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Influence of Bed Movement and Amount of Supplied Air on Updraft Gasification of Hardwood Pellet

Utjecaj pomaka tepiha materijala i dobave zraka na protusmjerno rasplinjavanje peleta od drva listača

ABSTRACT • *This work presents the results of hardwood pellet gasification with different amounts of air as a gasification medium. The effects of bed movement and the equivalence ratio (ER) on the temperature profile, gas composition, carbon conversion efficiency and the energy balance were taken into account. Slow movement of the bed promotes high combustion and reduction zones, while fast bed movement leads to high pyrolysis zones and higher caloric values of syngas. When the amount of air increased from 12 to 23 Nm^3/h, the gas yield increased from 1.4 to 1.6 $Nm^3/kg_{biomass}$ for slow bed movement, and from 1.0 to 1.3 $Nm^3/kg_{biomass}$ for fast bed movement. These results show that in both Cases similar specific energy values were obtained. However, in Case 1 lower fuel consumption was reached. Chemical energy in the syngas represents 80 % of the output energy for slow bed movement (265 MJ/h) and 75 % for fast bed movement (295 MJ/h). A significant effect of bed movement in the reactor suggests that the gasifier could be considered as a flow reactor, and additionally the fast movement of the bed with 20 Nm^3/h of supplied air yielded the highest-quality gasification process. Moreover, fast bed movement in the reactor leads to a high amount of generated char with high energy potential.*

Keywords: *gasification, updraft gasifier, hardwood, carbon conversion, bed movement*

SAŽETAK • *U radu su prikazani rezultati rasplinjavanja peleta od drva listača različitim količinama zraka kao sredstvom za rasplinjavanje. U ispitivanju je uzet u obzir utjecaj pomaka tepiha materijala i omjera ekvivalencije (ER) na temperaturni profil, sastav plina i učinkovitost pretvorbe ugljika te na energetsku ravnotežu. Usporeni pomak tepiha materijala pospješuje zone dobrog izgaranja i redukcije, dok brzi pomak tepiha materijala rezultira visokim zonama pirolize i višim kalorijskim vrijednostima sintetskog plina. Kada je količina zraka porasla s 12 na 23 Nm^3/h, prinos plina povećao se s 1,4 na 1,6 $Nm^3/kg_{biomase}$ pri laganom pomaku tepiha materijala, a od 1,0 do 1,3 $Nm^3/kg_{biomase}$ pri brzom pomaku tepiha materijala. Ti rezultati pokazuju da su u oba primjera dobivene slične vrijednosti specifične energije. Međutim, u prvom je primjeru postignuta niža potrošnja goriva. Kemijska energija u sintetskom plinu čini 80 % izlazne energije pri laganom pomaku tepiha materijala (265 MJ/h) i 75 % pri brzom pomaku tepiha materijala (295 MJ/h). Znatan učinak pomaka tepiha materijala u reaktoru sugerira da se rasplinjač*

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može smatrati protočnim reaktorom, a dodatno brz pomak tepiha materijala s 20 Nm³/h dobave zraka omogućio je najkvalitetniji proces rasplinjavanja. Štoviše, brzi pomak tepiha materijala u reaktoru dovodi do nastanka velike količine pougljenjenog materijala s visokim energetskim potencijalom.

Ključne riječi: *rasplinjavanje, protusmjerni rasplinjač, drvo listača, pretvorba ugljika, pomak tepiha materijala*

1 INTRODUCTION
1. UVOD

The gasification process, which is recognized as one of the most effective in terms of thermal utilization of biomass and municipal waste, is a very popular topic in global research (Arena, 2012). This process is typically classified based on the type of gasification system. A common construction is a fixed-bed gasifier working in the downdraft or updraft configuration (McKendry, 2002). Downdraft gasification systems generate gas with a lower tar content than updraft gasifiers. Therefore, many studies focused on different types of downdraft gasifiers can be found in the literature (Balu and Chung, 2012; Phuphuakrat *et al*., 2010; Nisamaneenate *et al*., 2012; Zainal *et al*., 2002; Erlich *et al*., 2011). In the case of updraft reactors, the high tar content in the produced gas has significantly slowed the development of this technology (Dudyński *et al*., 2012). However, studies based on updraft gasification are described in the literature. Blasi *et al*. (1999) used beechwood biomass in an updraft fixed-bed gasification process, which resulted in gas with a content of 28 % CO, 7 % CO_2, 7 % H_2 and 2 % CH_4.

Chen *et al*. (2011) studied the operating conditions of updraft gasification of mesquite and juniper and found that the heating value of syngas increased from 3.5 to 3.9 MJ/Nm³ for juniper and from 2.4 to 3.5 MJ/Nm³ for mesquite when the equivalence ratio (ER) decreased from 0.37 to 0.22. For both types of fuel, the maximum temperature in the combustion zone was above 1000 °C.

Pedroso *et al*. (2013) studied wood chip gasification in bottom-feed updraft gasification and showed that the gas produced contained 27 % CO and 4 % CH_4 and, relative to a typical updraft gasification system, a lower concentration of H_2 (6 %). The temperature of the bed in the reactor decreased from 885 °C in the combustion zone to 100 °C in the drying zone.

Recent research has focused on methods to clean the producer gas, optimize the updraft gasification process to decrease the high content of tar in the syngas, and obtain high-quality biochar (Taupe *et al*., 2016). Ismail and El-Sala (2017) carried out numerical simulations and experimental studies of the influence of temperature in the gasifier and ER on syngas composition and tar yields during updraft gasification of wood pellets. It was reported than the ER had a significant impact on bed temperature and gas quality. A higher ER ratio corresponds to a larger amount of oxygen in the combustion zone, which leads to a lower concentration of carbon monoxide and hydrogen and also increases the carbon dioxide content of the syngas. On the other hand, more oxygen supplied to the gasifier promotes oxidization reactions and leads to more heat generation and higher temperatures in the gasifier. These aspects were also presented by Ayyadurai *et al*. (2017), who studied large (1 m in length and 0.06 m in diameter) woody biomass gasification in a 60 kW$_{th}$ updraft gasifier. These authors found that the gasification process with ER=0.6 producer syngas attained a heating value of 4.5 MJ/Nm³ and that the gasification temperature reached a temperature of 955 °C in the oxidation zone.

Another interesting issue related to updraft biomass gasification has been presented by Huang *et al*. (2017). These authors studied the characteristics of residual carbon in biomass, including structure and gasification activity. These aspects were investigated using Raman spectroscopy. Residual carbon in the ash is the result of char particles spending only a short amount of time in the gasifier.

Based on current literature, there are no available works that provide detailed information about the influence of time that the fuel spends in the gasifier or rate of bed movement and the amount of supplied air on the gasification temperature and syngas characteristics. The primary objective of this work was to investigate an alternative way to stimulate the updraft gasification process by forcing different rates of bed movement at different amounts of supplied air. The main parameters presented in this work include the temperature profile along the gasifier (e.g., the characteristics of the temperature zones, gas composition and caloric value, carbon conversion rate and energy balance).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Proximate and ultimate analysis of fuel
2.1. Neposredna i krajnja analiza goriva

The hardwood pellets particles are a cylinder with diameter of 8 mm and length of up to 15 mm. The bulk density of hardwood pellets during experiments was 646 kg/m³. To conduct the proximate and ultimate analyses, the hardwood samples were first dried using a moisture analyzer (RADWAG) to determine their moisture content. The analysis of elementary composition was carried out using a CHNS-O Flash 2000 analyzer. The determination and calculation of the calorific value was executed using a KL-11 calorimeter. The results of the proximate and ultimate analyses are presented in Table 1.

2.2 Gasification stand
2.2. Postrojenje za rasplinjavanje

The experimental setup for the updraft gasification is shown in Figure 1. The gasifier was constructed using boiler steel and clad on mineral wool isolation. The total height of the reactor was 135 cm and its internal radius was 22 cm. The air inlet (three axially spaced
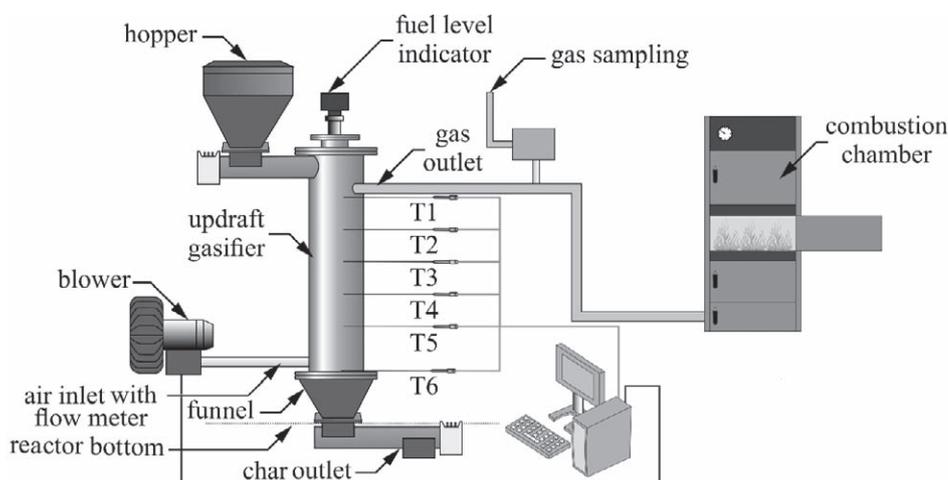
Figure 1 Schematic diagram of the experimental setup
Slika 1. Shematski prikaz istraživačkog postrojenja

Table 1 Duncan's test results for main effects
Tablica 1. Rezultati Duncanova testa za glavne utjecajne činitelje

	Hardwood pellets
	Peleti od drva listača
HHV, MJ/kg	19.6
Moisture, wt.%. as delivered	6.1
Proximate, wt.%$_{db}$[a]	
Neposredno, wt.%$_{db}$[a]	
Volatiles / *hlapljive komponente*	76.3
Fixed Carbon / *fiksni ugljik*	21.4
Ash / *pepeo*	2.3
Ultimate, wt.%$_{db}$[a]	
Krajnje, wt.%$_{db}$[a]	
C	48.5
H	5.3
O[b]	45.8
N	0.4

[a] db – oven-dry basis / *na bazi standardno suhe tvari*
[b] by difference / *prema razlici*

nozzles with a diameter of 8 mm) was installed 52 cm from the bottom of the reactor, ended with a funnel with 43 cm and it was connected with the char outlet tube with a diameter of 104 mm. The syngas outlet was installed 111 cm from the bottom.

During the experimental investigation, fuel from the hopper was loaded by a screw feeder, and tube with a diameter of 104 mm, to the reactor 10 cm below the syngas outlet. Six thermocouples (Type N and S) were installed in order to measure temperature within the gasifier. These thermocouples were placed 30, 55, 72, 88, 90 and 119 cm from the bottom of the reactor. The air was supplied to the gasifier via an electric blower and controlled using an inverter and a thermal mass flow meter. The syngas left the reactor and passed to the combustion chamber, through an outlet tube with a diameter of 54 mm. On the outlet tube, part of the produced gas was directed to the gas sampling system.

2.3 Experimental procedure
2.3. Postupak istraživanja

Prior to starting gasification, a batch of 3 kg feedstock was loaded into the gasifier in each experiment.

The initial level of the feedstock was maintained at the level of the air inlet nozzles until a high bed temperature was obtained. After a high bed temperature was obtained, the gasifier was filled to the level of the indicator. In each experiment, the height of the fuel bed was kept at the same level using a rotary fuel level indicator (i.e. 112 cm from the bottom). The amount of supplied air was set at 12, 17, 20 and 23 Nm³/h, and the duration of each experiment was 120 minutes from the point when the gasification process reached a steady-state condition (i.e. a constant temperature in each zone and a steady amount of received char). The gasification process was performed at atmospheric pressure in the range of 900-1100 °C. The solid residue (char and ash) was gathered from the bottom of the reactor using an inverter coupled with a cyclical screw at a frequency of 5 sec/5min (*Case 1*) and 10 sec/2.5 min (*Case 2*), which stimulated slow and fast bed movement in the reactor (char outlet velocity).

2.4 Measurements of gas composition
2.4. Mjerenje sastava plina

After steady-state conditions of gasification were achieved, the samples of syngas were sampled using tedlar bags. The analysis of the syngas content was performed using a SRI Instruments 310 gas chromatograph with a ShinCarbon ST 80-100 packed column and a thermal conductivity detector. The gas analyzer was pre-calibrated using a standard mixture of gas (CO, CO_2, CH_4 and H_2), and argon was used as a carrying medium.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Temperature profile in the gasifier
3.1. Temperaturni profil u rasplinjaču

Experimental investigations of hardwood pellet updraft gasification revealed a similar temperature profile trend in the gasifier, which is consistent with the literature (Chen *et al*., 2012; Joseph *et al*., 2016). The results indicated a significant impact of bed movement velocity in the gasifier on the height of individual pro-
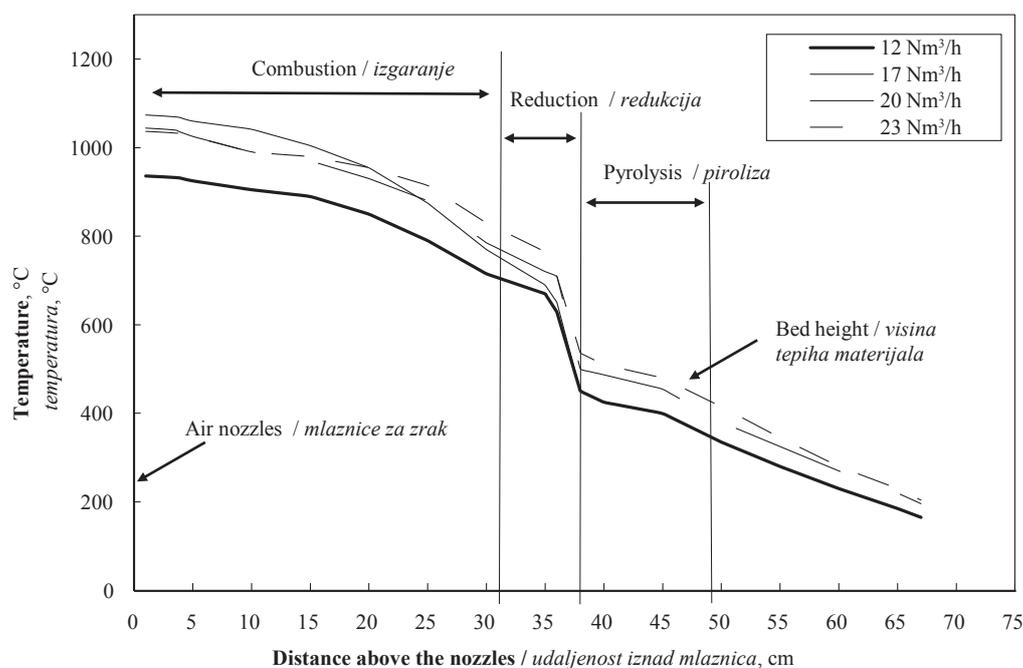
Figure 2 Characteristic temperature profile and gasifier zones in *Case 1*
Slika 2. Karakteristični temperaturni profil i zone rasplinjavanja u primjeru 1.

cess zones (Figure 2 and Figure 3). Based on the literature, the boundary of the combustion and reduction zone was established at 1000 °C and 750 °C (Chen *et al.*, 2012; Sircar *et al.*, 2014; Mani *et al.*, 2011). Our results show that, in *Case 1* (slow bed movement in the reactor), the combustion zone attained a height of about 32 cm from the air nozzles and the reduction zone reached a maximum height of 7 cm.

Since the level of the fuel in the gasifier was set at 50 cm from the air nozzles, the pyrolysis zone attained a height of 11 cm. In *Case 2* (fast bed movement in the reactor), the height of the combustion (reduc-

tion) zone attained a maximum of 16 cm. *Case 2* promoted the pyrolysis process with a zone height of 17 cm. Lower temperatures in pyrolysis zone in *Case 2* are associated with the intensification of supplied fresh fuel and consumed heat, supplied by oxidation of biomass at the lower part of the reactor, in endothermic pyrolysis reactions (high temperature gradient between 35 and 40 cm from the air nozzles, Figure 3).

The results of the hardwood updraft gasification also indicated that the gradient of the bed temperature was about 6 °C/cm for 12 Nm³/h of supplied air and 10 °C/cm for all other amounts of air in *Case 1*. In *Case 2*,
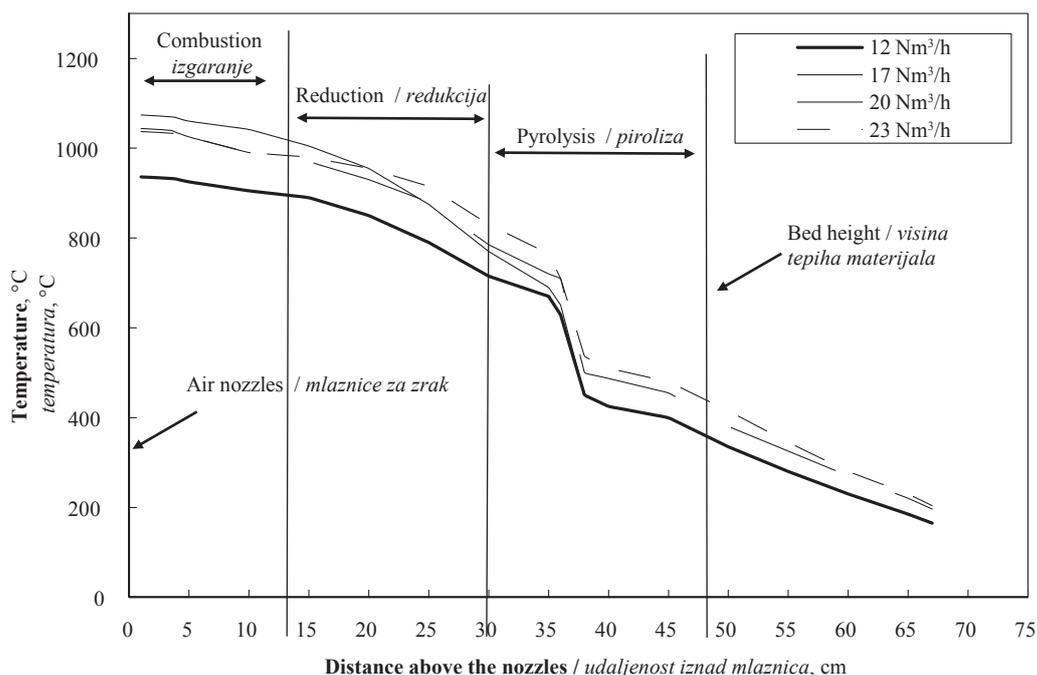
Figure 3 Characteristic temperature profile and gasifier zones in *Case 2*
Slika 3. Karakteristični temperaturni profil i zone rasplinjavanja u primjeru 2.

Table 2 Performance of the gasification process
Tablica 2. Obilježja procesa rasplinjavanja

Case *Primjer*	Air, Nm³/h *Zrak*, Nm³/h	Fuel consumption, kg/h *Potrošnja goriva*, kg/h	ER *ER*	Temperature, °C *Temperatura*, °C
Case 1 / *primjer 1.*	12	14.6	0.16	774
	17	19.61	0.16	1092
	20	23.0	0.16	1094
	23	27.0	0.16	1056
Case 2 / *primjer 2.*	12	26.2	0.09	936
	17	27.1	0.12	1074
	20	28.8	0.13	1044
	23	33.7	0.13	1038

the corresponding values were 12 °C/cm and 13 °C/cm. Faster bed movement in the reactor resulted in a slightly steeper temperature gradient.

3.2 Performance of the gasification process
3.2. Obilježja procesa rasplinjavanja

Experimental investigation showed the importance of comparing the amount of air supplied, fuel consumption, equivalence ratio and temperature. The results presented in Table 2 show similar temperature and fuel consumption trends as a function of the amount of air. However, in *Case 1* the same value of ER was rated (0.16) in each experiment. In *Case 2* ER value increased from 0.09 to 0.13, which is related to similar fuel consumption with the simultaneous increase in the amount of supplied air. It is noteworthy that, in *Case 2*, increasing of the amount of air supplied to 23 Nm³/h led to a significant increase in fuel consumption (from 28.8 to 33.7 kg/h), which may be caused by the increase of the intensity of oxidation/reduction processes.

3.3 Gas calorific value
3.3. Ogrjevna vrijednost plina

In an updraft gasifier, carbon dioxide is generated via the oxidation of wood pellets in the lower part of the reactor, and carbon monoxide is produced by a char reduction reaction (Boudouard reaction) in the reduction zone between the bottom and the middle parts of the reactor. Pyrolytic gas is produced in the pyrolityc zone at the lower-middle part of the gasifier (McKendry, 2002).

Different rates of bed movement, apart from variable amounts of supplied air, also affected significantly the generated zone heights and syngas composition. Fast bed movement in the gasifier (*Case 2*) promoted pyrolysis process with the height of the zone (Figure 3), which led to a slightly reduced production of pyrolytic gas and higher calorific value of the syngas (Table 3). In *Case 1*, slow movement of fixed bed resulted in the formation of a high zone of oxidation and reduction (Figure 2) that influenced the lower content of carbon dioxide, hydrogen and methane and increased the amount of generated syngas.

Based on the literature, the amount of produced gas was calculated using the nitrogen tracer method (Chen *et al.*, 2012; Thanapal, 2010), which relies on knowing the amount of nitrogen in the supplied air. The results revealed that the slow bed movement in the gasifier led to a larger gas yield per kg of biomass; the peak value was 1.6 Nm³/kg$_{biomass}$ for 23 Nm³/h of supplied air. At fast bed movement in the gasifier, the corresponding value was 1.3 Nm³/kg$_{biomass}$. Furthermore, an increase in the amount of air supplied to the gasifier resulted in an increase in the amount of gas yield per kg of biomass for both cases, which is consistent with the literature (Chen *et al.*, 2012;, Ismail and El-Sala, 2017).

Specific gas energy (MJ/kg) is an additional parameter representing the amount of energy obtained from a kilogram per hour of solid fuel in the form of gaseous fuel (Taupe *et al.*, 2016) and allows to determine the energy efficiency of the gasification process. For both Cases, experimental results showed that the specific gas energy reached similar value (Table 3). However, in *Case 1* these values were reached at lower fuel consumption (Table 2). It is caused by lower heating values of produced gas (4.8 - 6.2 MJ/Nm³) with a

Table 3 Syngas composition
Tablica 3. Sastav sintetskog plina

Case *Primjer*	Air / *Zrak* Nm³/h	ER *ER*	Syngas components, % *Sastav sintetskog plina*, %				LHV of gas *LHV plina* MJ/Nm³	Gas yield *Prinos plina* Nm³/kg$_{biomase}$	Specific energy *Specifična energija* MJ/kg
			CO	CO₂	H₂	CH₄			
Case 1 *primjer 1.*	12	0.16	25.3	5.6	6.9	2.4	4.8	1.4	6.72
	17	0.16	33.8	4.8	8.2	1.8	5.8	1.5	8.70
	20	0.16	32.2	5.7	8.4	1.3	5.5	1.6	8.80
	23	0.16	35.5	4.4	8.5	2.1	6.2	1.6	9.92
Case 2 *primjer 2.*	12	0.09	34.6	9.6	14.4	3.9	7.3	1.0	7.30
	17	0.12	33.4	7.1	12.1	3.1	6.7	1.2	8.04
	20	0.13	33.3	8.3	11.3	2.7	6.4	1.4	8.96
	23	0.13	36.8	7.5	11.5	2.6	6.8	1.3	8.84
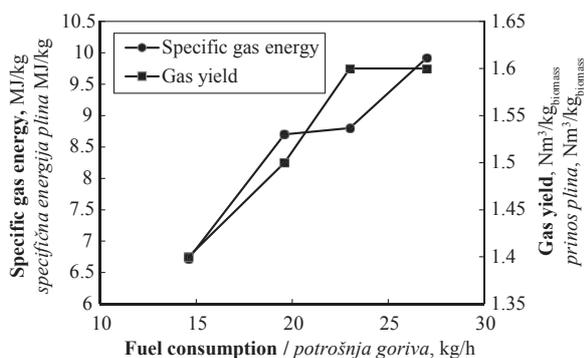
Figure 4 Relation of fuel consumption and specific gas energy and gas yield in *Case 1*
Slika 4. Odnos potrošnje goriva i specifične energije plina te prinosa plina u primjeru 1.
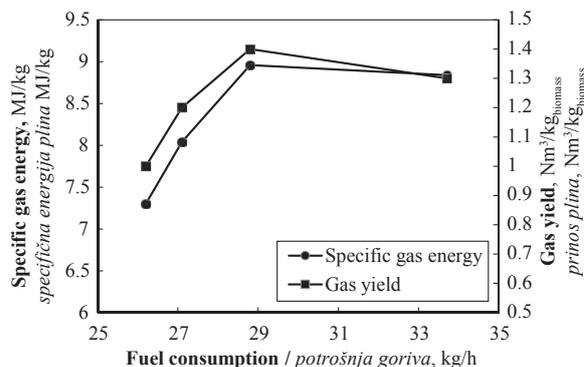
Figure 5 Relation of fuel consumption and specific gas energy and gas yield in *Case 2*
Slika 5. Odnos potrošnje goriva i specifične energije plina te prinosa plina u primjeru 2.

higher gas yield (1.4 - 1.6 $Nm^3/kg_{biomass}$) in *Case 1*, and accordingly higher heating values of produced gas (6.4-7.3 MJ/Nm^3) with a lower gas yield (1.0-1.4 $Nm^3/kg_{biomass}$) in *Case 2*. Moreover, the results showed that, for the slow fuel motion in the reactor (*Case 1*), the gasification process reached the maximum gas yield with a fuel consumption of 23 kg/h (ER=0.21) (Figure 4). In *Case 2* (Figure 5) maximum gas yield was reached with a fuel consumption of 28.8 kg/h. This aspect indicates the potentially optimal process conditions for the presented Cases (char outlet velocity).

3.4 Char characteristic
3.4. Svojstva pougljenjenog materijala

Experimental investigations of hardwood pellet gasification revealed the impact of stimulated bed movement in the reactor on fuel consumption (Table 4). As the amount of supplied air increased from 12 to 23 Nm^3/h, the fuel consumption increased from 14.6 kg/h to 27 kg/h in *Case 1* and from 26.2 kg/h to 33.7 kg/h in *Case 2*. This relation was also presented by Pedroso *et al*. (2013), who showed that the increase in the amount of air from 21 to 28 Nm^3/h caused an increase in fuel consumption from 10 to 14 kg/h during updraft gasification of woodchips. Furthermore, a larger amount of oxygen supplied to the gasifier intensified the oxidization reaction, which led to an increase in the carbon conversion rate. In *Case 1*, an increase in the amount of supplied air from 12 to 23 Nm^3/h resulted in increased carbon conversion from 70 to 94 %. In *Case*

2, the corresponding data were 78 and 83 %, respectively. A larger amount of oxygen supplied to the gasifier promoted oxidization reactions and led to increased CO_2 generation. These aspects were presented by Kalström *et al*. (2015). These authors found that an increase in carbon dioxide concentration from 13 to 60 % significantly affected the char conversion rate during CO_2 gasification of char particles from torrefied fuels like pine shell, olive stones and straw.

The carbon conversion was calculated as the ratio of the carbon difference in biomass and char after gasification compared with the amount of carbon in the biomass. The theoretical amount of char was based on the difference in the mass of carbon in the fuel and the resulting syngas. These calculations did not take into account the tars. The experimental results revealed that optimum conditions were achieved for fast movement of fixed bed in the gasifier (*Case 2*) for 20 Nm^3/h, where the smallest difference between the received and calculated amount of produced char was obtained, which may indicate the high fuel conversion rate, lowest accumulation of carbon (char) in the reactor and low tar content.

3.5 Mass and energy balance
3.5. Masa i energetska bilanca

An important parameter for comparing the impact of the rate of bed movement in the gasifier and the amount of supplied air on the updraft gasification process is a mass and energy balance. The energy input

Table 4 Performance data of gasification process
Tablica 4. Podatci o procesu rasplinjavanja

		Case 1 / *Primjer 1.*				**Case 2** / *Primjer 2.*			
Amount of supplied air / *Količina dobave zraka*	Nm^3/h	12	17	20	23	12	17	20	23
Fuel consumption / *Potrošnja goriva*	kg/h	14.6	19.6	23.0	27.0	26.2	27.1	28.8	33.7
Carbon in the fuel / *Ugljik u gorivu*	kg/h	7.1	9.5	11.2	13.1	12.7	13.1	13.9	16.4
Char received / *Količina pougljenjenog materijala*	kg/h	2.6	1.1	0.8	0.8	3.4	3.2	3.5	2.9
Carbon content in the char / *Sadržaj ugljika u pougljenjenome materijalu*	%	84.0	87.4	97.5	97.8	82.3	87.3	92.8	96.8
Carbon conversion / *Pretvorba ugljika*	%	70	91	93	94	78	79	76	83
Mass of carbon in the gas / *Masa ugljika u plinu*	kg/h	3.5	6.2	8.1	9.5	6.5	7.2	9.1	10.3
Theoretical char / *Teorijska količina pougljenjenog materijala*	kg/h	4.2	3.8	3.2	3.6	7.9	6.8	5.2	7.5
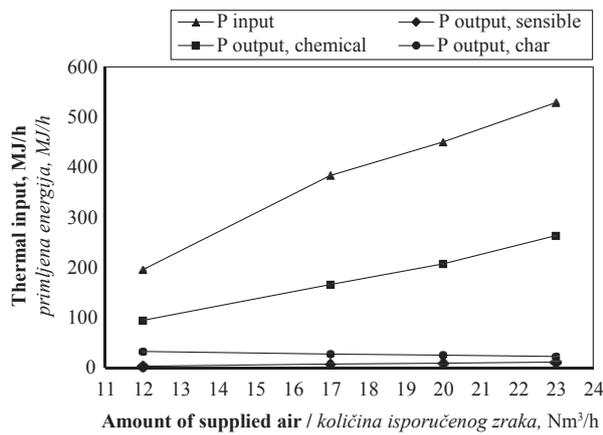
Figure 6 Characteristics of input and output energy during updraft gasification in *Case 1*
Slika 6. Obilježja primljene i otpuštene energije tijekom protusmjernog rasplinjavanja u primjeru 1.
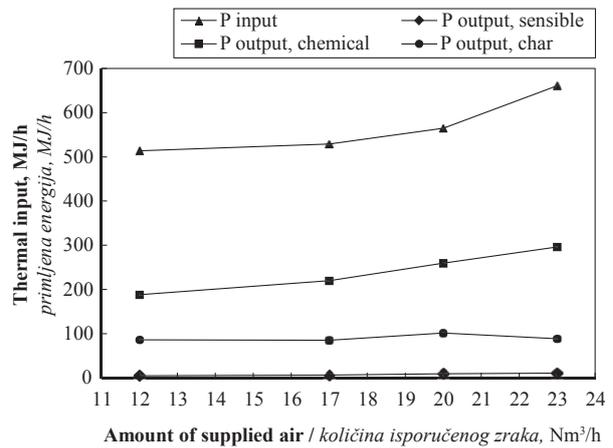
Figure 7 Characteristics of input and output energy during updraft gasification in *Case 2*
Slika 7. Svojstva primljene i otpuštene energije tijekom protusmjernog rasplinjavanja u primjeru 2.

flow was defined as the product of fuel consumption per unit time (Table 4) and the higher heating value of hardwood pellets (Table 1):

$$P_{input} = \dot{m}_{fuel} \cdot HHV_{fuel} \; (MJ / h) \qquad (1)$$

The energy output flow associated with chemical energy in the syngas was calculated from the volumetric composition of the combustible species contained in the syngas and their caloric value (Table 2):

$$P_{out,chemical} = \sum_i V_i \cdot HHV_i \; (MJ / h) \qquad (2)$$

The syngas produced at the outlet of the reactor was very hot and also carried a certain amount of heat (sensible heat), which can be defined as a product of the specific heat capacity, the molar flow of each component and the outlet temperature of the syngas:

$$P_{out,sensible} = \sum_i \dot{n}_i \int_{T_{ambient}}^{T_{gas,outlet}} c_{p,i} dT \; (MJ / h) \qquad (3)$$

The specific heat capacity $c_{p,i}$ at different temperatures is well known in the literature (Nederlandse Gasunie, 1988), and the molar flow of each component was calculated from the data given in Table 4. The syngas temperature at the outlet of the gasifier was no more than 230 °C.

A certain amount of char was collected during gasification of hardwood pellets in each experimental series (from 0.8 to 3.5 kg/h; Table 4). For this reason, the energy output contained in the char $P_{out,char}$ was also taken into account and was defined as the product of char received per unit time (Table 3) and its higher heating value:

$$P_{out,char} = \dot{m}_{char} \cdot HHV_{char} \; (MJ / h) \qquad (4)$$

Our experimental results revealed that the energy input contained in the hardwood pellets reached, at 23 Nm³/h of supplied air, 530 MJ/h in *Case 1* and 660 MJ/h in *Case 2* (Table 4). For both cases, the largest fraction of the calculated output energy was chemical energy in the syngas (Figure 4 and Figure 5), from 94 MJ/h (at 12 Nm³/h of supplied air) to 530 MJ/h (at 23 Nm³/h of supplied air) in *Case 1* (Figure 4) and from 513 to 660 MJ/h, respectively, in *Case 2*. The higher output energy in *Case 2* is associated with the promotion of the pyrolysis process and the production of syngas with a higher calorific value.

The analysis of heat input and output during updraft gasification of hardwood pellets revealed a deviation of 33-47 % in the heat balance (Table 5), which might be caused by our not taking into account the energy output of tars and the heat loss of the installation.

According to the findings of Ayyadurai *et al.* (2017), it is difficult to heat balance the gasification process. These authors showed that the deviation in the heat balance reached 22 %. They also found that the chemical energy contained in the syngas represented nearly 60 % of the output energy. In our study, the work chemical energy was balanced from 57-88 % in *Case 1* and from 67-74 % in *Case 2*.

The char was gathered from the bottom of the reactor using an inverter coupled with a cyclical screw at a frequency of 5 sec/5min (*Case 1*) and 10 sec/2.5 min (*Case 2*), which stimulated bed movement in the reactor.

Table 5 Energy balance
Tablica 5. Energetska bilanca

		Case 1 / *Primjer 1.*				**Case 2** / *Primjer 2.*			
Amount of supplied air / *Količina dobave zraka*	Nm³/h	12	17	20	23	12	17	20	23
Fuel consumption / *Potrošnja goriva*	kg/h	14.6	19.6	23.0	27.0	26.2	27.1	28.8	33.7
Thermal input / *Toplinski ulaz*	MJ/h	196	384	450	529	513	529	564	660
Thermal output / *Toplinski izlaz*	MJ/h	168	205	246	303	284	316	375	401
Deviation / *Odstupanje*	%	15	47	45	43	45	40	33	39

Table 6 Energy characteristics of char
Tablica 6. Energetska obilježja pougljenjenog materijala

	Case 1 / *Primjer 1.*				Case 2 / *Primjer 2.*			
Air / *Zrak,* Nm³/h	12	17	20	23	12	17	20	23
Fuel consumption / *Potrošnja goriva,* kg/h	14.6	19.6	23.0	27.0	26.2	27.1	28.8	33.7
Char received / *Količina pougljenjenog materijala,* kg/h	2.6	1.1	0.8	0.8	3.4	3.2	3.5	2.9
Carbon content in char / *Sadržaj ugljika u pougljenjenome materijalu,* %	84.0	87.4	97.5	97.8	82.3	87.3	92.8	96
$P_{out,char}$, MJ/kg	32.81	27.63	25.39	23.04	86.51	85.28	101.83	88.52

The energy output contained in the char P_{out} is also an important part of the output energy. As shown in Table 6, in *Case 2*, the thermal output reached 100 MJ/h with a fuel consumption of 28.8 kg/h (20 Nm*3*/h of air) and remained at a similar level (85 MJ/h) for the other cases. An increase in air supplied to the gasifier for the slow movement of the bed (*Case 1*) caused a decrease in the quantity of received char (from 2.6 to 0.8 kg/h) and a decrease in the char output energy from 66 to 23 MJ/h. This aspect shows that fast bed movement in the reactor, stimulated by char outlet velocity, leads to a high amount of the char with a high energy potential, which can react with steam and form clean energy gas.

Our experimental investigation revealed that sensible heat contained in the producer gas did not constitute a significant infraction of the output energy balance; the sensible heat reached 11 MJ/h in *Case 1* and 10 MJ/h in *Case 2* (Figure 4 and Figure 5).

4 CONCLUSIONS
4. ZAKLJUČAK

Updraft gasification of hardwood pellets with different bed movement in the reactor and for 12, 17, 20 and 23 Nm³/h of supplied air has been developed and evaluated. The following conclusions were drawn:
1. The results indicated a significant effect of bed movement in the reactor suggesting that the gasifier could be considered as a flow reactor.
2. Slow bed movement promotes a higher combustion and reduction zone, which leads to syngas maximum calorific value of about 6 MJ/Nm³, while fast movement of the bed promotes a higher pyrolysis zone and generates more calorific gas (6-7 MJ/Nm³).
3. The results indicate that slow bed movement, in comparison to fast bed movement, generated a higher syngas yield, with its lower caloric value. These results showed that in both Cases similar specific energy values were obtained. However, lower fuel consumption was reached in *Case 1*.
4. Fast bed movement in the reactor leads to a high amount of generated char with high energy potential.
5. An energy balance analysis was carried out for all considered cases. The total calculated input energy flow attained a maximum of 560 MJ/h for slow bed movement and 660 MJ/h for fast bed movement (at 23 Nm³/h of supplied air), and the output energy flow was 303 and 400 MJ/h, respectively. The devia-

tion of 30-40 % in heat balance was caused by not taking into account the tars and heat losses. Furthermore, it was noted that the chemical energy in the syngas represented 60-80 % of the output energy.
6. Both cases of updraft hardwood pellet gasification generated high-quality gas. However, based on the temperature characteristics, performance data, carbon conversion efficiency and energy balance analysis, it was found that the fast movement of the bed with 20 Nm³/h of supplied air yielded the highest-quality gasification process.

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