

BIOMASS GASIFICATION WITH PREHEATED AIR: ENERGY AND EXERGY ANALYSIS

by

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Due to the irreversibilities that occur during biomass gasification, gasifiers are usually the least efficient units in the systems for production of heat, electricity, or other biofuels. Internal thermal energy exchange is responsible for a part of these irreversibilities and can be reduced by the use of preheated air as a gasifying medium. The focus of the paper is biomass gasification in the whole range of gasification temperatures by the use of air preheated with product gas sensible heat. The energetic and exergetic analyses are carried with a typical ash-free biomass feed represented by $CH_{1.4}O_{0.59}N_{0.0017}$ at 1 and 10 bar pressure. The tool for the analyses is already validated model extended with a heat exchanger model. For every 200 K of air preheating, the average decrease of the amount of air required for complete biomass gasification is 1.3% of the amount required for its stoichiometric combustion. The air preheated to the gasification temperature on the average increases the lower heating value of the product gas by 13.6%, as well as energetic and exergetic efficiencies of the process. The optimal air preheating temperature is the one that causes gasification to take place at the point where all carbon is consumed. It exists only if the amount of preheated air is less than the amount of air at ambient temperature required for complete gasification at a given pressure. Exergy losses in the heat exchanger, where the product gas preheats air could be reduced by two-stage preheating.

Key words: biomass, gasification, air preheating, exergy efficiency

Introduction

Designing a combine heat and power (CHP) plant¹, which should consist of a downdraft biomass gasifier, a gas-cleaning system, and a gas engine due to the limited potential for heat energy consumption plenty of excess heat emerged. The use of this heat to improve gasification efficiencies by preheating the gasifying air was the motive for this paper. The bases are works of Prins *et al.* [1] and Mathieu *et al.* [2].

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Prins *et al.* [1] analyzed exergy losses that occur during the gasification of carbon by dividing the process into several sub-processes: instantaneous chemical reaction, heat transfer from reaction products to reactants (internal thermal energy exchange) and product mixing. They concluded that internal thermal energy exchange is responsible for an exergy loss of 5-7% of expended exergy, and recommended the replacement of air with oxygen, or alternatively, preheating of air by heat exchanged with product gas.

Examining gasification of wood, given by the general formula $\text{CH}_{1.43}\text{O}_{0.66}$, with a constant amount of air preheated at different temperatures, Mathieu *et al.* [2] showed that preheating of air up to 300 °C increased chemical efficiency of the process. By analyzing the wood gasification with a constant amount of air equal to 1/4 of the stoichiometric amount in theoretical combustion, the authors concluded that a critical air temperature exists above which the preheating is no longer efficient. Why the authors obtained the optimal air preheating temperature and what happens at different biomass gasification pressures and temperatures is the intention of this analysis to answer. This is important because different types of gasifiers operate at different temperatures, *i. e.* require different amounts of air for complete gasification.

Prins *et al.* [1] applied exergy analysis, which is frequently used to analyze energy conversion processes such as biomass gasification. In this process, chemical energy of a biofuel is converted into the chemical and thermal energy of the product gas. During each energy conversion process, the energy is conserved, but the quality of energy decreases due to the irreversible increase in entropy. This means that from the transformed form of energy less work can be obtained. Exergy is the thermodynamic property that considers irreversible increase in entropy, *i. e.* the second law of thermodynamics, and is defined as a measure of the actual potential of a system to perform work. An energy conversion process, which is suitable to be analyzed by the use of exergy, can be improved by implementing technical measures that reduce the irreversible increase in entropy. This is the reason why the exergy analysis was frequently used in analyzing energy conversion processes [3-6].

The use of sensible heat of product gas to preheat gasifying air has already been applied solution. In a CHP plant designed by Kramreiter *et al.* [7], the authors used the sensible heat of the product gas to preheat the air, whereas in the Viking gasification concept [8], the sensible heat of the product gas is used to preheat the air and to heat a screw pyrolyser.

The idea of using highly preheated agents in gasification emerged at the beginning of the 21st century as highly efficient regenerative preheater were developed [9]. In the thesis [9] from KTH University a detailed literature review of the use of highly preheated gasifying agents together with technological and theoretical achievements were given. A group of researchers from the same university examined and in detail documented the influence of air preheating on the gasification of various biomass wastes in an updraft fixed bed gasifier [10]. In the report [10], the authors stated several benefits of the use of highly preheated air: better conversion of biomass into the product gas, larger heating values, and smaller amount of tar in the product gas. Ponzio [9] performed a particle study, *i. e.* examined mass conversion, heating, ignition, devolatilization front rate, bed temperatures, and gas quality depending on the high agent temperatures. The author [9, 11] also thermodynamically investigated a concept for autothermal gasification system using highly preheated air as gasifying agent. Although the analysis and experiments were carried out with an updraft gasifier, which is, as it is going to be seen, not suitable for modelling with the model used in this work, many interesting findings regarding gasifier and system study were given. The most interesting were: the use of highly preheated air reduced temperature gradients in the bed of the gasifier, *i. e.* the gasification in the examined gasifier was thermally homogeneous, and air-to-fuel ratios were reduced which further in-

creased the value of the produced gas. Ponzio [9] also argued that two regimes of operation in function of the agent temperature exist: a regime corresponding to “high” agent temperatures and one corresponding to “low” agent temperatures – with transition zone in between. The regimes are separated by the minimum agent temperature to guarantee spontaneous ignition regardless of the particle temperature. This transition zone lies between 623 and 803 K and delimits the zone of “high” agent temperatures, where the conversion process is very fast and controlled by the convective heat transfer from the preheated agent, and the zone of “low” agent temperatures, where the conversion is considerably slower and controlled by the heat released by exothermic reactions. Marginal beneficial effects, although reported for a downdraft gasifier by Jayah *et al.* [12], that air preheated to 450 and 600 K had on gasification of rubber wood, confirms Ponzio [9] findings. The present analysis uses air preheated to temperatures in all three identified regions and in comparison with [9] covers gasification temperatures that are met in other types of gasifiers: fluidized bed, downdraft, and entrained flow.

The development of regenerative honeycombed ceramic preheater enabled a part of the product gas to be burned for high temperature preheating of gasifying medium [9]. Sugiyama *et al.* [13] used this kind of heat exchanger to preheat air to 1000 °C when examined gasification of coal in a pebble bed slagging gasifier. Due to preheating, they reported higher heating values of the product gas.

For presenting the aim of the paper, it is important to define carbon-boundary point (CBP). The CBP is obtained when exactly enough gasifying medium is added to avoid carbon formation and achieve complete gasification. Ptasinski *et al.* [14] reported that the CBP is the optimum point for gasification with respect to energy-based efficiencies as proved by Desrosiers [15], and Double *et al.* [16], and with the respect to exergy-based efficiency as proved by Prins *et al.* [17]. It is a characteristic of the gasification process and depends on the fuel that is gasified, the medium used, and the heat transport of energy during the process.

Based on the model presented and validated in [18], methodology presented in [1, 14, 18], and proceeding from the results given in the previously cited literature, the aim of the analysis is to answer the following questions:

- (1) What is the benefit of air preheating to the gasification of biomass at the CBP? Particularly, how the preheating temperature influence: the temperature at the CBP, the required amount of air for complete gasification, the composition of product gas, energy and exergy efficiencies of the process at 1 and 10 bar pressure?
- (2) What is the benefit of air preheating to the gasification of biomass that takes place at the temperatures higher that at the CBP, *i. e.* in the range CBP-1373 K?

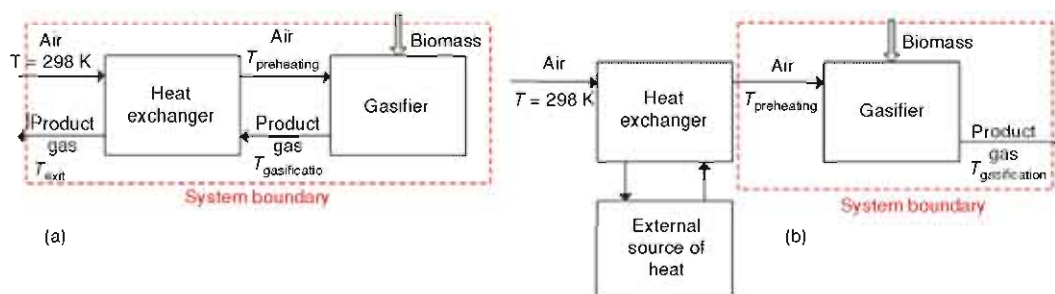


Figure 1. Schemes of examined systems for biomass gasification with preheated air: (a) air preheated by the product gas sensible heat, (b) air preheated by the use of external heat source

- (3) Does the optimal air preheating temperature exist, as it was concluded by Mathieu *et al.* [2], and does it exist for the system shown in fig. 1?

The biofuel used in the analysis is a typical dry, ash-free biomass represented by the general formula $\text{CH}_{1.4}\text{O}_{0.59}\text{N}_{0.0017}$, that was also used in [15, 17, 18]. This use gives a generality to the analysis since the organic masses of different biofuels differ slightly. The effect of pressure is studied at 0.1 MPa and at an elevated pressure of 1 MPa. The moisture content in the biomass is varied in the range from 0 wt.% to 30 wt.% for the gasification at the CBP, whereas at higher temperatures it is kept constant at 15 wt.% due to concise interpretation of results. This moisture content is in the recommended range from 10 to 15 wt.% for biomass gasification [19]. The gasifying medium is the combustion air at 25 °C consisting of 21 mol% oxygen and 79 mol% nitrogen.

For the purpose of the analysis the following results depending on air preheating and gasification temperature are given: required amount of air for complete gasification, compositions, chemical energies, physical and chemical exergies of the product gas, and energy and exergy based efficiencies. Together with obtained results their limitations and applicability are discussed.

Process modelling

Two-stage equilibrium and quasi equilibrium models were presented and validated in [18]. The two-stage equilibrium model [18] expanded with a submodel of countercurrent heat exchanger is used for fulfilling the aim of the paper. For the system shown in fig. 1(a), the heat exchanger is modelled with two simple models where:

- (1) air preheating temperature is taken as a parameter; this submodel is used for preheating temperatures lower than the gasification temperature, and
- (2) the preheating and gasification temperatures are not known in advance; this submodel is used to determine the maximal theoretical benefit of air preheating by heat exchange with the product gas for gasification at the CBP.

The pressure drop in the heat exchanger is neglected in both cases. In the first case, in which the preheating temperature is a parameter, the energy balance of the heat exchanger for gasification of 1 kg of biomass is:

$$n_{\text{air}}c_{p\text{air}}(T_p - T_0) = n_{\text{gas}}c_{p\text{gas}}(T_{\text{gas}} - T_{\text{gas, exit}}) \quad (1)$$

where T_p is a parameter presenting the air preheating temperature, $T_{\text{gas, exit}}$ – the unknown temperature of the product gas at the outlet of the heat exchanger, n_{air} – the amount of air in kmol required for the gasification of 1 kg of biomass, during which n_{gas} [kmol] of the product gas was obtained. $T_0 = 298 \text{ K}$ is the ambient temperature, T_{gas} – the unknown gasification temperature, $c_{p\text{air}} - c_{p\text{gas}}$ [$\text{kJ kmol}^{-1}\text{K}^{-1}$] are the average molar specific heat capacities at constant pressure between the inlet t_1 and outlet t_2 temperatures of air and product gas, respectively. These are calculated for the temperature range from t_1 to t_2 in °C by:

$$c_{p12} = \frac{c_{p2}t_2 - c_{p1}t_1}{t_2 - t_1} \quad (2)$$

Molar specific heat capacities at constant pressure of all involved gases are taken from [20].

In the second case, where both air preheating and gasification temperatures are unknowns, the simplified equations of the ε -NTU method for a counter flow heat exchanger are used [21]. When $n_{\text{gas}}c_{p\text{gas}} < n_{\text{air}}c_{p\text{air}}$ than:

$$T_{\text{gas,exit}} = T_{\text{gas}} - \frac{\varepsilon n_{\text{gas}} c_{p\text{gas}} (T_{\text{gas}} - T_0)}{n_{\text{gas}} c_{p\text{gas}}} \quad (3)$$

in the opposite

$$T_{\text{gas,exit}} = T_{\text{gas}} - \frac{\varepsilon n_{\text{air}} c_{p\text{air}} (T_{\text{gas}} - T_0)}{n_{\text{gas}} c_{p\text{gas}}} \quad (4)$$

Since the intention in the second case was to obtain maximal possible positive effect the heat exchanger is assumed ideal, *i. e.* $\varepsilon = 1$.

Since there are a few reports in the literature on gasification of biomass with preheated air, for validation of the expended model the results of Sugiyama *et al.* [13] are used. They examined the gasification of Uinta premium coal, whose proximate and ultimate analysis are given in [13], with a constant amount of air preheated at 1000 °C, while changing the amount of steam in the mixture that was used as a gasifying medium. The authors reported the amount of used steam, as the molar ratio $\text{H}_2\text{O}/\text{C}$.

This kind of validation can be justified by the following facts: (1) for the model it is not relevant what is the fuel used, (2) coal is nothing but old biomass subjected to chemical transformation in the Earth's crust, and (3) there are a few published examination of biomass gasification with air preheated to a high temperature.

Table 1. The comparison of data predicted by the model with the experimental and modelling results [13], for the gasification of Uinta premium coal with the mixture of air and steam preheated at 1000 °C

		CO [vol.%]	CO ₂ [vol.%]	CH ₄ [vol.%]	H ₂ [vol.%]	N ₂ [vol.%]	RMS error
Experiment 4 (H ₂ /C = 0.31 T = 1358 °C)	Measured values	22.3	7.4	0.3	18	52	–
	Model [13]	23.6	6.3	0.0	16.6	53.5	1.20
	This model	23.2	5.5	0.0	18.6	52.8	1.05
Experiment 5 (H ₂ /C = 0.29 T = 1338 °C)	Measured values	22.6	6.5	0.1	14.2	56.6	–
	Model [13]	21.9	7.0	0.0	13.9	57.2	0.49
	This model	21.8	6.4	0.0	14.9	56.9	0.48
Experiment 6 (H ₂ /C = 0.15 T = 1366 °C)	Measured values	23.9	5.8	0.1	14.7	55.6	–
	Model [13]	24.5	5.2	0.0	13.4	56.9	0.91
	This model	24.7	4.4	0.0	14.2	56.6	0.88
Experiment 7 (H ₂ /C = 0.31 T = 1329 °C)	Measured values	19.2	9.0	0.3	16.2	55.3	–
	Model [13]	19.5	8.8	0.0	15.5	56.2	0.55
	This model	18.0	8.9	0.0	15.5	57.5	1.16

The error in this comparison is estimated by the root-mean-square (RMS) defined as:

$$RMS_j = \sqrt{\frac{\sum_k (OR_k - Mod_k)^2}{D}} \quad (5)$$

where OR is the value taken from other researchers, Mod – the value predicted by the model, and D – the number of data.

The model was written in Modelica language. It is the object-oriented language for physical systems modeling. A tool that supports Modelica language was used to solve the non-linear system of equations, which, if such is the case, provides an indication when the initial values of the variables are not proper.

Table 1 shows a good agreement of the results of the model with the experimental and modelling results reported in [13]. The deviations from the experimental data are due to: the simplifying assumptions used in defining the model in [18], and the absence of heat loss reporting in the experimental data.

The applied model is based on the assumptions that: (1) perfect mixing and uniform temperature distribution are achieved in the gasifier, (2) reaction rates are fast enough and residence time is sufficiently long to reach equilibrium state, (3) the model does not give information about reaction pathways and formation of intermediates, and (4) tar is not modelled. The applied model and this kind of models are well verified for downdraft [18, 22] but cannot be used for predicting behaviour of updraft gasifiers. In addition, due to high operating temperatures entrained-flow gasifiers have good approach to equilibrium. For fluidized bed reactors only the first of the above assumptions is valid. Nevertheless, the already mentioned experimental results [9, 10] advocate in favour of the model predictions because the use of highly preheated air led to the faster conversion process, efficient heat transfer and reduced tar content. This means that the higher the preheating temperature, the more reliable are the predicted results. As a general analysis that does not include a specific type of gasifier is conducted in the paper, the results shown in tab. 1 testify on reliability of the model when predicting the gasification with preheated air.

Energy and exergy efficiencies

The used methodology has already been applied [14, 17, 18], and only its main points are presented here. The chemical efficiency represents the chemical energy that is conserved in the produced gas and is calculated by:

$$\eta = \frac{n_{\text{gas}} LHV_{\text{gas}}}{LHV_{\text{biomass}}} \quad (6)$$

This and all other efficiencies are calculated per 1 kg of biomass.

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

$$\psi_{\text{ch}} = \frac{n_{\text{gas}} e_{\text{ch, gas}}}{e_{\text{ch, biomass}}} \quad (7)$$

The exergy efficiency is the ratio between exergy flows out and into a system [23]. In this efficiency, the sensible heat of the product gas, which is ignored in eqs. (6) and (7), is taken into account as the physical exergy of the product gas. At higher gasification temperatures, the portion of the physical exergy is considerable in the total exergy of the product gas. For an air-blown adiabatic gasifier the exergy efficiency is:

$$\psi = \frac{n_{\text{gas}} (e_{\text{ch, gas}} + e_{\text{ph, gas}})}{e_{\text{ch, biomass}} + n_{\text{air}} e_{\text{air}}} \quad (8)$$

The statistical correlation of Szargut *et al.* [24], taken from [14], is used to calculate the exergy of solid biomass:

$$e_{\text{ch,biomass}} = z_{\text{org}}(\beta \text{LHV}_{\text{org}}) + z_{\text{S}}(e_{\text{ch,S}} - C_{\text{S}}) + z_{\text{W}}e_{\text{ch,water}} + z_{\text{A}}e_{\text{ch,ash}} \quad (9)$$

The factor β is the ratio of the chemical exergy to the LHV of the organic fraction of biomass [24], taken from [14]:

$$\beta = \frac{1.044 + 0.0160H/C - 0.3493O/C (1 + 0.0531H/C) + 0.0493N/C}{1 - 0.4124O/C} \quad (10)$$

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

Results

Gasification at the CBP

Figure 2 shows that the increase in air preheating temperature decreases the amount of air required for the complete gasification, and increases the temperature at the CBP, as it is shown in fig. 3.

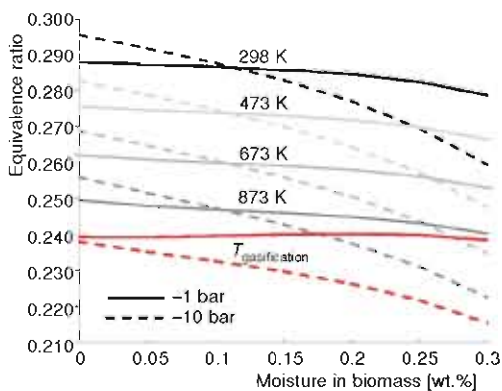


Figure 2. The amount of air required for complete gasification depending on the air preheating temperature and moisture in the biomass for the processes at 1 and 10 bar pressure

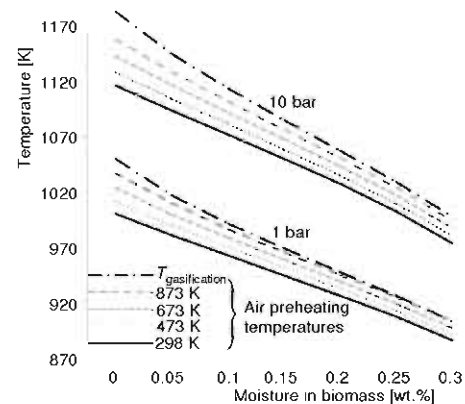


Figure 3. The temperature at CBP depending on the air preheating temperature and moisture content in the biomass for adiabatic gasification at 1 and 10 bar

The rise of air preheating temperature for 200 K, on both examined pressures, on the average decreases the amount of air required for complete gasification for 0.013 ER. Where ER is the equivalence ratio, which is the amount of air added relative to the amount of air required for stoichiometric combustion. The energy required for endothermic gasification reactions is released by coupled exothermic oxidation reactions with air (oxygen). When preheated air is used for gasification, a part of the energy required for the endothermic gasification reactions is obtained as its sensible heat. Because of this, the amount of air required for complete gasification decreases with the increase of air preheating temperature. On the other side, endothermic reac-

tions whose chemical equilibrium is at higher temperature dominate in the group of gasification reactions. This influences the rise of the temperature at the CBP, as it can be seen in fig. 3.

The rise of air temperature influences the composition of the product gas, as it can be seen in fig. 4. It increases the amounts of CO and H₂, and decreases the amounts of CO₂, H₂O, and N₂ in the product gas. This change in composition occurs due to the introduction of less air, and due to the rise of gasification temperature, which favors endothermic gasification reactions:



and



For air-blown autothermal gasification of biomass its moisture content represents ballast. The influences of moisture and gasification pressure on the product gas composition were explained in [18, 19].

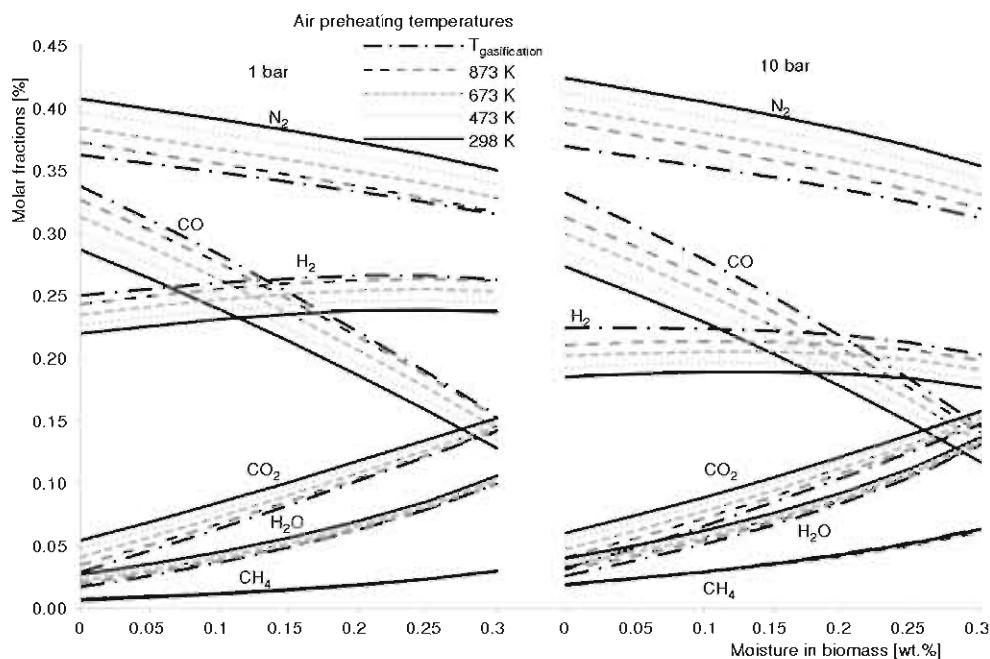


Figure 4. The composition of the product gas depending on the air preheating temperature and moisture content in the biomass for adiabatic gasification at 1 and 10 bar pressure

The use of preheated air increases the chemical energy and exergy contained in the product gas. Figure 5 shows these effects, together with the lower heating value (LHV) and physical exergy of the product gas. The preheating of air from ambient to gasification temperature on the average increases the LHV of the product gas by 13.6%. Figure 5 shows how much "the investment" of the physical exergy of the product gas is paid off through an increase in its chemical exergy. Exergetically speaking, the air preheating process by the use of physical exergy of product gas is nothing but the investment of exergetically less valuable physical exergy into more valuable chemical exergy of the product gas.

Figure 5. The impact of air preheating to the physical and chemical energies, and exergies of the product gas depending on moisture in the biomass for process at 1 bar

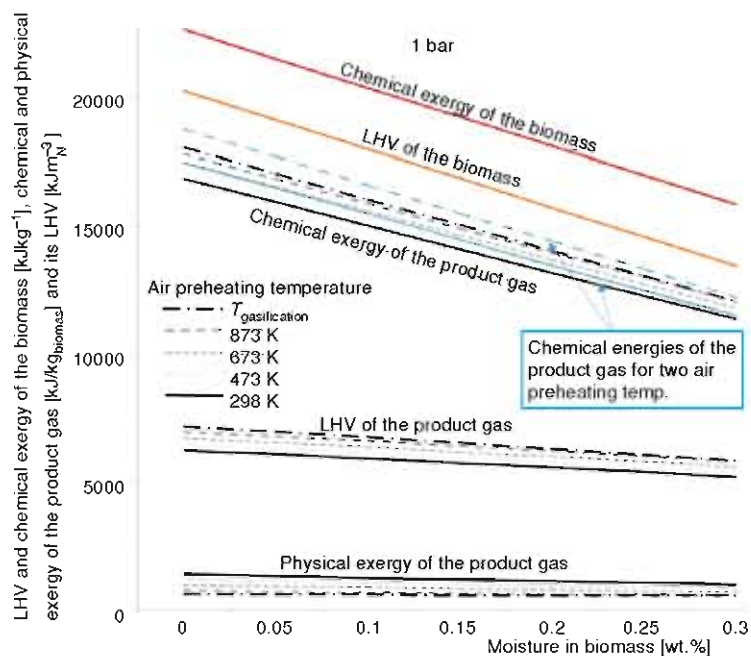


Figure 6 shows the beneficial effect of air preheating to the energetic and exergetic efficiencies. The higher the preheating temperature the larger the influence to the energetic and exergetic efficiencies based on chemical energy and exergy. Table 3 shows the average positive

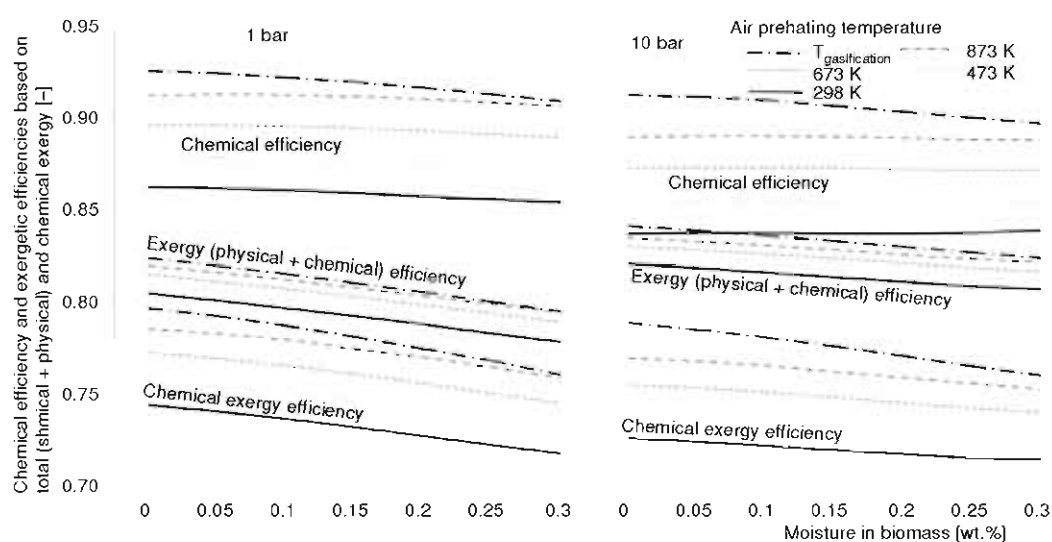


Figure 6. The efficiencies based on chemical energy, chemical, and total (chemical + physical) exergy for the gasification with air preheated by the product gas sensible heat depending on preheating temperature and moisture in the biomass for the processes at 1 and 10 bar pressure

effect of air preheating from ambient (25 °C) to the gasification temperature on the energetic and exergetic efficiencies. It should be stressed once again, that this is not gasification at constant temperature, but the process at the optimal temperature that changes according to the diagram shown in fig. 3.

Table 2. The average increase in energetic and exergetic efficiencies for the gasification with air preheated from ambient to the gasification temperature, for processes at 1 and 10 bar pressure and moisture in the biomass in the range 0-30 wt. %

Gasification pressure	1 bar	10 bar
The average increase in η	6%	6.8%
The average increase in ψ_{ch}	4.9%	5.6%
The average increase in ψ	1.8%	1.9%

Table 2 shows that the influence of air preheating is greater for the efficiency based on chemical energy than for the efficiency based on chemical exergy. The reason for the previous influence lies in two facts: the LHV of biomass is smaller than its chemical exergy and the chemical exergy of product gas is smaller than its chemical energy. Ptasiński *et al.* [14] explained both facts. They explained larger chemical exergies than LHV for biomass by the fact that polymers such as cellulose

and hemi-cellulose are highly ordered structures, and work can be delivered if these are decomposed. On the other hand, for small molecules CO and H₂ whose contents the use of preheated air increase in the product gas (see fig. 4), the chemical exergy is less than their LHV, *e. g.* 97.6% for H₂ and 97.2% for CO.

The influence of air preheating to the efficiency based on chemical exergy is larger than to the efficiency based on total exergy. This occurs because the latter takes into account the physical exergy of the product gas, which is considerable at higher gasification temperatures, and which is used to preheat the air.

The preheating of gasifying air with the product gas sensible heat is more beneficial for the process at 10 bar pressure than for the process at 1 bar. This occurs because the process at higher pressure has higher temperature at the CBP (see fig. 3) that causes larger entropy loss due to the internal thermal energy exchange. The air preheating reduces this loss.

The fact that the exergy loss due to internal thermal energy exchange in air-blown gasification must be equal to the exergy gain due to air preheating to the gasification temperature must be stressed to compare the obtained results with the results of Prins *et al.* [1]. They obtained the loss to be 5-7% of expanded exergy. In this analysis exergy gains of 4.9% and 5.6% for gasification at 1 and 10 bar, respectively are obtained. The difference between these two data is due to the difference between analyzed fuels: here is the general biomass, and in [1] pure carbon that has higher temperature at the CBP.

Gasification with preheated air above the CBP

This analysis covers the usual temperature range for gasification of biomass 1073-1373 K, which is usually gasified above the temperature at the CBP [22]. For biomass gasification there is a feedstock-specific "no-go" temperature range between the softening and slagging temperatures of the ash [25]. Downdraft and fluid-bed biomass gasifiers operate below softening temperature of the ash, whereas entrained-flow reactors operate above the ash slagging temperature. Due to the aggressive quality of molten slag and problems with size reduction of fibrous biomass, successful examples of biomass gasification in entrained-flow reactors, such as *Choren* process [26] are rare.

Figure 7. The amount of air required for complete gasification depending on the air preheating temperature and the gasification temperature for the general biomass with 15 wt.% moisture

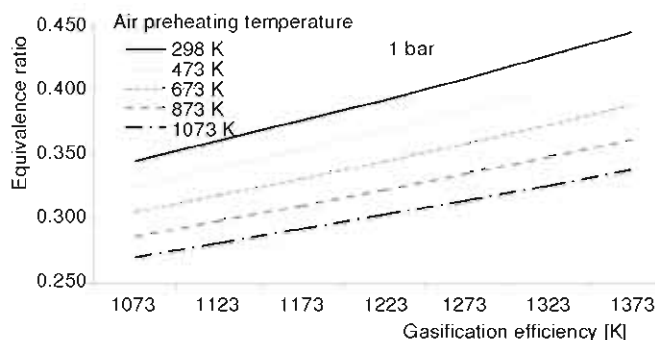
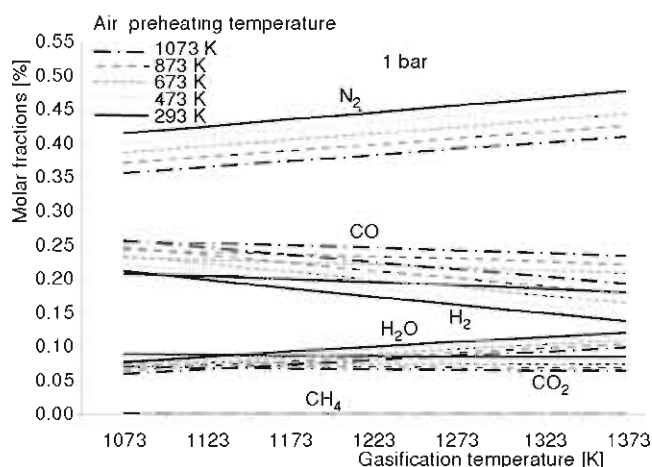


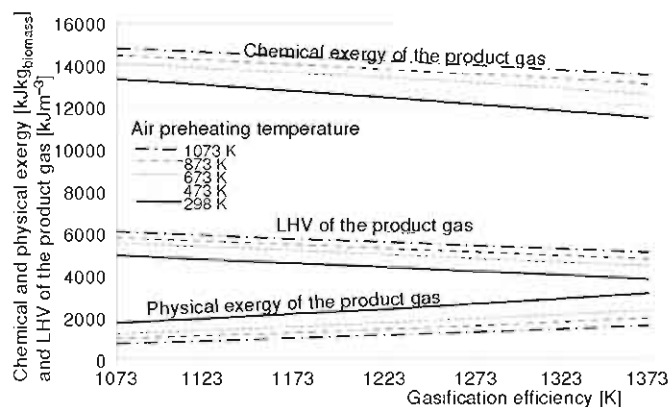
Figure 8. The composition of the product gas depending on the gasification and the air preheating temperature for the typical biomass with 15 wt.% moisture



In the examined temperature range the air preheating has the same effect as for the gasification at the CBP: decreases the amount of air required for complete gasification (see fig. 7), increases the contents of CO and H₂ and decreases N₂, CO₂, and H₂O in the product gas (see fig. 8)

Figure 9 shows the physical and chemical exergies of the product gas and its LHV depending on the gasification and air preheating temperatures. Physical exergies of the product

Figure 9. Chemical and physical exergies and LHV of the product gas depending on the gasification and the air preheating temperature for the typical biomass with 15 wt.% moisture



gas are given for the system shown in fig 1. (a), *i. e.* at the outlet of the heat exchanger. Figure 10 shows that the preheating is beneficial to all examined efficiencies. Figures 9 and 10 show that all lines tend to distant each other at higher gasification temperatures. This means that the effect of air preheating is greater at higher gasification temperatures because they require larger amounts of air for complete gasification.

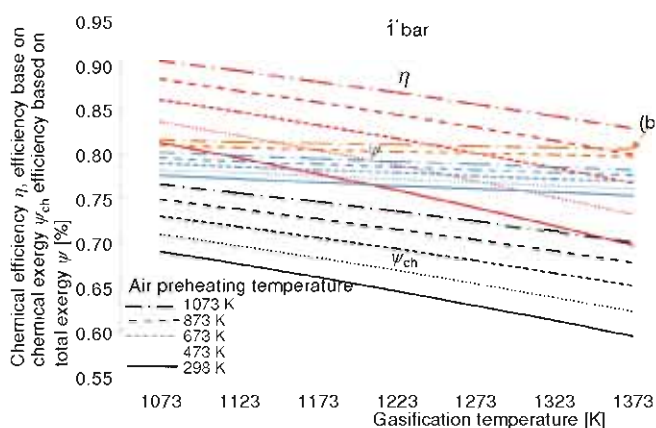


Figure 10. Chemical and efficiencies based on the chemical and physical exergy depending on the gasification and air preheating temperature for the typical biomass with 15 wt.% moisture. The efficiencies based on total exergy are given for the system shown in fig. 1(a). (b) are the efficiencies based on total exergy for the system shown in fig. 1(b) for air preheating temperatures of 873 and 1073 K

The effect of air preheating is larger for the chemical efficiency than for the efficiency based on chemical exergy due to the already mentioned, larger heating values of small molecules CO and H₂ than their chemical exergies.

A real benefit of the preheating process can be seen in fig. 10. It *e. g.* shows that the gasification process at 1373 K with air preheated at 873 K has larger energetic and exergetic efficiencies than the process at 1073 K with ambient air. By preheating air from 298 K to 1073 K, for biomass gasification at 1173 K, which is a frequently used temperature in downdraft gasifiers, the exergy efficiency is improved by 2.7%. The obtained result is realistically achievable because the preheated temperature of 1073 K belongs to "high" agent temperatures, which according to Ponzio [9] improves the conversion kinetics, reduces tar content and significantly reduces the temperature gradients in the bed. The use of preheated air drives the process towards the equilibrium conditions for which the applied model gives the most accurate results.

The preheating process has several characteristic trends that can be noticed in fig. 10: (1) a larger influence of the preheating to the chemical efficiency than to the chemical exergy efficiency, (2) the preheating has the lowest effect on the efficiency based on total exergy, and (3) the effect of the preheating is larger for the process shown in fig. 1(b) than for the process shown in fig. 1(a).

The first trend occurs due to the already mentioned fact that gaseous products such as CO and H₂, whose formation air preheating favors, have lower chemical exergy than LHV.

The second trend occurs since the increase of gasification temperature increases the physical exergy of the product gas, which is spent to increase the chemical exergy of the product gas (see fig.9).

Comparing with the system shown in fig. 1(b), the system shown in fig. 1(a) has smaller exergy efficiency, because it takes into consideration the exergy loss that occur in the counter flow heat exchanger. This exergy loss occurs due to the temperature difference between the product gas and air. This explains the third trend.

The optimal air preheating temperature for biomass gasification

Examining gasification of wood, given by the general formula $\text{CH}_{1.43}\text{O}_{0.66}$, with constant amount of air preheated at different temperatures, Mathieu *et al.* [2] concluded that a critical air temperature exists above which the preheating is no longer efficient. In the cited paper the authors confirmed their claim with a diagram (fig. 5 in [2]) that gives the gasification efficiency and reaction temperature vs. the air temperature for the process with a constant amount of air $ER = 0.25$ at 1 bar.

Taking into consideration the conclusion of Mathieu *et al.* [2] the following assertion is made: there is not a unique optimal air preheating temperature, because the optimal is always gasification at the CBP. It depends on the thermodynamic state and composition of the fuel and gasifying medium. In other words, for the gasification of fuel at given pressure and temperature with a given amount of air there is the optimal air preheating temperature that influences gasification to take place at the CBP. This temperature exists if the amount of used air is less than the amount of air at ambient temperature that causes gasification to take place at the CBP. The optimal air preheating temperatures are shown in fig. 2. This conclusion is not in the opposition to the conclusion of Mathieu *et al.* [2], but it states that for a different amount of air for gasification there is a different optimal air preheating temperature.

In order to confirm the previous assertion the gasification of typical biomass with 15 wt.% moisture with constant amount of air $ER = 0.259$ at 1 bar is examined and the results are shown in tab. 3 and fig. 11. Figure 2 shows that the optimal air preheating temperature is 673 K that corresponds to the gasification at the CBP. The obtained results are very similar to the results presented in [2] because of the similarity of examined fuels.

Figure 11. Energetic and exergetic efficiencies and gasification temperature depending on the air preheating temperature for gasification with $ER = 0.259$ of the typical biomass with 15 wt.% moisture at 1 bar pressure

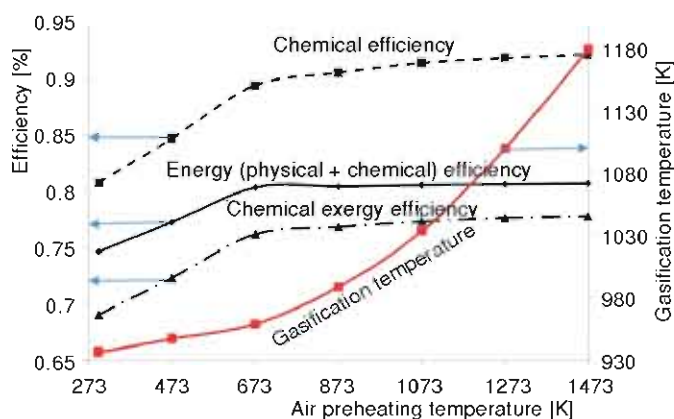


Table 3 shows that air preheating decreases the amount of unconverted carbon and increases the chemical exergy contained in the product gas. The rise of air preheating temperature increases the physical exergy of the product gas due to the rise of gasification temperature. The physical exergy of the product gas, shown in tab. 3, decreases because it is given at the outlet of the heat exchanger for the system shown in fig. 1(a). Figure 11 shows that the rise of air preheating temperature above the temperature that correspond to the CBP steeply increases the gasification temperature. It means that the air preheating above the temperature that corresponds to the temperature at the CBP increases rather physical than chemical exergy of the product gas.

Table 3. The characteristics of the gasification of typical biomass with 15 wt.% moisture, gasified with the constant amount of air ($ER = 0.259$) preheated at different temperatures. The amount of unconverted char is given in wt.%.

T_p	CO	CO ₂	CH ₄	H ₂	N ₂	H ₂ O	Uncon- -verted char	n_{gas}	Chemical exergy	Physical exergy
K	[mol%]						[%]	[mol]	[kJ per kg _{biomass}]	[kJ per kg _{biomass}]
298	0.199	0.109	0.017	0.243	0.368	0.064	7	0.106	13297	1088
473	0.216	0.100	0.016	0.247	0.363	0.058	3.8	0.107	13926	966
673	0.235	0.090	0.015	0.251	0.358	0.052	0	0.109	14673	817
873	0.247	0.081	0.007	0.260	0.353	0.052	0	0.110	14808	700
1073	0.257	0.072	0.003	0.264	0.350	0.054	0	0.111	14913	613
1273	0.265	0.065	0.001	0.262	0.348	0.059	0	0.112	14970	573
1473	0.272	0.059	0.000	0.257	0.348	0.065	0	0.112	14997	560

Conclusions

The preheating of gasifying air by heat exchanging with the product gas is beneficial for the energetic and exergetic efficiencies of the gasification process. The higher the preheating temperature the larger are the efficiencies. In comparison with the efficiency based on total exergy the impact of air preheating is larger to the efficiencies based on chemical energy and exergy.

The preheating at the CBP is more beneficial to the process at 10 bar pressure than for the process at 1 bar, because the temperature at the CBP for the former process is higher and contributes to a larger entropy loss due to the need to preheat reactants (biomass and air) from ambient to a higher gasification temperature.

The impact of air preheating is larger at higher gasification temperatures. Comparing with the gasification at the CBP, the gasification at higher temperatures has lower energetic and exergetic efficiencies. Nevertheless, it is possible to obtain larger efficiencies for biomass gasification in usual temperature range 1073-1173 K with preheated air than for the process at the CBP with ambient air.

Comparing with the system shown in fig. 1(a), the system shown in fig. 1(b) has larger exergetic efficiency based on the total exergy. This happens because the latter system does not include the entropy losses that occur in the heat exchanger. Considering this fact and taking into account that a gasifier is only a unit in complex systems for co-generation or fuel production it is advisable to preheat gasifying air in two stages. In the first stage, air should be preheated with a waste heat at a lower temperature, and in the second stage with the sensible heat of the product gas. This arrangement would decrease the exergy loss in the heat exchanger where ambient air is preheated by heat exchange with the product gas.

The optimal air preheating temperature is the one that causes gasification to take place at the CBP. It exists only if the amount of preheated air is less than the amount of air at ambient temperature required for complete gasification at a given pressure. There is also, the minimal amount of gasifying air for which the optimal air preheating temperature by heat exchange with

the product gas exists. This amount is determined by the highest possible air preheating temperature by heat exchange with the product gas, which depends on technical and economical parameters related to the design of the heat exchanger.

Nomenclature

C_s	– calorific value of sulphur, [kJkg^{-1}]
e	– specific molar exergy, [kJkmol^{-1}]
$e_{\text{ch,biomass}}$	– chemical exergy of biomass, [kJkg^{-1}]
LHV_{biomass}	– lower heating value of biomass, [kJkg^{-1}]
LHV_{org}	– lower heating value of the organic fraction of biomass, [kJkg^{-1}]
LHV_{gas}	– lower heating value of product gas, [kJkmol^{-1}]
n_{air}	– molar amount of air, [kmol]
n_{gas}	– molar amount of product gas, [kmol]
z_A	– weight fraction of ash, [wt.%]
z_{org}	– weight fraction of organic fraction in biomass, [wt.%]
z_S	– weight fraction of sulfur, [wt.%]
z_w	– weight fraction of moisture, [wt.%]

Greek symbols

β	– ratio of the chemical exergy and the LHV of dry organic substances, [–]
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η	– chemical efficiency, [%]
ψ	– exergy efficiency, [%]

Subscripts

ch	– chemical
exit	– at the exit of heat exchanger
gas	– product gas
org	– organic matter
p	– preheating
ph	– physical
1, 2	– conditions at the inlet and outlet of the heat exchanger, respectively

Acronyms

CBP	– carbon-boundary point
CHP	– combine heat and power plant
ER	– equivalence ratio
LHV	– lower heating value

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