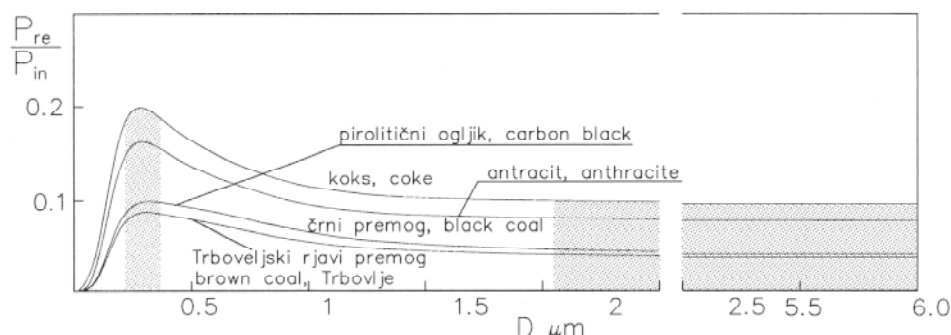
Fig. 7. Power of the global incident solar radiation absorbed by particles per unit of particle geometrical cross-section.

Trbovelj kažejo, da je največja specifična absorptivnost premoga dosežena pri delcih s premerom $D=0,9 \mu\text{m}$, največja specifična reflektivnost pa pri delcih premera okoli $D = 0,3 \mu\text{m}$. Največ se odbije 8,5 % energije sončnega sevanja, ki ga delec fizično prestreže. Specifični odboj je pri delcih vseh drugih premerov manjši.

Glede na velikost delcev snovi iz ogljika obstajajo v elektromagnetnem polju sončnega sevanja tri značilna območja (sl. 6 do 8). Prvo je območje najmanjših delcev, pri katerih je odbojnost na enoto geometrijskega prereza delcev najmanjša.

The results for the coal from Trbovlje show that the maximum specific absorptivity is attained for the diameter $D = 0.9 \mu\text{m}$, and the maximum specific reflectivity is attained at around $D = 0.3 \mu\text{m}$. The maximum reflected power is 8.5% of the solar radiation power that the particle physically intercepts. Particles of all other diameters reflect less energy flux.

Regarding the particle diameter of carbonaceous materials, there are three significant intervals of optical properties in the electromagnetic field of solar radiation, see Fig.6 to 8. The first is the interval of the smallest particles, where the reflection



Sl. 8. Delež odbitega energijskega toka, ki ga delec odbija iz vpadnega sončnega sevanja, ki pade na enoto njegovega geometrijskega prereza.

Fig. 8. Power of incident solar radiation reflected by particles per unit of particle geometrical cross section.

Pri delcih te velikosti je učinek absorbiranja sončnega sevanja lahko tudi do stokrat močnejši od učinka odbijanja. Največja absorptivnost in reflektivnost se pojavita v območju nekoliko večjih delcev. Pri nekaterih snoveh iz ogljika je odbojnost izredno poudarjena, saj npr. delci koks v tem območju velikosti odbijajo tudi do 20 % energijskega toka sončnega sevanja, ki pade na površino delca. Tretje območje je pri velikosti delcev nad 2,0 μm . Tu je absorptivnost sorazmerno velika pri vseh snoveh iz ogljika, reflektivnost pa je lahko bistveno različna. Očitno je reflektivnost najšibkejša pri delcih trboveljskega premoga.

4 RAZLAGA DOBLJENIH REZULTATOV

Iz prikazov spektralnih učinkovitosti absorpcije K_{ab} za rjavi premog na sliki 6 je razvidno, da se največji delež oslabiljene gostote sevanja spremeni v toploto v delcih najmanjših premerov. Računski podatki kažejo, da se faktor učinkovitosti absorpcije, torej zmožnost absorbiranja, hitro povečuje s premerom delcev in ostane visok pri vseh raziskanih snoveh in premerih delcev. Lastnost izrazite zmožnosti absorbiranja potrjujejo tudi vrednosti globalnih absorptivnosti, ki so prikazane na sliki 7. Posebnost je, da so v širokem območju premerov delcev iz ogljika vrednosti izraza P_{ab}/P_{in} večje od 1. To pomeni, da je energijski tok, ki se absorbira v delcu večji od energijskega toka vpadnega sevanja, ki ga delec fizično prestreže s površino geometrijskega prereza. Ta pojav je raziskan in v literaturi tudi opisan [14], njegova fizikalna osnova temelji na lomu svetlobe okoli majhnih delcev iz izrazito absorptivnih snovi. Iz prikazanih rezultatov je razvidno, da delci do velikosti 0,2 μm pri vseh obravnavanih snoveh ustrezajo pogojem za absorptivno snov v plinski suspenziji absorberja sončnega sevanja. Pri izvedbi absorberjev je treba upoštevati, da bo debelina absorptivne suspenzije večja pri uporabi delcev z manjšo zmožnostjo absorbiranja kakor pri suspenziji, v kateri bodo bolj absorptivni delci, seveda pri enaki

by a unit of a geometrical cross-section of particles is minimal. In this interval the absorption effect can be more than one hundred times stronger than reflection. The maximum reflectivity and absorptivity appears in the second interval. For some carbonaceous materials the reflectivity can be strong, for instance coke particles from this size interval can reflect up to 20% of the solar radiation power that a particle physically intercepts (Fig.8). The third is the interval where the particle diameters exceed 2.0 μm . In this interval the absorption is sufficiently high for almost all carbonaceous materials, but the reflection is the lowest for the brown coal from Trbovlje.

4 RESULTS AND DISCUSSION

On the basis of the value K_{ab} plotted in Fig.6, where the spectral properties are presented, it is obvious that most of the extinguished intensity is converted into heat flux by the particles with the small diameters. The calculations show that the efficiency factor for absorption and absorptivity rapidly increase with the diameter of the particles and remain high for all the substances and the particle diameters investigated. This property is also evident in the global absorptivity presented in Fig.7, from where we can see that over a wide range of diameters for the carbonaceous particles, the value of the term P_{ab}/P_{in} is greater than 1. This means that the energy flux that the particle removes and is absorbed from the incident flux is greater than the energy flux that falls on its cross-sectional area. This phenomena is known and has been investigated by several authors, [14]. Its physical nature is associated with the special character of the diffraction of electromagnetic waves from particles of some characteristic absorptive substances. If we use the smallest particles, with diameters up to 0.2 μm the absorptivity and reflectivity of all the investigated materials and particles fit the conditions for absorptive matter in a gas-particle receiver. In the case that the absorptivity is lower the suspension in the absorber with the same volumetric concentration of particles should be deeper than by using bigger particles with

prostorski koncentraciji delcev. Z večanjem premerov delcev se veča tudi zmožnost sipanja energijskega toka sevanja vendar predvsem v smeri širjenja sevanja (sl. 1). Izrazito nesimetrično sipanje pri delcih z $D \geq \lambda$ je značilno predvsem za delce ogljika. Energijski tok, ki ga delci sipajo naprej v smeri širjenja sevanja, v našem primeru ni toliko pomemben, bolj je pomemben energijski tok odbitega sevanja. S slike 6 je razvidno, da se največja vrednost faktorja učinkovitosti odboja pri delcu danega premera vedno pojavi pri isti valovni dolžini. Za delec premera $0,2 \mu\text{m}$ je na sliki 6 posebej označeno, da je največja spektralna učinkovitost odboja dosežena pri valovni dolžini $0,5 \mu\text{m}$. Isti primer je narisano tudi na sliki 1, kjer je prikazano sipanje elektromagnetnega sevanja z valovno dolžino $\lambda = 0,5 \mu\text{m}$. V povečanem izseku slike, označenem z B, je razvidno, da so vrednosti funkcije kotne porazdelitve sipanja največje pri delcu premera $D = 0,2 \mu\text{m}$. Največje vrednosti odboja obstajajo v določenem območju velikosti delcev tudi za globalno sončno sevanje (sl. 8).

Pri večanju premerov delcev naletimo pri obsevanju s sončnim sevanjem na tri značilna območja. Prvo je območje delcev velikosti do $0,1 \mu\text{m}$, v katerem je odbojnost šibka, absorptivnost pa sorazmerno velika pri vseh snoveh iz ogljika. V drugem območju velikosti delcev do $1,5 \mu\text{m}$ sta zmožnost absorpcije in zmožnost odbijanja sevanja največja. V tretjem območju velikosti delcev nad $2,0 \mu\text{m}$ postane zmožnost odbijanja opazno manjša, le pri delcih rjavega in črnega premoga. V tem območju odbijajo delci rjavega premoga od 3 do 4 %, delci antracita skoraj 8 % in delci oglja okrog 10 odstotkov vpadne energije sončnega sevanja. Rezultati torej kažejo, da imajo delci rjavega premoga iz Trbovelj izrazito najprimernejše optične lastnosti kot absorbenti sončnega sevanja. Delci tega premoga imajo visoko zmožnost absorpcije pri vseh velikostih, medtem ko je zmožnost odbijanja majhna predvsem pri velikih delcih. Pridobivanje premogovih delcev velikosti nad $2 \mu\text{m}$ je mogoče s postopkom sočasnega klasificiranja delcev med mletjem.

5 SKLEPI

Uplinjanje premogov s toploto sončne energije je mogoče izvajati s postopkom prostorninskega absorpcije zelo koncentriranega sončnega sevanja v plinski suspenziji premogovih delcev. Uplinjanje je smiselno le premoge z velikim deležem lebdečih delcev. Trboveljski premog, ki vsebuje tudi do 50 % izparljivih snovi, je torej kot premog primeren za uplinjanje. Po kemični sestavi smo za snov in za delce trboveljskega premoga določili značilne podatke za absorpcije in odbijanje elektromagnetnega valovanja. Te značilnice lahko izračunamo s faktorji učinkovitosti, geometričnih

višje absorptivnosti. The scattering efficiency and the power that the particle scatters also rapidly increases with diameter, but primarily as forward scattering (Fig.1). Very strong asymmetric scattering when $D \geq \lambda$ is characteristic for most carbonaceous substances. The power scattered by the particles in the forward direction is not very significant in our case; the reflected power is more important. From Fig.6 it is evident that the maximum value of the efficiency factor for reflection exists at a given wavelength and diameter of particle. For a particle diameter of $0.2 \mu\text{m}$ the maximum spectral reflection appears at a wavelength of $0.5 \mu\text{m}$. The relation between the particle diameter, the wavelength and the maximum values of efficiency factor for the reflection is also illustrated in Fig.1, where the spectral scattering is presented for $\lambda = 0.5 \mu\text{m}$. In segment B we can see that the maximum values of the efficiency function for the reflected intensity are at the particle diameter $D = 0.2 \mu\text{m}$. The existence of a reflection maximum is also seen from the global values of the reflected solar energy flux after integration over the entire spectral irradiance, see Fig.8.

When increasing the diameter of the carbonaceous particles we can see that there are three significant intervals in connection with the absorbed and reflected solar energy flux. The first is the interval of the smallest particles, up to $0.1 \mu\text{m}$, where the reflection is minimal, but the absorption remains sufficient for all the treated substances. In the second interval of particle diameters, up to $1.5 \mu\text{m}$, the absorption and reflection are at the maximum. In the third interval, where the particle diameters are greater than $2.0 \mu\text{m}$, the reflection is significantly smaller again only for black and brown coal. In the third interval the brown coal particles reflect 3 % to 4 %, anthracite almost 8 % and char particles around 10 % of the energy flux of the incident solar radiation. The results therefore show that brown coal from Trbovlje has very appropriate optical properties for the absorption of concentrated solar radiation. The ability to absorb is very high for all particle diameters, while the ability to reflect is low, especially for bigger particles. The production of pulverised coal with a granulation greater than $2 \mu\text{m}$ is achievable by a micronising process with the simultaneous classification of particles.

5 CONCLUSIONS

The gasification of highly volatile coals with the heat from concentrated solar radiation is realizable by the process of volumetric absorption in a coal-particle-gas suspension. From the point of view that gasification is reasonable only by coals with high content of volatile matter, the separated coal from Trbovlje is very convenient since it contains up to 50 % of evaporative matter. On the basis of the chemical composition, the absorption and reflection properties of the coal particles from Trbovlje were determined. The radiative properties can be

prerezov delcev in spektralnih gostot vpadnega sončnega sevanja. Ker je zmožnost absorpiranja izrazita in ni problematična pri vseh velikostih delcev, smo posebej pozorno proučili energije sevanja, ki ga delci odbijajo. Šibka reflektivnost delcev je osnovni pogoj za visok izkoristek postopka absorpiranja v plinski suspenziji. Rezultati kažejo, da je specifična odbojnost najmanjša pri delcih premera do premerov 0,1 μm . Proizvajanje delcev takih velikosti z mletjem premoga je izrazito težavno, problematično je tudi ohranjanje velikosti takih delcev zaradi izrazitega nagnjenja k aglomeriranju. Zaradi poudarjene zmožnosti odbijanja sončnega sevanja se je treba izogibati uporabi delcev velikosti med 0,15 μm in 1,5 μm .

Analiza rezultatov kaže, da so delci premera s premeri, večjimi od 2 μm , tudi v pogledu optičnih lastnosti najbolj primerni. Imajo veliko specifično absorptivnost in šibko specifično odbojnost, saj odbijajo manj ko 5 % energijskega toka vpadnega sevanja. Za uspešen postopek uplinjanja trboveljskega premoga s sončno energijo ni potrebna priprava izrazito majhnih delcev premoga. Velik izkoristek postopka uplinjanja rjavega premoga s koncentriranjem sončnega sevanja v plinski suspenziji torej je mogoč tudi s premogovim prahom, ki ga pripravimo z običajnimi metodami mletja in so delci v njem zelo veliki v primerjavi z valovnimi dolžinami sončnega sevanja.

calculated in terms of the efficiency factors, the geometrical cross-sections of the individual particles and the spectral intensity of incident radiation. Our attention was focused on the reflection intensity, because the calculations show that the absorptivity is not problematic and remains high for all particle diameters. Low reflectivity of the particles is the condition for the high efficiency of the absorber, i.e., the process. The result shows that reflection by the smallest particles of diameters up to 0.1 μm is minimal. In any case the production of such coal particles is very difficult because of their high predisposition to agglomeration. On the other hand because, of their of maximum reflectivity, the usage of brown coal particles with diameters from 0.15 μm up to 1.5 μm should be avoided.

The results show that particles with diameters greater than 2 μm are the most appropriate as a result of their high specific absorptivity and low specific reflectivity, which is under 5%. In fact for brown coal from Trbovlje there is no need to produce extreme small particles because the highest efficiency of the particle-gas absorber can also be attained when the sizes of the particles are very large compared to wavelength of solar radiation and can be prepared by the common pulverized-coal systems.

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Prejeto: 1.6.2004
Received:

Sprejeto: 30.9.2004
Accepted:

Odprto za diskusijo: 1 leto
Open for discussion: 1 year