ENERGY RECOVERY FROM UNCONVERTED BIOMASS CHAR

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Abstract: For the market of the Republic of Serbia the most interesting are biomass cogeneration plants with the thermal input between 100 and 300 kW. In this middle-power range, gas engines are the most suitable technology for electricity production from biomass. To convert biomass into the product gas, downdraft gasifiers are commonly used due to their reliable and tar-free functioning. The drawback of these reactors is the product gas, because it is laden with particulates and has a relatively small heating value. These particulates and the residues from gasifiers consist of unconverted char and ash. Depending on the design, there are typically from 3 to 15% of unconverted char. The increase in the amount of unconverted char linearly decreases the chemical efficiency of gasification process. Because of the heating value of char, the energy loss contained in unconverted char is significant and different measures are performed for its reduction: recuperation, recycling and non-energy use. In this paper, an original downdraft gasifier with a system for char recycling is presented. The advantage of the proposed solution is an enlarged reduction zone, which influences a longer residence time of solids inside the gasifier.

Key words: biomass gasification, cogeneration, unconverted char, downdraft gasifier, char recovery system.

1. INTRODUCTION

According to the availability of biomass and the size of companies in wood processing and agricultural industry, the most interesting biomass cogeneration plants for the market of the Republic of Serbia are those with the thermal input between 100 and 300 kW [1]. In this middle-power range, gas engines are the most suitable technology for electricity production [2] cited by [3]. To fuel gas engines, biomass gasification is used to convert solid biomass into the product gas, which has a useable heating value. This process takes place in a gasifier, which is an integral part of biomass cogeneration systems. Except a gasifier and a gas engine, a cogeneration system includes a product gas cleaning subsystem and auxiliary equipment such as: a hopper, feeding system, heat exchangers etc. In the considered power range, downdraft biomass gasifiers are the most frequently used reactors due to their capability to reliably produce tar-free gas [4]. The shortcoming of downdraft gasifiers is the product gas, because it is laden with particulates and has a relatively small heating value. The conversion of biomass in these type of rectors is never complete due to their kinetic limitations and non-even distribution of air. Depending on the design of a downdraft gasifier, the biomass may also form bridges or channels that influence the conversion rate. There is always an unconverted carbonaceous fraction, which is known as char. Depending on the design of a fixed bed gasifier, the produced amount of char can be as high as 10% of the initial input feedstock, with the values to fluctuate between 2 and 5% [5]. The carbon content of char is typically within the range of 50% to 80% and, thus, char tends to have significant heating value not only per mass of material, but also in respect of the total energy balance [6]. Several potential pathways for utilization of char have been identified: manufacturing of filters, application on agricultural fields, as a catalyst in fluidized bed gasifiers, and in building applications as insulated material [7]. In the same article, Vakalis et al. [7] investigated the possibility of an onsite energy production of additional electricity by introducing a secondary reactor that would convert char and flue gases into a gaseous fuel. The produced gaseous fuel would be utilized for electricity production in a smaller internal combustion engine.

The focus of the paper is the usage of ungasified char inside downdraft gasifiers. The unconverted char is often used in large scale fluidized bed reactors, primarily in a specific design that implements the concept of two-stage parallel gasification. In the concept, the solid mass stream is divided into at least two partial streams, which are processed in several parallel-arranged reactors [8]. The principle is to combust the ungasified char in a separate reactor and then to transfer the heat into the gasifier where endothermic gasification reactions take place. In these gasifiers, steam is used as a gasifying medium. The heat released by the combustion of ungasified char in the combustor is transferred to the gasifier via: a) circulating fluidized bed [8-10] or b) liquid metal heatpipes used to create high heat fluxes between the combustor and the gasifier [3]. Figure 1 shows the examples of allothermal gasifiers, which are heated by the combustion of ungasified char: (a) Battelle (Sylvagas) process [9], and (b) Fast Internally Circulating Fluidised Bed gasification concept [10].
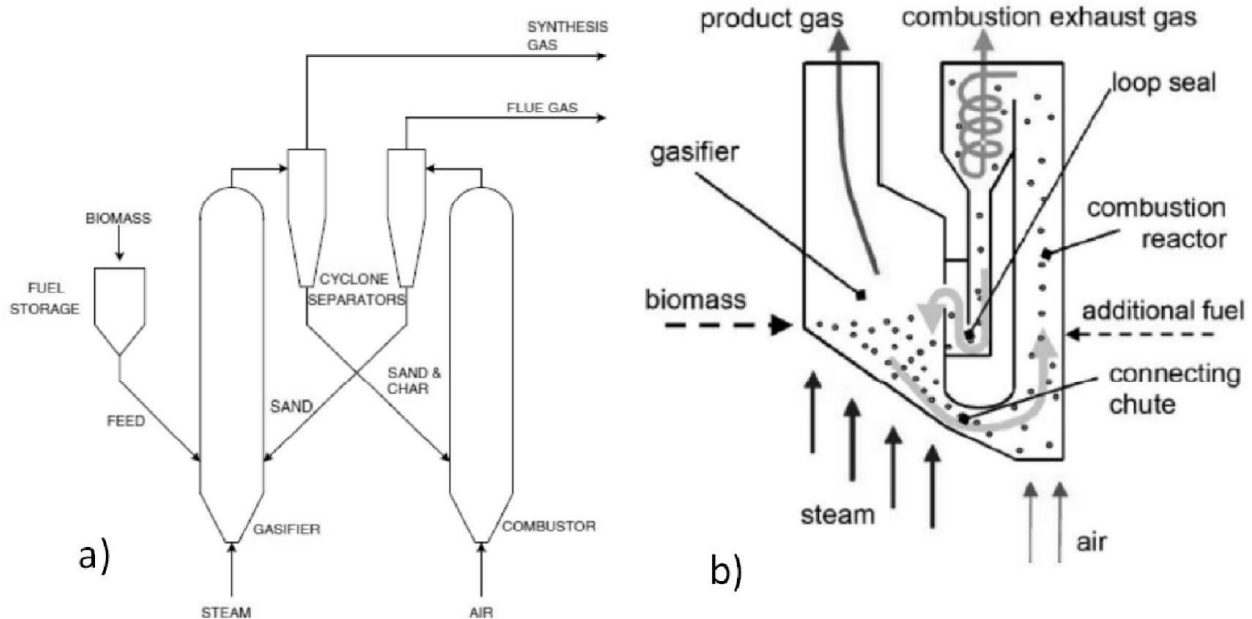
Figure 1. The principles of dual fluidized bed gasifiers in which the combustion of ungasified char is used to provide the heat for allothermal gasifiers: a) SilvaGas (Battelle) process [9], (b) Fast Internally Circulating Fluidised Bed gasification concept [10].

In biomass cogeneration systems with the size in the considered power range, the energy contained in unconverted char is typically used for air preheating and/or district heating. Figure 2 shows the Sankey diagram of a commercially available biomass cogeneration plant [11]. The diagram confirms the findings presented in [5] and shows that 7.8% of the input energy is contained in the unconverted char. The plant has a system that recuperates 2/3 of this energy, which is otherwise lost.
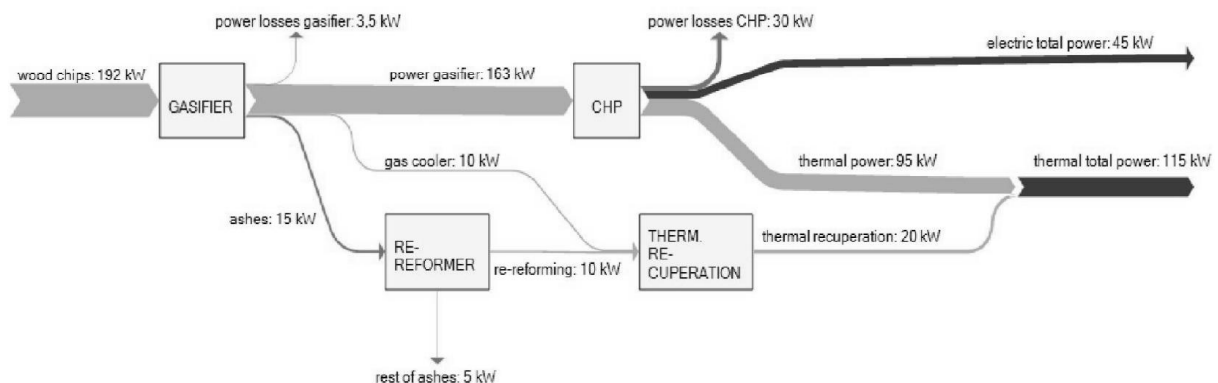
Figure 2. The Sankey diagram for a commercially available biomass cogeneration plant [11].

The goal of the paper is to present:

- the impact of unconverted char on the gasification efficiency and product gas composition,
- a technical solution for the usage of unconverted char.

Table 1 shows the properties of wood chips, which are used for the analyses in the paper. It also shows the composition of char [7] obtained by gasification of a similar biomass. Due to small amounts of hydrogen and nitrogen in the char (see Tab. 1), it is assumed that it consists only of carbon and ash.

Table 1. Fuel properties.

Ultimate analysis			Proximate analysis	
wt%	Wood chips	Char [7]	wt%	Wood chips
C	43.2	64	Organic mass	84.5
H	5.1	0.7	Ash	0.9
O	35.7	-	Moisture	14.6
N	0.5	0.3	LHV (kJ/kg)	15917
A	0.9	-		
H_2O	14.6	35		

Gasification process at 1 bar is analyzed because biomass cogeneration systems with a gas engine do not require pressurized product gas.

2. GASIFICATION MODELING

Figure 3 shows the structure of the stoichiometric chemical equilibrium model developed and validated in [12]. It is a two-stage model, which enables quasi-equilibrium approach too.

In the development of the model perfect mixing and uniform temperature distribution across the gasifier were assumed. In addition, it was assumed that the reaction rates are fast enough and that the residence time is sufficiently long to reach equilibrium state inside the gasifier. The model does not give the information about reaction pathways and formation of intermediates. Tar is not included in the model too. The previously mentioned assumptions and drawbacks are common for all equilibrium models and are discussed in detail in [12].

Gasification implies adding sufficient oxygen until all carbon is converted into the gaseous phase. This is covered by the first part of the model that can function independently, and is used to determine the equilibrium composition below and at the carbon boundary point (CBP), i.e. heterogeneous equilibrium. The CBP is obtained when exactly enough gasifying medium is added to avoid carbon formation and achieve complete gasification. Desrosiers [13], Double and Bridgwater [14] proved that the CBP is the optimum point for gasification with respect to energy-based efficiency, and Prins et al. [15] proved that it is the optimum point with respect to exergy-based efficiency. The addition of oxygen above the CBP leads to the decrease of the heating value and the increase of the sensible heat contained in the product gas until complete combustion takes place. This homogeneous equilibrium is covered by the second, dependent part of the model. The unknowns in the first part of the model are the required amount of gasifying medium, the temperature, and the amount and composition of the product gas. The gasifying medium, the gasification pressure, and the heat gain or loss of a gasifier are the common parameters for both parts of the model, which mean they are constant during simulation runs. The amount of unconverted solid carbon is the parameter only in the first part of the model.

The following chemical reactions are relevant in the first part of the model:

$$C + 2H_2 = CH_4 \tag{1}$$
$$C + H_2O = CO + H_2 \tag{2}$$
$$C + CO_2 = 2CO \tag{3}$$
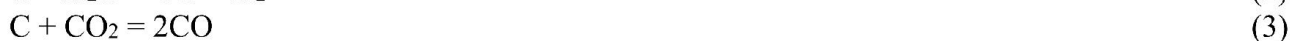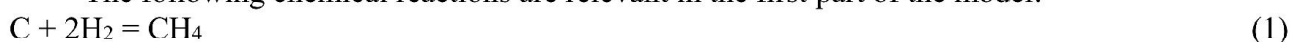
The exothermic methane formation (1) is coupled with the endothermic water-gas (2) and Boudouard (3) reactions.

In the second, dependent part of the model, the following homogeneous chemical reactions are relevant:

$$CO + H_2O = CO_2 + H_2 \tag{4}$$
$$CO + 3H_2 = CH_4 + H_2O \tag{5}$$
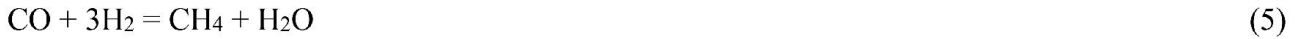
The water-gas shift reaction (4) is coupled with the homogeneous methane formation reaction (5).

The unknowns in the second part of the model are the required amount of gasifying medium, the amount and composition of the product gas, whereas the parameter is the temperature of gasification.

Although gasification temperature in real biomass gasifiers is above the temperature at the CBP, there is unconverted carbon due to kinetic limitations. Thus, when modeling a real gasifier, the modeling procedure is somewhat modified in regard to the one described in the paragraph just prior to Eq. (1). The first part of the model calculates the heterogeneous thermodynamic equilibrium of the product gas and a given amount of unconverted carbon. The obtained gas composition data are then used in the second part of the model to calculate the homogeneous equilibrium at a given gasification temperature. The unconverted carbon is assumed to leave the gasifier at a temperature obtained in the first part of the model, i.e. at the temperature of the heterogeneous equilibrium, which is lower than the gasification temperature. For the amounts of unconverted carbon that are encountered in practice, the exit temperature of the first part of the model is in the range of $600 \div 700\ °C$ for gasification at 1 bar depending on the moisture content in biomass.

The equivalence ratio (ER) is the amount of air added relative to the amount of air required for stoichiometric combustion. As it is shown in Fig. 3, the ER is used in the model as the initial value instead of the molar amount of air used for gasification. The relation between them for a fuel that does not contain sulfur is:

$$ER = \frac{0.21\ n_{air}}{n_C + 0.5\ n_H - n_O} \tag{6}$$

where n_{air} is the molar amount of air used for gasification, and n_C, n_H, n_O are the molar amounts of carbon, hydrogen, and oxygen in biomass, respectively.
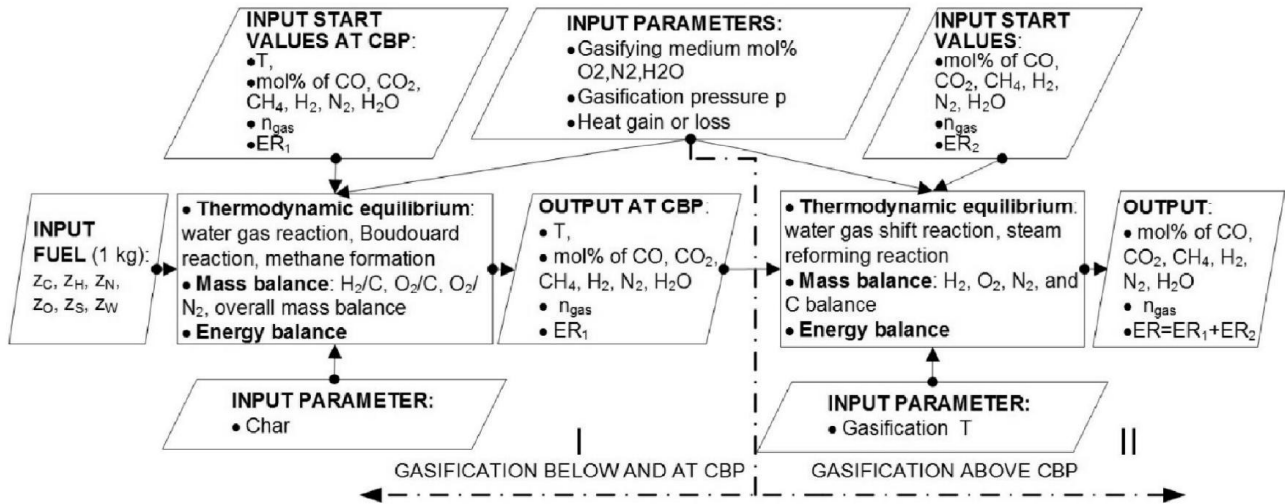

Figure 3. The structure of the model.

The chemical efficiency represents the chemical energy that is conserved in the produced gas and is calculated by:

$$\eta = \frac{V_{gas} \cdot LHV_{gas}}{LHV_{biomass}} \tag{7}$$

where V_{gas} in $[m^3/kg]$ is the volume of product gas obtained by the gasification of 1 kg of biomass. LHV_{gas} in $[kJ/m^3]$ is the lower heating value of the product gas calculated by [16]:

$$LHV_{gas} = 12626\ x_{CO} + 35795\ x_{CH_4} + 10789\ x_{H_2} \tag{8}$$

The energy contained in the char E_{char} in $[kJ/kg_{biomass}]$ is:

$$Q_{char} = Char \cdot C\left(32793.5 + \int \frac{7.166 + 4.271 \frac{T}{1000} - 8.\_\_\frac{T^2}{10^6}\_\_}{12} + 0.71 \cdot Ash \cdot \_\_\right), \tag{9}$$

where C [-] is the weight fraction of carbon in the fuel, and *Char* [-] is the weight fraction of unconverted carbon. The first term in the parenthesis on the right hand side of Eq. (9) i.e. 32793.5 kJ/kg is the heating value of carbon [16]. The second term in the parenthesis is the enthalpy change of carbon in [kJ/kg] between the temperature at the standard reference state $T_0=298$ K and the temperature T [K] at which the unconverted char leaves the gasifier. The numerator in the integral in Eq. (9) is the heat capacity of solid carbon depending on temperature, which is taken from [17]. The last term on the right hand side of Eq. (9) is the enthalpy change of ash between T_0 and T. It was assumed that all ash is composed of SiO_2. Ash is the weight fraction [-] of ash in the biomass, and 0.71 kJ/kg is the specific heat capacity of SiO_2 [18]. Compared with the chemical and physical energy contained in unconverted carbon the enthalpy of ash is insignificant due to a very small amount of ash in the used biomass (see Tab. 1).

3. RESULTS

As can be expected, the larger the amount of unconverted carbon, the smaller are the amounts of air required for complete gasification and produced gas. This is shown in Fig.4. In the figure, weight fraction 0.1 means that 10% of the carbon in biomass is unconverted and that the total amount of char is: 0.009(ash)$+0.1*0.432$ (carbon) $= 0.0522$ kg/kg$_{biomass}$ (see Tab. 1). It means that a biomass cogeneration system with the thermal input of 200 kW produces typically from 50 to 60 kg of char per day. Figures 4 – 6 cover the most common range in which the amounts of unconverted char in small downdraft gasifiers fluctuate, i.e. between 2 and 5% [5],. Theoretically, 0.934 m^3_N of oxygen misses in the gasifier per 1kg of unconverted carbon. However, gasifiers are usually supplied with sufficient amounts of air required for complete biomass conversion. The unconverted char emerges in downdraft gasifiers due to a non-even distribution of air through the bed. The maldistribution of air occurs due to its non-uniform distribution in the oxidation zone and due to the formation of bridges and channels inside the bed of biomass.
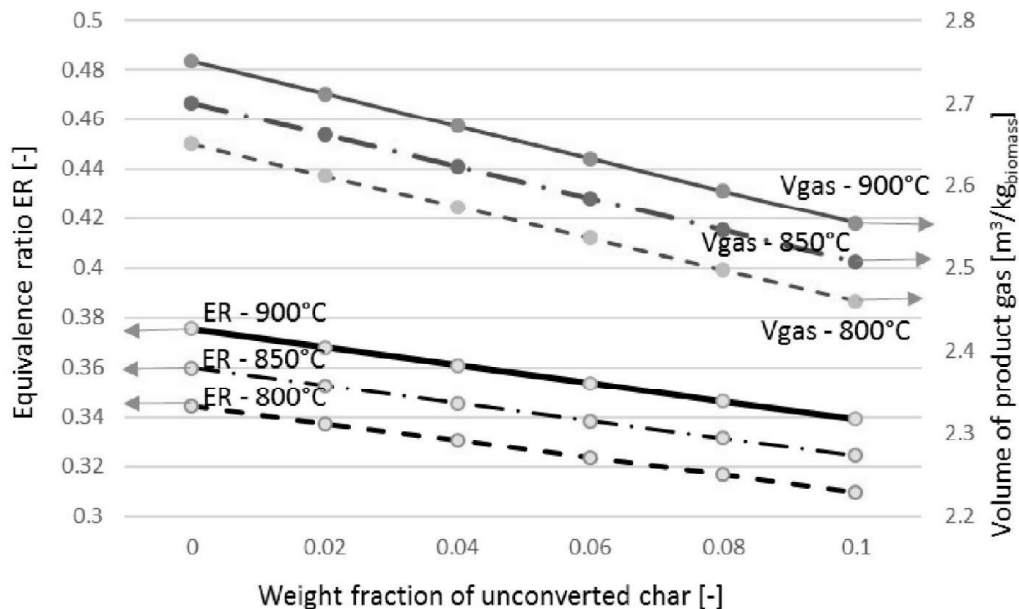

Figure 4. Equivalence ratio ER and the volume of product gas depending on the amount of unconverted carbon and the gasification temperature.

Figure 5. shows that the changes in composition and heating value of the product gas are not substantial in the examined range of unconverted char. These changes are smaller compared with the change of the produced volume of the product gas (see Fig. 4). The decreases of the produced volume

of the product gas and its LHV with the increase of the unconverted char decreases linearly the chemical efficiency of the gasification process, as can be seen in Fig. 6. As can be expected, the increase of unconverted carbon decreases the amounts of CO and CH_4, and slight increases the amounts of CO_2 and H_2O in the product gas. The latter increase is because the smaller amount of converted chemical energy per 1 kg of biomass should maintain the desired gasifying temperature, here at 900 °C.
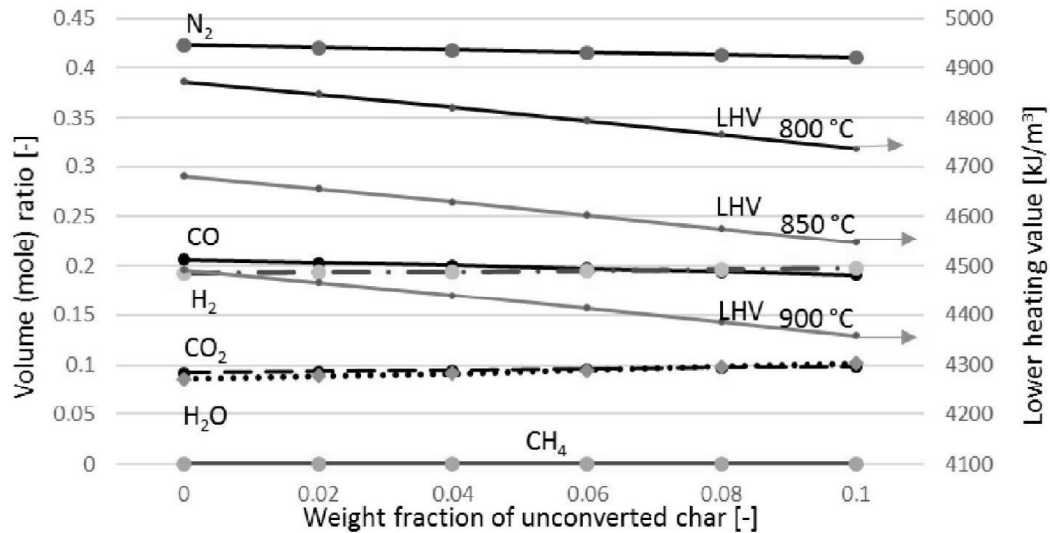

Figure 5. The composition of the product gas at 900 °C and LHV of the product gas depending on the weight fraction of unconverted carbon.

Figure 6 shows that the unconverted char has the biggest impact on chemical efficiency because of the dominance of the chemical energy in the total energy of the char. As the ordinate axis in Fig. 6 is relative to the heating value of the biomass (see Table 1), the chemical energy of the product gas represents chemical efficiency of the gasification process.
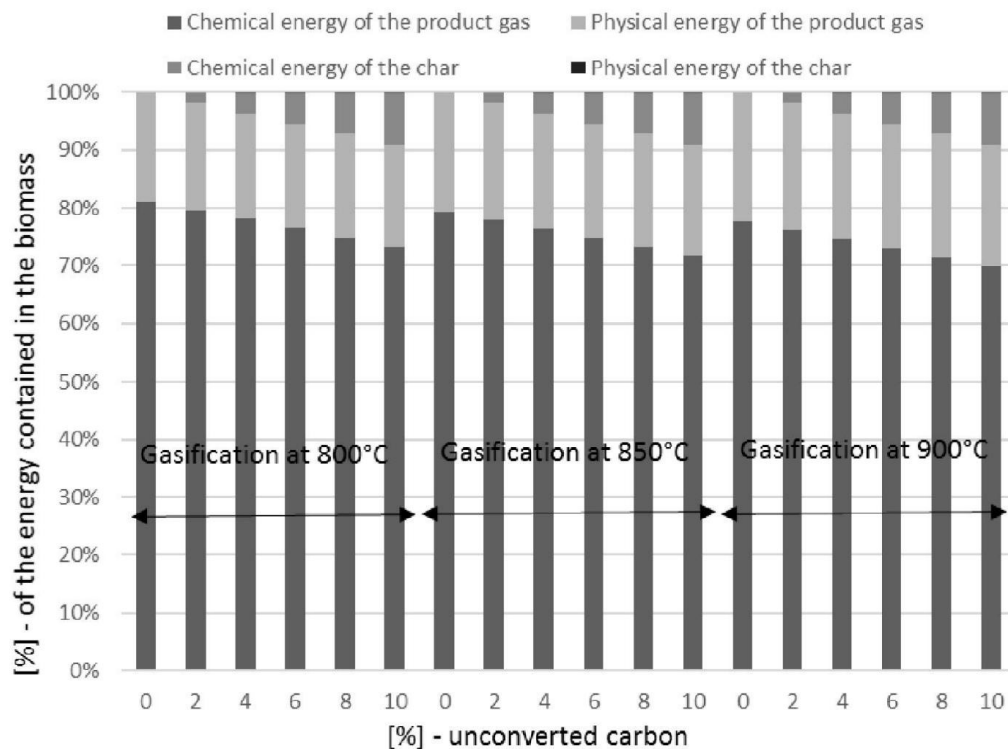

Figure 6. Relative energy balances of gasification processes depending on the amount of unconverted carbon for three different gasification temperatures.

4. PROPOSED TECHNICAL SOLUTION

The technical solution for the recuperation of energy contained in unconverted char depends on: its composition, its availability, the priority of the biomass cogeneration plant (whether it is to produce as much electricity or to satisfy heat consumption), etc. The ungasified char could be: recuperated for air preheating and/or thermal power production, recycled to the gasifier, or used for gasification in other reactor, like in the solution proposed in [7].

Figure 7 shows the technical solution for recycling of unconverted char. The advantage of the proposed solution over the system for recuperation is that there is no an indirect heat exchange, which produces additional irreversibilities due to heat transfer over a finite temperature difference.
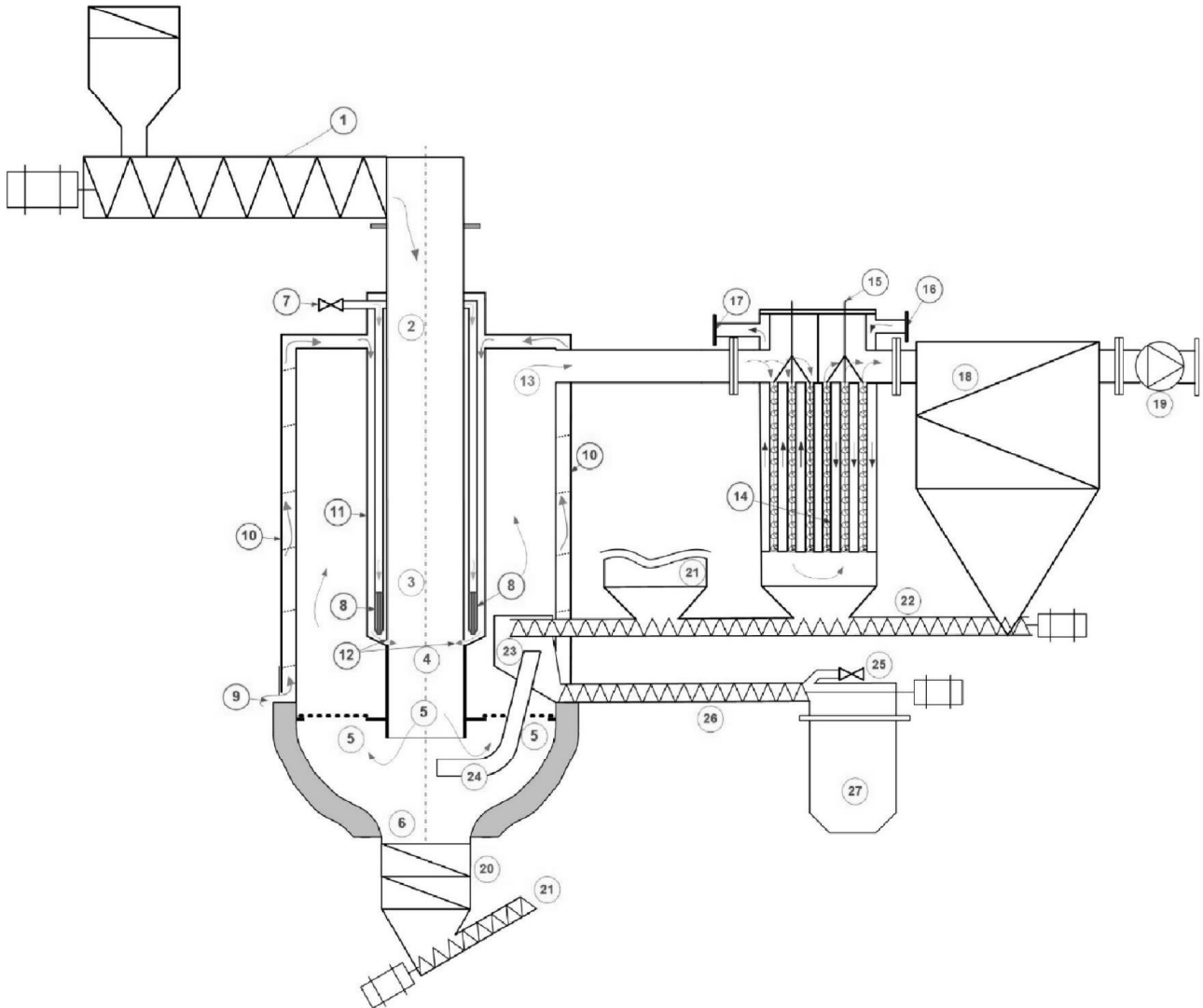
Figure 7. The system for the usage of ungasified char in a downdraft gasifier. 1 – biomass feeding system, 2 – biomass drying zone, 3 – biomass pyrolysis zone, 4 – oxidation zone of the gasifier, 5 – reduction zone of the gasifier, 6- unconverted char and ash, 7 –ignition air, 8- ceramic igniter, 9 – the inlet of gasifying air, 10 – outer annular heat exchanger (product gas/gasifying air), 11 – inlet annular heat exchanger (product gas/gasifying air), 12 – air inlets, 13 – product gas laden with particulates, 14 – heat exchanger (product gas/district heating water), 15 – turbulators that periodically move up and down to shake off the accumulated particles, 16 – the inlet of district heating water, 17 – the outlet of district heating water, 18 – candle filter, 19 – blower, 20 – twin flap valve, 21 – screw conveyor, 22 – screw conveyor, 23 – combustion chamber, 24 – chute, 25 – combustion air, 26 – screw conveyor, 27 – ash bin.

Through the feeding system 1, biomass is introduced into the inner most cylinder of the gasifier. At the top of the cylinder the biomass is dried 2, then it enters the pyrolysis zone 3. The products of pyrolysis enter the combustion zone 4. The gasifying medium is preheated air. The air enters into the

combustion zone via the radial openings 12. The combustion products together with solid mass arrive in the reduction zone 5. This zone occupies the bottom part of the reactor.

The ignition of the biomass is achieved via separate air passages that distribute air through two ceramic igniters 8. The air used for ignition enters into the combustion zone via already mentioned radial openings 12. The gasifying air is preheated through two-stage radiant and convective air preheater 10 and 11. By this arrangement, the hot product gas is used to preheat the gasifying air. The heat loss of the gasifier is reduced by the exchanger too.

The second phase of product gas cooling takes place outside of the gasifier in a shell and tube heat exchanger. In the exchanger, the product gas gives off heat to a district heating system. As the product gas 13 is laden with particulates, the exchanger is equipped with turbulators, which not only enhance heat transfer but periodically move up and down to shake off the accumulated particles. The last stage of the product gas cleaning is the candle filter 18. The blower 19 is used to circulate all the gas streams in the system.

The unconverted char and ash are removed from the bottom of the gasifier via the ash removal valves 20. The removed unconverted char and ash are transported by the screw conveyor 21 to the other screw conveyor 22. The conveyor 22 transports into the combustion chamber 23 not only the unconverted char and ash from the bottom of the gasifier but also the particulates removed in the filter 18 and the heat exchanger 14. There is no need for any kind of ignition system in the chamber as the hot product gas 13 passes over it. From the chamber 23, the ash is removed by the conveyor 26. The ash gives to the combustion air 25 part of its sensible heat. The combustion air 25 is supplied to the chamber 23 through the conveyor 26. The ash is collected in the bin 27. It is preferable to use always a constant amount of air 25 and to combust unconverted char with an air deficit. The flue gas from the combustion chamber 23 is than via the chute 24 transferred into the reduction zone 5 of the gasifier. The energy of the flue gas is used for the endothermic gasification reactions that take place in the reduction zone 5. In the presented manner a two-stage conversion i.e. recycling of the solids is achieved. The advantage of the design is an enlarged reduction zone 5 of the gasifier.

5. CONCLUSIONS

The amount of unconverted char depends on the used biomass and the design of a fixed bed gasifier and can be as high as 10% of the initial input feedstock, with the values that fluctuate between 2 and 5% [5]. The unconverted char is not formed due to an insufficient amount of air (gasifying medium) but due to a non-even distribution of air through the bed. This maldistribution occurs due to a non-uniform distribution of air in the oxidation zone and due to the formation of bridges and channels of biomass inside the bed.

Compared with the decrease in the produce volume of the product gas with the increase in the amount of unconverted char, the change in composition and the decrease in heating value of the product gas is not substantial. The increase in the amount of unconverted char linearly decreases the chemical efficiency of the gasification process.

The unconverted char is used for air preheating and/or thermal power production, recycled to the gasifier, or used for gasification in other reactor. The technical solution presented in this paper uses a two-stage conversion i.e. recycling of the solids. The advantage of the design is an enlarged reduction zone, which influences a longer residence time of solids inside the gasifier. Compared with the recuperation systems, the advantage of the proposed solution is that there is no heat transfer over a finite temperature difference.

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