



## The Use of Preheated Low-Enriched Air in Downdraft Gasifiers: Energy and Exergy Analysis

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**Abstract:** In comparison with air, the use of oxygen as a gasifying agent is less exergetically efficient. For small-scale cogeneration plants, smaller than 1MW of thermal power, the use of oxygen is expensive and inefficient. The improvement in the technology of membrane separation of gases gives rise to the possible inclusion of oxygen-enriched air as a gasifying medium. The article aims at presenting a numerical study analyzing the gasification of treated wood in downdraft gasifiers with preheated low-enriched air (from 21 vol% to 30 vol%). The analyzed system consists of three subsystems: (i) for air enrichment by polymeric membrane, (ii) for preheating of enriched air by heat exchange with the product gas, and (iii) a downdraft gasifier. The increase of oxygen level in enriched air increases the temperature at the carbon boundary point (optimal gasification point), the amounts of combustible gases in the product gas, energy and exergy efficiencies and decreases the amount of air (oxygen) required for complete gasification as well as the amount of N<sub>2</sub> in the product gas. The preheating of enriched air by heat exchange with the product gas is more beneficial for the gasification with lower levels of enrichment.

**Keywords:** Biomass gasification, Exergy analysis, Medium preheating, Oxygen enrichment, Treated wood.

### 1. Introduction

The global campaign for a larger use of renewable energy justified by the need for sustainable development causes the increase of biomass use as a fuel and development of new, energy efficient technologies for its transformation. Turkenburg [1] recognizes three main energy conversion routs for biomass: thermochemical and biochemical conversions, and extraction. Among thermochemical conversions there are: combustion, gasification, pyrolysis, liquefaction, and hydro thermal upgrading [2].

Gasification is the conversion of biomass or any carbonaceous fuel to a gaseous product with a useable heating value [3] and can be used for production of heat and/or electricity, and other biofuels: synthetic natural gas, biodiesel, methanol, hydrogen. The generation of electricity and useful heat from the same power plant is called “cogeneration” or “combined heat and power” (CHP).

In the Republic of Serbia, like in many countries, there are incentives for using renewable energy for electricity generation. The feed-in tariffs for the electricity produced from wood and agriculture biomass recognize three categories depending on the installed capacity [4]: (i) for plants with the capacity up to 1 MWel the electricity price is 13.26 c€/kWh, (ii) for plants with capacity between 1 and 10 MWel, the price is calculated as 13.82-0.56P (where P is capacity of the plant in MWel and the price is in c€/kWh), and (iii) for plants with the capacity larger than 10 MWel the price is 8.22 c€/kWh. In the domestic market small and medium-sized companies are dominant in the sawmill industry and their production volumes and thus their needs for heat are such that they do not require the CHP installations bigger than 1 MWel [5]. In this power range of currently available power systems the most efficient are those that use: gas engines, micro turbines

and fuel cells [6]. To use biomass, all these CHP systems require biomass gasification, which is usually the bottleneck in those processes [7].

Prins et al. [8] showed that in comparison with air-blown gasification, oxygen-blown gasification of carbon is less exergy efficient because separation of oxygen from air by the use of cryogenic distillation produces additional process losses. Except by cryogenic process, oxygen is produced by pressure swing adsorption and membrane separation [3, 9]. These processes are especially efficient for low (less than 30 vol% of oxygen) and medium (from 30 vol% to 90 vol%) levels of enrichment. Membrane separation has been continually improving [10] and is deemed particularly well suited to small scale oxygen enriched air requirements [11].

Gasification with low oxygen enriched air is not a widely researched topic. Recently, Silva and Rouboa [12] examined gasification of pine biomass with enriched air by varying oxygen concentrations from 21 to 40 vol% at the carbon boundary point (CBP). 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 the energy-based efficiency, and Prins et al. [15] proved that it is the optimum point with respect to the exergy-based efficiency, as cited by Ptasiński et al. [16].

Regarding the aforementioned, the aim of this paper is to answer:

- how the optimal gasification point (CBP) changes depending on oxygen content and preheating temperature of the enriched air,
- how the gasification parameters (composition, product gas heating value, exergy...) change depending on oxygen content and preheating temperature of enriched air at an typical gasification temperature of 900 °C that can be encountered in downdraft gasifiers,
- whether the addition of low-enriched air improves energy and exergy efficiencies of the gasification process?

The reason to study gasification at the CBP is that this optimal gasification point changes depending on the fuel type, gasifying medium, temperature and pressure of the process. This paper should also answer is it possible to achieve that gasification in real reactors could be carried out at the CBP by preheating low oxygen-enriched air? Air preheating is beneficial and improves the efficiencies of the gasification process, raises the temperature at CBP, lowers tar content in the product gas, and improves the conversion of biomass to the product gas [17].

Biomass gasifiers usually work at temperatures higher than that corresponding to the CBP because the temperature of 800–900°C is required to gasify the most refractory part of almost any biomass [Higman] and the lower temperature range has a very high tar make. On the other hand gasifiers have “no-go” [3] temperature range between the softening and slagging temperatures of the ash. These are the reasons why fixed and fluidized bed gasifiers work in the range from 800-900°C. The examples of gasifying biomass in entrained flow reactors at temperature higher than 1100 °C, like Carbo-V® process [18], are rare.

The majority of the commercial CHP plants with capacities smaller than 1 MWel downdraft gasifiers due to their reliable operation and production of almost tar-free gas. Their deficiencies are the inability to change their capacity and production of the gas with: low heating value, high particulate load, and high temperature. This is the reason why gasification at 900°C, which is a very common temperature for downdraft reactors, is used in this paper.

Fig. 1 shows the schemes of the analyzed systems. These are gasifications with: (a) oxygen enriched air, (b) oxygen enriched air preheated by the product gas sensible heat, and (c) system that consists of: a subsystem for production of oxygen enriched air by the use of a permeable membrane, a heat exchanger that preheats oxygen enriched air by heat exchange with the product gas, and a biomass gasifier.

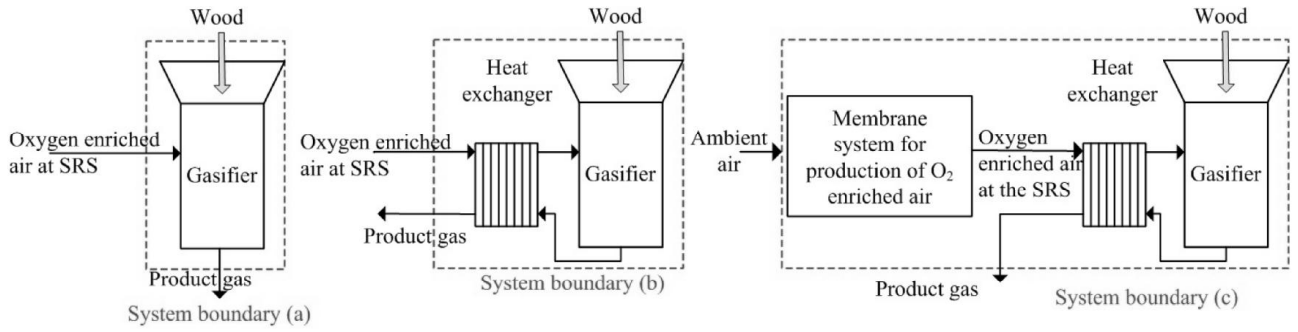


Figure 1. Schematic diagram of the examined processes. SRS – standard reference state (0.1MPa, 298K).

Table 1 gives the characteristics of treated wood [16], the biofuel used in the analysis. Possibly its moisture content represents the average that can be found in the Republic of Serbia wood processing industry. The lowest moisture on the market have sawdust from the furniture factories and biomass pellets ~ 8 wt% and a moisture content of 20 wt% can be obtained by air-drying of biomass.

Table 1. The characteristics of treated wood [16].

Proximate analysis (wt%)			LHV	Exergy
Organic fraction	Moisture	Ash	[kJ/kg <sub>wood</sub> ]	[kJ/kg <sub>wood</sub> ]
81.0	14.7	4.44	15917	18262
Ultimate analysis (wt% of organic fraction)				
C	H	O	N	S
51.5	6.03	41.3	1.22	0.09

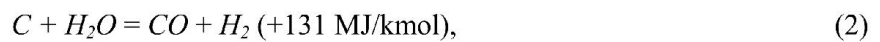
The combustion air consisting of 21 mol% oxygen and 79 mol% nitrogen is used to model ambient air.

## 2. Methodology

### 2.1. Biomass gasifier

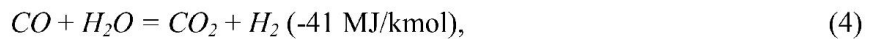
For the purpose of the present analysis, a two-stage chemical equilibrium model that uses mass and energy balances, developed in [19] and validated in [19,20], is used. It enables the determination of the CBP and analysis of the gasification below and above this point with preheated gasifying medium.

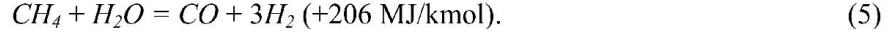
Fig. 2 shows the model structure. Gasification implies adding sufficient oxygen until all carbon is converted into the gaseous phase. This is covered by the first part of the model that can function independently, and is used to determine the equilibrium composition below and at the CBP, i.e. heterogeneous equilibrium. Further 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 losses 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. When gasification occurs at the CBP, the amount of unconverted solid carbon equals zero. The following chemical reactions are relevant in the first part of the model [19]:



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:





The water-gas shift reaction (4) is coupled with the homogeneous methane formation reaction (5).

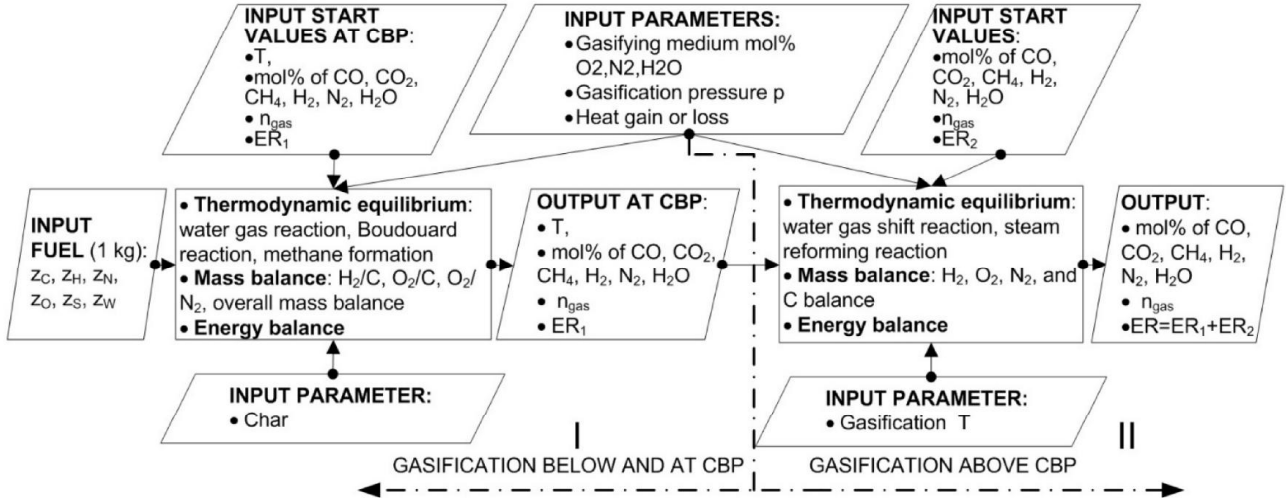


Figure 2. The structure of two-stage equilibrium model.

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

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. 2, 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:

$$ER = \frac{0.21n_{air}}{n_C + 0.5n_H - n_O}, \quad (6)$$

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

The heat exchanger shown in Fig. 1 is simulated as an ideal heat exchanger without heat loss.

## 2.2. The membrane

The membranes are thin barriers that are semipermeable to some compounds and that selectively allow one or some compounds more than others [9]. Their use for partial air separation progressed rapidly in the 1980s as a promising alternative to cryogenics and adsorption [21] cited by [22]. For oxygen separation from air, the preference is given to the polymeric membranes and from a few years also to the ceramic-based membranes [11]. The latter produce very high purity oxygen, but are still developmental and exhibit low oxygen permeability and productivity and require high operating temperatures (800 to 900°C) [11].

The diffusion of some gas compounds through polymeric membranes, which operate at ambient temperatures, is driven by pressure difference between the two sides of the membrane. As the oxygen molecule has a smaller size than that of nitrogen, membranes are usually more permeable to oxygen [9]. Membrane systems do not give pure oxygen as a product but an oxygen-enriched air. In the oxygen-enriched stream oxygen concentration usually ranges from 25% to 50% in volume and polymeric membrane systems can provide up to 20 tons/day of enriched stream [23] cited by [9]. Polymeric membrane separators typically contain small hollow fibers of 100–500  $\mu\text{m}$  diameter and are assembled into bundles as large as 0.25 m diameter and up to 3 m in length. A dense polymer separating layer, as thin as 35 nm, is supported on the porous walls of the hollow fiber [11].

The behavior of a membrane is indicated by its permeability (P) and selectivity ( $\alpha$ ). Permeability is related to the quantity of gas that can pass through the membrane. As a consequence, for a given required mass flow of one gas compound through the membrane, the higher the permeability will be, the lower the membrane area requirement [9]. To decrease the cost of a membrane system the tendency is to decrease the membrane area. Permeability is commonly given in Barrers (1 Barrer =  $0.33 \times 10^{-15} \text{ mol m/m}^2 \text{ s Pa}$ ) [9].

Membrane selectivity represents how much the membrane will let go through one compound over another. In the process of oxygen separation from air, the membrane selectivity of O<sub>2</sub> over N<sub>2</sub> is defined by:

$$\alpha = \frac{p_{O_2}}{p_{N_2}}. \quad (7)$$

It has been recognized that selectivity decreases when the permeability of the most permeable component increases. For the O<sub>2</sub>/N<sub>2</sub> separation the best available membrane systems follows the empirical upper bond correlation given by Robeson [10]:

$$P_{O_2} = 1396000\alpha^{-5.666}. \quad (8)$$

The molar flow rate of any compound *i* that crosses the membrane is given by:

$$\dot{n}_i = A\left(\frac{P_i}{L}\right)\Delta p_{p,i}. \quad (9)$$

In this equation,  $\dot{n}_i$  is the molar flow rate of compound *i*, *A* is the membrane area,  $P_i$  the permeability of the membrane to component *i*, *L* the membrane thickness and  $\Delta p_{p,i}$  the difference of partial pressure of component *i* on the two sides of the membrane. Equations (7-9) together with mass and energy balances allow modeling of a membrane.

A pressure difference between two sides of a membrane is required for its operation and is accomplished either by the air compression at the entrance or by the vacuum formation at the exit of a membrane. The mass flow rates of the different compounds of air are then controlled by permeability and area. Fig.3 schematically shows these two systems.

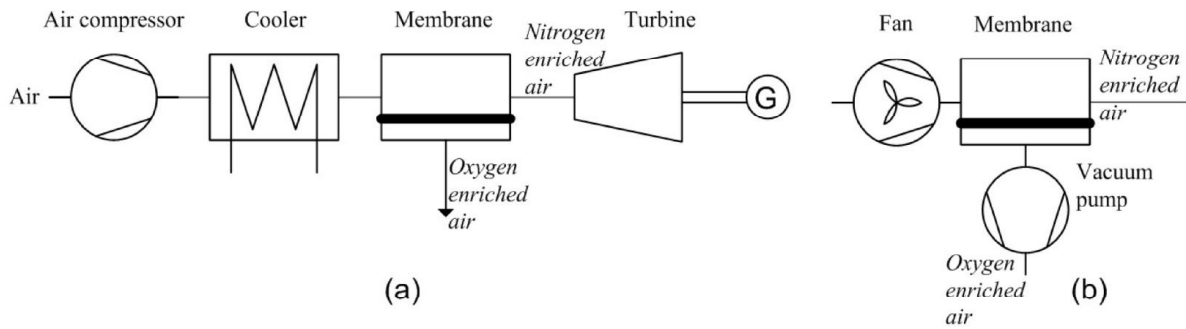


Figure 3. Schematic of simple membrane processes: (a) with a compressor coupled with a recovery turbine, (b) with vacuum pump.

Instead modelling the systems shown in Fig. 3, it was decided to use a simpler approach by using the datum given by Bisio et al. [24], who for the membrane system that produces 37.5 vol% oxygen enriched air obtained the energy requirement of 210 kWh per ton of equivalent O<sub>2</sub>. Figure 4 shows how the exergy analysis of the system given in Fig. 1 (c) is performed. There are two air streams: one 37.5 vol% oxygen enriched and the other of ambient air. They are mixed in different ratios to achieve oxygen enrichment from 21 vol% to 37.5 %. The analysis is carried out for gasifying medium (enriched air) at ambient temperature and at an elevated temperature 800°C.

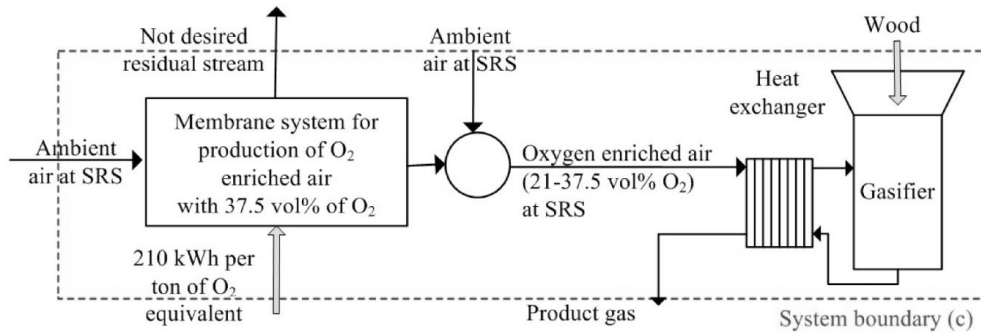


Figure 4. Schematic diagram for the exergy analysis of the system (c) in Fig. 1.



### 3. Exergy and energy analysis

Exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment [25] (taken from [26]). This thermodynamic property considers the irreversible increase in entropy, i.e. the second law of thermodynamics, and is suitable for analyzing the energy conversion processes.

The chemical exergy efficiency is defined as the ratio between the chemical exergies of the product gas and the biomass:

$$\psi_{ch} = \frac{n_{gas}e_{ch,gas}}{e_{ch,biomass}}. \quad (10)$$

where  $n_{gas}$  is the molar amount of product gas produced by gasification of 1 kg of treated wood, and  $e_{ch,gas}$  and  $e_{ch,biomass}$  are chemical exergies per 1kg of biomass of the product gas and biomass, respectively. This and all other efficiencies used in this paper are calculated per 1 kg of biomass.

The exergy efficiency represents the ratio between exergy flows out and into a system [27]. In this efficiency, the sensible heat of the product gas, which is ignored in Eq. (39), is taken into account as the physical exergy of the product gas  $e_{ph,gas}$ . At higher gasification temperatures, the portion of the physical exergy is considerable in the total exergy of the product gas. For the system (b) in Fig. 1 the exergy efficiency is:

$$\psi = \frac{n_{gas}(e_{ch,gas}+e_{ph,gas})}{e_{ch,biomass}+n_{enriched\ air}(x_{O_2}e_{O_2}+x_{N_2}e_{N_2})}. \quad (11)$$

whereas for the system (c) shown in Fig.1 and in Fig. 4 the exergy efficiency is:

$$\psi = \frac{n_{gas}(e_{ch,gas}+e_{ph,gas})}{e_{ch,biomass}+n_{enriched\ air\ 37.5\% O_2} \cdot Mr \cdot \frac{210 \cdot 3600}{1000}}. \quad (12)$$

In this equation  $Mr=29.5$  kg/kmol is the molar mass of air enriched with 37.5 vol% of oxygen. The second term in Eq. (12) is the exergy per 1 kg of biomass used to produce the air stream enriched with 37.5 vol% of oxygen (see Fig. 4). In Eqs. (11-12) it was assumed that the biomass and air are at the standard reference state (0.1 MPa, 298K). This is the reason why physical exergy of the wood and the exergy of ambient air are zero.

The statistical correlation of Szargut and Styrylska [28], taken from [29], is used to calculate the exergy of solid biomass:

$$e_{ch,biomass} = z_{org}(\beta LHV_{org}) + z_S(e_{ch,S} - C_S) + z_W e_{ch,water} + z_A e_{ch,ash}. \quad (13)$$

The factor  $\beta$  is the ratio of the chemical exergy to the LHV of the organic fraction of biomass [29]:

$$\beta = \frac{1.044 + 0.0160H/C - 0.3493O/C(1 + 0.0531H/C) + 0.0493N/C}{1 - 0.4124O/C}. \quad (14)$$

where  $H/C$ ,  $O/C$ , and  $N/C$  represent the atomic ratios in the biomass.

The unknown exergies in Eqs. (39) and (40) are determined according to [27,29], whereas the standard chemical exergies are taken from Szargut et al. [30].

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

$$\eta = \frac{n_{gas}LHV_{gas}}{LHV_{biomass}}. \quad (15)$$

The LHV of the product gas and biomass are calculated by the equations given in [19].

### 4. Results

Figure 5. (A) shows that the increase in oxygen level in enriched air increases the temperature at the CBP and decreases the amount of air (oxygen) required for complete gasification of the treated wood. The decrease of the required air (oxygen) is less pronounced at higher preheating temperatures. This happens because for the same preheating temperature, the increase of oxygen in enriched air decreases the amount of

air supplied to the gasification process and consequently decreases the sensible heat supplied to the process. The air enriched with 30 vol% of oxygen and preheated at a temperature larger than 600°C increases the temperature at the CBP almost to the temperature that can be met in real downdraft gasifiers.

Figure 5 (B) shows that the increase in oxygen enrichment level increases CO, CH<sub>4</sub>, H<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O, and decreases substantially N<sub>2</sub> in the product gas at the CBP. The increase of CO and H<sub>2</sub> is caused by higher gasification temperatures (see Fig. 5 (A)), which favorize the endothermic water-gas (2) and Boudouard (3) reactions. The preheating of oxygen enriched air additionally increases the amounts of desirable CO and H<sub>2</sub> in the product gas. This happens because the preheated enriched air provides a part of the heat necessary to drive endothermic gasification reactions whereas the rest is provided by exothermic reactions. The increase in valuable gases CO, H<sub>2</sub>, and CH<sub>4</sub> increases the heating value and chemical exergy contained in the product gas as can be seen in Fig. 5 (C). In comparison with the increase in chemical exergy, the increase in lower heating value is larger because for some of the small molecules contained in the product gas, the chemical exergy is less than their LHV, *e.g.* 97.6% for H<sub>2</sub> and 97.2% for CO. This is also the reason why the energy efficiency is larger than chemical exergy efficiency as can be seen in Fig. 5 (D).

Figure 5 (D) shows how the efficiencies increase with the level of enrichment. Compared with the increase of exergy efficiency, the increase of chemical energy and exergy efficiency is more noticeable with the rise of the enrichment level. This happens because the increase in the enrichment level decreases the amount of the product gas and consequently its physical exergy, as can be seen in Fig. 5 (C). The exergy efficiency in Fig. 5 (D) is shown for the case (b) in Fig. 1.

The increase in O<sub>2</sub> level has the same influence at 900°C as it has at the CBP, as can be seen in Table 2. The table shows the results for the gasification of treated wood with low-level enriched air at 25°C and at an elevated temperature of 800°C. The results show all the trends noticed and explained for the gasification of treated wood at the CBP.

Table 2. Gasification of treated wood at 900 °C.

O <sub>2</sub>	ER	$x_{CO}$	$x_{CO_2}$	$x_{CH_4}$	$x_{H_2}$	$x_{N_2}$	$x_{H_2O}$	$n_{gas}$	LHV <sub>gas</sub>	$e_{ch, gas}$	$e_{ph, gas}$	$\eta$	$\Psi_{ch}$
[%]	[-]	$\left[\frac{m_N^3}{m_N^3}\right]$	$\left[\frac{m_N^3}{m_N^3}\right]$	$\left[\frac{m_N^3}{m_N^3}\right]$	$\left[\frac{m_N^3}{m_N^3}\right]$	$\left[\frac{m_N^3}{m_N^3}\right]$	$\left[\frac{m_N^3}{m_N^3}\right]$	$\left[\frac{kmol}{kg}\right]$	$\left[\frac{kJ}{m_N^3}\right]$	$\left[\frac{kJ}{kg}\right]$	$\left[\frac{kJ}{kg}\right]$	[-]	[-]
enriched air at 25°C													
21	0,376	0,202	0,091	1,9E-05	0,180	0,434	0,094	0,123	4492	11962	2001	0,776	0,655
22	0,370	0,210	0,092	2,2E-05	0,187	0,416	0,095	0,119	4675	12067	1942	0,783	0,661
24	0,361	0,225	0,094	2,9E-05	0,201	0,383	0,097	0,113	5011	12244	1843	0,794	0,670
26	0,354	0,239	0,096	3,6E-05	0,213	0,353	0,099	0,107	5311	12389	1752	0,803	0,678
28	0,347	0,251	0,098	4,3E-05	0,224	0,327	0,101	0,103	5581	12509	1696	0,811	0,685
30	0,342	0,262	0,099	5,0E-05	0,234	0,303	0,103	0,100	5826	12610	1640	0,817	0,691
enriched air at 800°C													
21	0,292	0,252	0,072	6,0E-05	0,227	0,373	0,075	0,111	5640	13515	1763	0,880	0,740
22	0,291	0,258	0,074	6,5E-05	0,232	0,359	0,077	0,108	5770	13527	1728	0,880	0,741
24	0,290	0,269	0,076	7,0E-05	0,242	0,333	0,080	0,104	6010	13548	1666	0,881	0,742
26	0,290	0,279	0,079	8,0E-05	0,251	0,309	0,082	0,101	6228	13566	1613	0,882	0,743
28	0,289	0,288	0,081	9,0E-05	0,259	0,288	0,085	0,098	6426	13583	1569	0,883	0,744
30	0,289	0,296	0,083	9,9E-05	0,266	0,268	0,087	0,095	6608	13597	1530	0,883	0,745

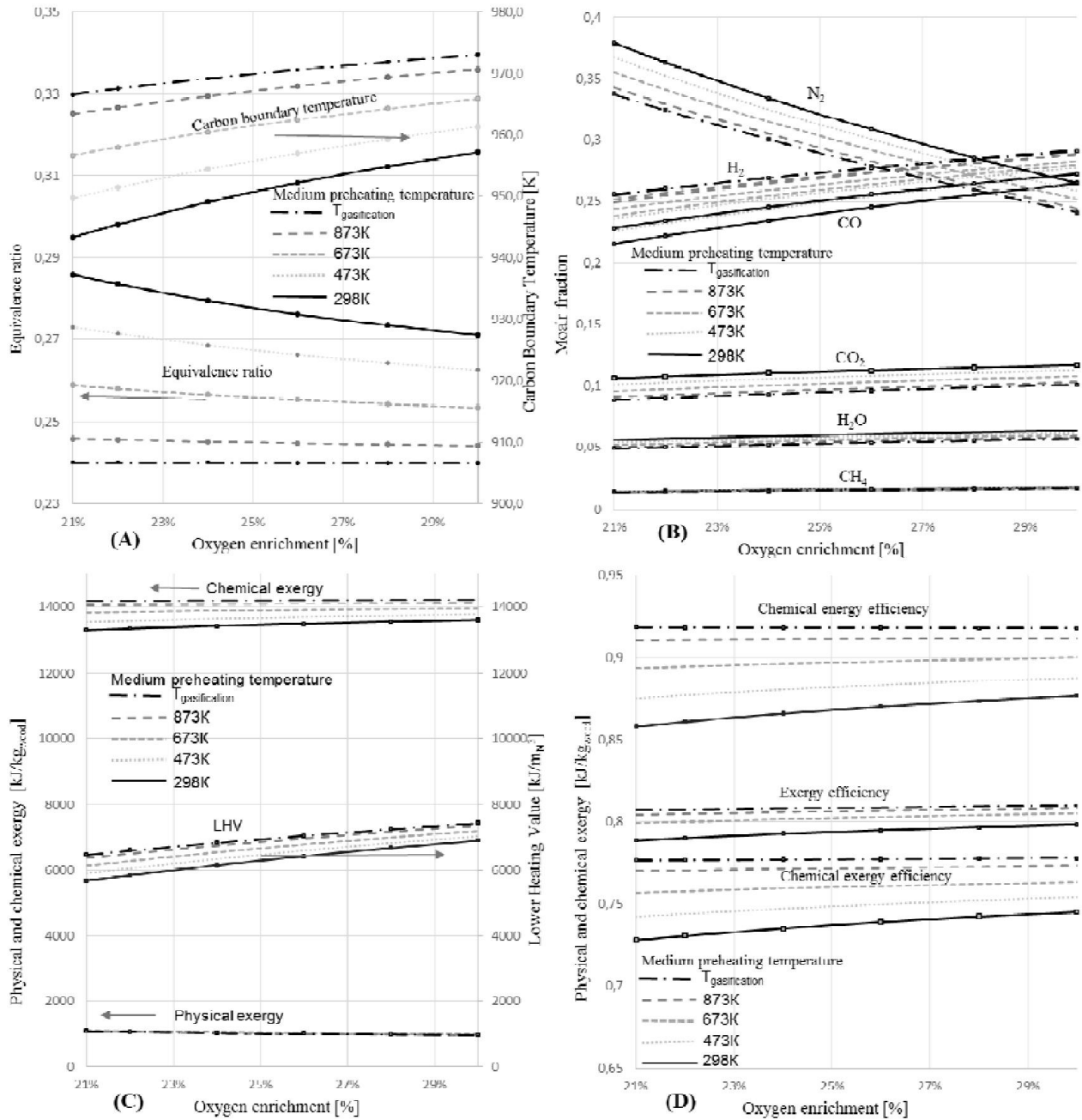


Figure 5. (A) Equivalence ratio and the temperature at the CBP for the gasification of treated wood depending on the level of enrichment and preheating temperature. (B) The composition of the product gas depending on the level of enrichment and preheating temperature for the gasification of treated wood at the CBP. (C) Chemical and physical exergies and lower heating value of the product gas depending on the level of enrichment and preheating temperature for the gasification of treated wood at the CBP. (D) Energy and exergy efficiencies for the gasification of treated wood at the carbon boundary point depending on the level of enrichment and preheating temperature.

Figure 6 shows the change of exergy efficiency for the gasification of treated wood in dependence of the enrichment level for 4 cases: (1) for the case (a) in Fig. 1, (2) for the case (c) in Fig.1 but without the medium preheating (without the heat exchanger), (3) case (b) in Fig. 1 with medium preheated at 800°C, and (4) for case (c) in Fig.1 with the medium preheated at 800°C. The differences between the cases (1) and (2), and (3) and (4) are due to the irreversibilities encountered during the production of oxygen enriched air in the membrane system. The larger the enrichment level the large the irreversibilities. Figure 6 shows that at present level of the membrane technology, the use of oxygen enriched air at ambient temperature increases the exergy efficiency for the gasification of treated wood at 900°C. Paradoxically, the exergy efficiency decreases with the increase of the level of enrichment for gasification of treated wood at 900°C when the medium is preheated at 800°C. This happens due to the irreversibilities that occur during the heat exchange



and the production of oxygen enriched air (see Fig. 1 (c)). It means that for the taken level of the membrane separation technology, the preheating temperature must be chosen to make the temperature difference in the heat exchanger as small as possible

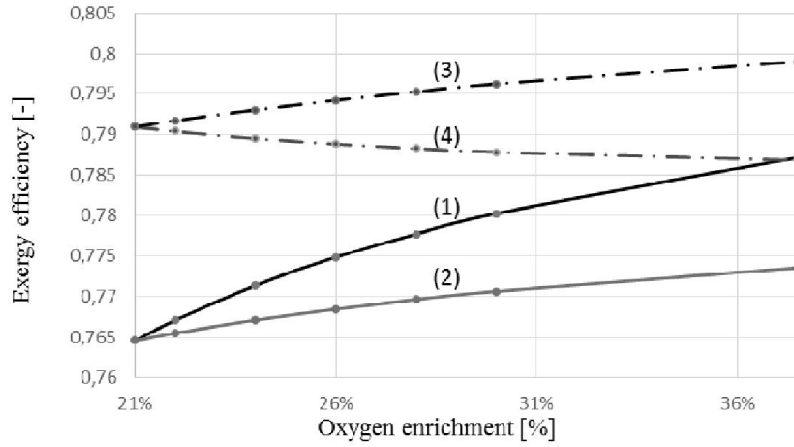


Figure 6. Exergy efficiency for the gasification of treated wood in dependence of the enrichment level for 4 cases: (1) for the case (a) in Fig. 1, (2) for the case (c) in Fig.1 but without medium preheating (without the heat exchanger), (3) case (b) in Fig. 1 with medium preheated at 800 °C, and (4) for case (c) in Fig.1 with medium preheated at 800 °C.

## 5. Conclusions

Finalizing the consideration above, it could be concluded that:

- the increase of the oxygen level in enriched air increases the temperature at the CBP and decreases the amount of air (oxygen) required to complete the gasification of the treated wood. The air enrichment is a measure that increases the temperature at the CBP and influences this temperature to approach the temperature in real gasifiers, which are higher to solve the problems of kinetic limitations, tar cracking, *etc.*
- the increase in the air enrichment increases CO, CH<sub>4</sub>, H<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O, and decreases substantially N<sub>2</sub> in the product gas.
- in comparison with the exergy efficiency, the efficiencies based on chemical energy and exergy increase faster with the increase of oxygen level in enriched air.
- the preheating of enriched air by the heat exchange with the product gas is more beneficial for the gasification with lower levels of enrichment.
- the gain of air enrichment is larger at higher gasification temperatures.
- according to the model performed in this paper the inclusion of a membrane separation system for oxygen enrichment of air increases the efficiency of the gasification process.
- if enriched air is preheated for the gasification process by heat exchange with the product gas care should be given to obtain the smallest possible temperature difference in the heat exchanger.

## Nomenclature

### Latin symbols

A	–	Membrane area, in [m <sup>2</sup> ].
A	–	Ash in treated wood, in [wt%].
C	–	Carbon.
C <sub>S</sub>	–	Calorific value of sulfur, in [kJ/kg].
e	–	Specific molar exergy, in [kJ/kg <sub>biomass</sub> ].
e <sub>ch,biomass</sub>	–	Chemical exergy of biomass, in [kJ/kg].
ER	–	Equivalence ratio, in [-].

H	–	Hydrogen.
L	–	Membrane thickness, in [μm].
LHV <sub>biomass</sub>	–	Lower heating value of treated wood, in [kJ/kg].
LHV <sub>gas</sub>	–	Lower heating value of product gas, in [kJ/kmol].
LHV <sub>org</sub>	–	Lower heating value of the organic fraction of biomass, in [kJ/kg].
N	–	Nitrogen.
n <sub>air</sub>	–	Molar amount of air, in

		[kmol/kg <sub>biomass</sub> ].
$n_C$	–	Molar amount of carbon in biomass, in [kmol/kg <sub>biomass</sub> ].
$n_{gas}$	–	Molar amount of product gas, in [kmol/kg <sub>biomass</sub> ].
$n_H$	–	Molar amount of hydrogen in biomass, in [kmol/kg <sub>biomass</sub> ].
$n_O$	–	Molar amount of oxygen in biomass, in [kmol/kg <sub>biomass</sub> ].
O	–	Oxygen.
$p_{O_2}$	–	Partial pressure of oxygen, in [Pa].
$p_{N_2}$	–	Partial pressure of nitrogen, in [Pa].
$x$	–	Molar fraction of CO, CO <sub>2</sub> , CH <sub>4</sub> , H <sub>2</sub> , N <sub>2</sub> or H <sub>2</sub> O in the product gas, in [mol% or vol%].
$x_{O_{2air}}$	–	Molar fraction of oxygen in air, in [mol%].
$x_{N_{2air}}$	–	Molar fraction of nitrogen in air, in [mol%].
$z_A$	–	Weight fraction of ash in biomass, in [wt%].
$z_{org}$	–	Weight fraction of organic fraction in the biomass, in [wt%].
$z_w$	–	Weight fraction of moisture in the biomass, in [wt%].
$z_S$	–	Weight fraction of sulfur in the biomass, in [wt%].

## Greek symbols

$\alpha$	–	Membrane selectivity, in [-].
$\beta$	–	Ratio of the chemical exergy and the LHV of dry organic substances, in [-].
$\Delta p_{p,i}$	–	The difference of partial pressure of component i on the two sides of membrane, in [Pa].
$\eta$	–	Chemical efficiency, in [-].
$\psi$	–	Exergy efficiency, in [-].

## Abbreviations

CBP	–	Carbon boundary point.
CHP	–	Combined heat and power.
LHV	–	Lower heating value.
SRS	–	Standard reference state (0.1 MPa, 298 K).

## Subscripts

<i>air</i>	–	Air used for gasification
<i>ash</i>	–	Ash in the treated wood
<i>biomass</i>	–	Treated wood
<i>ch</i>	–	Chemical
<i>enriched air</i>	–	Air with more than 21 vol% of
<i>gas</i>	–	Product gas
<i>i</i>	–	O <sub>2</sub> or N <sub>2</sub>
<i>org</i>	–	Organic matter
<i>ph</i>	–	Physical
<i>water</i>	–	Moisture in the treated wood

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