Utilization of char from biomass gasification for onsite energy production – Introduction and modelling of a secondary reactor

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Highlights

- *Apparatus that utilizes char residue from gasification and emissions from ICE for syngas production*
- *Airtight vessel with an electric plate and fluidized bed design*
- *The vessel is surrounded by an external vessel, where the output (hot) gas flows through before it is cooled down by a heat-exchanger*
- *The flue gases from the ICE are preheated before entering the apparatus*
- *Heat is recovered from the produced syngas*

Abstract

Gasification of biomass as a technological option for energy conversion is a concept that is widely discussed and taken into consideration. Due to financial incentives, i.e. increased feed – in tariffs, several small scale gasification units have been developed in Europe. In principle, the two main products of gasification are syngas, which is a gaseous fuel and char, which is a solid fraction which results from pyrolysis of carbon based materials. Char may have carbon content between 50% and 80% and has significant calorific value. It is the case that small gasification units tend to produce a considerable amount of char that can be as high as 10 % of the initial mass of the feedstock. Several potential pathways for the utilization of char have been identified, like manufacturing of filters or application on

agricultural fields. Nonetheless, due to the scale restrictions of small scale units, organized strategies have not yet been developed. In addition, char contains heavy metals and PAHs in such concentrations that the utilization as material is not always possible. Thus, usually char is treated as a waste/ by-product that needs proper disposal. Last but not least, gasification units demand electricity for the operation of the auxiliary units.

This paper has the scope to investigate the possibility of onsite energy production of additional electricity by introducing a secondary reactor that would convert char to a gaseous fuel. The two streams entering the reactor would be the flue gases from the internal combustion engine and the char which is created as a by-product from the process of gasification. This secondary reactor may be applied in all types of small scale gasifiers, but the optimal condition is when it is applied on a downdraft gasifier. The conversion of the input streams to a gaseous fuel will propagate by means of char-gas reactions mainly the Boudouard reaction and the water-gas reaction. The produced gaseous fuel will be consisted of Hydrogen, Carbon Monoxide, Carbon Dioxide and Nitrogen. This fuel can be utilized for electricity production in a smaller internal combustion engine which can be located in the facility.

1. Introduction

Gasification of biomass as a technological option for energy conversion is a concept that is widely discussed and taken into consideration [1]. Due to financial incentives, i.e. increased feed – in tariffs, several small scale gasification units have been developed in Europe. In addition, new optimized technologies have provided consisted, automated and easy-to-use technological options which may operate reliably and ensure high quality of products [2]. Small-scale gasifiers are usually are in principle autothermal and fixed bed gasifiers, hence downdraft and updraft gasifiers [2]. Nonetheless, this manuscript has the scope to introduce a novel apparatus that is designed to work with downdraft gasifiers. Thus the focus will be on downdraft gasification.In principle, the two main products of gasification are producer gas, which is a gaseous fuel and char, which is a solid fraction which results from pyrolysis of carbon based materials. Producer gas is consisted by carbon dioxide, hydrogen, carbon monoxide, methane and nitrogen and may be utilized as an energy fuel or in the chemical industry for the production of goods [3]. On the other hand, char is the solid product of gasification and along with ash represents the solid fraction of gasification process. Finally gasification produces several by-products like tar and dust which represent a much smaller amount of the final products mix [4].

The operating principle of downdraft autothermal small scale gasification is shown on Figure 1. A part of the input feedstock is (partially) combusted in the oxidation zone in order to recover the necessary amount of energy for the propagation of the other process that take place in the zones drying, pyrolysis and gasification which are (primarily) endothermic [5]. Gasification reactions could be divided in several major groups like oxidation, methanation, the gas-shift reaction, steam reforming and char – gas reactions [5].

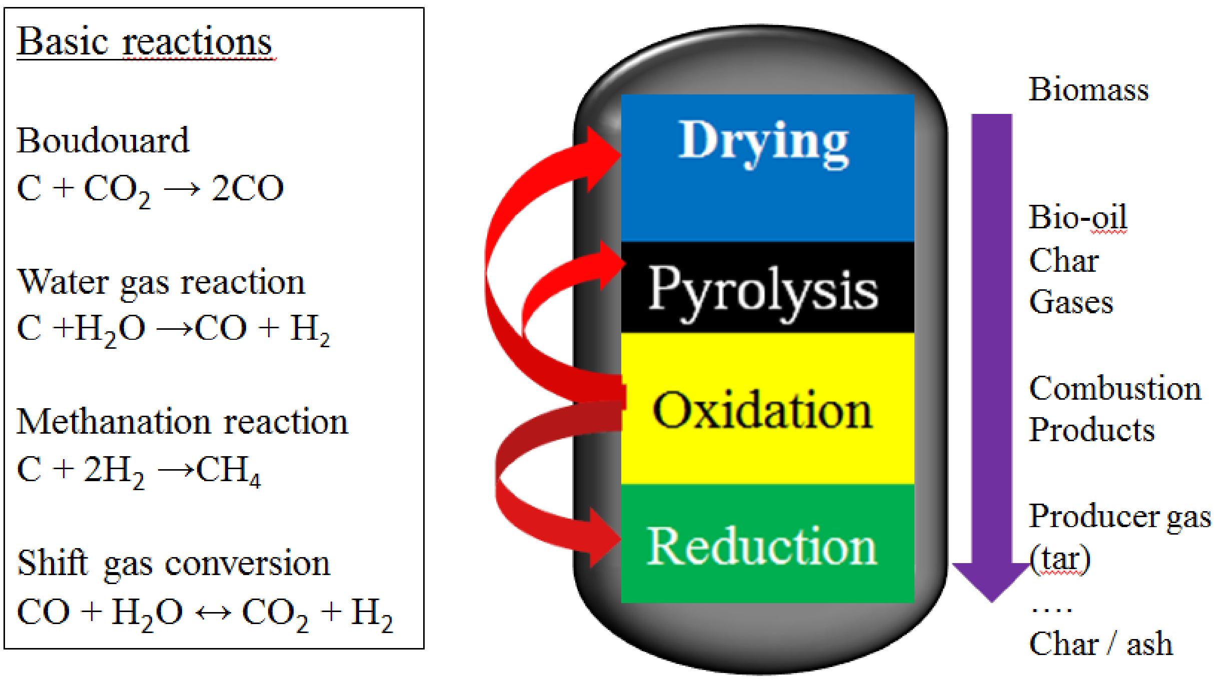

Figure 1. Downdraft gasification - basic reactions and zone separation

Char may have carbon content up to 80% and significant calorific value. Char in small gasification typical has a yield from 2 up to 10 % of the initial mass of the feedstock [6]. Several potential pathways for the utilization of char have been identified, like manufacturing of filters or application on agricultural fields. Nonetheless, due to the scale restrictions of small scale units, organized strategies have not yet been developed [3]. In addition, char contains heavy metals and PAHs in such concentrations that the utilization as material is not always possible. Nzihou and Stanmore showed that 'Effectively all heavy metals except mercury are retained in the ash' [7]. Thus, usually char is treated as a waste/ by-product that needs proper disposal. Until now, no energetic utilization concepts have been introduced except from (usually uncontrolled) combusting or combustion onto rotary kilns.

In addition, there is another issue that arises during the operation of small scale gasifiers. Gasification facilities demand electricity for the operation of the auxiliary units. A basic process scheme of a small scale gasification unit is shown on Figure 2. Typically, a set of pumps is necessary in order for the facility to operate properly and undisruptive. Moreover, several other auxiliary units operate in addition to the pumps like the turbo-compressors at the engine and the loading augers. On average, 17% of the produced energy from these facilities (and 3% from the total input energy) is utilized for the operation of the auxiliary units [8].

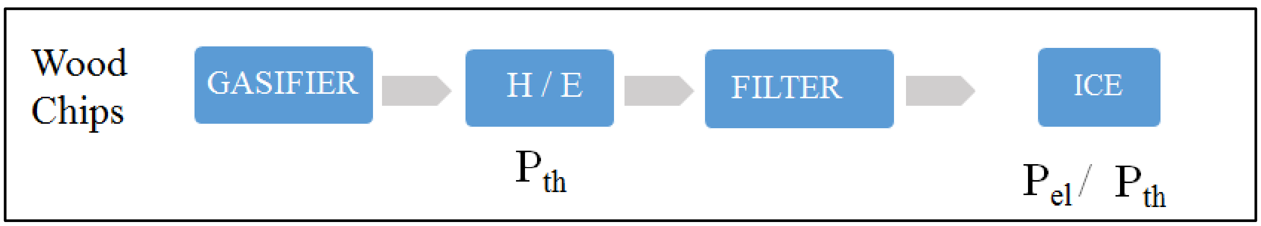

Figure 2. Basic process scheme of small scale gasification unit

Thus, this paper has the scope to investigate the possibility of onsite energy production of additional electricity by introducing a secondary reactor that would convert char to a gaseous fuel. The two streams entering the reactorwould be the flue gases from the internal combustion engine and the char which is created as a by-product from the process of gasification.This secondary reactor may be applied in all types of small scale gasifiers, but the optimal condition is when it is applied on a downdraft gasifier.The conversion of the input streams to a gaseous fuel will propagate by means of char-gas reactions mainly theBoudouardreaction and the water-gas reaction. The produced gaseous fuel will be consisted of Hydrogen, Carbon Monoxide, Carbon Dioxide and Nitrogen. This fuel can be utilized for electricity production in a smaller internal combustion engine which can be located in the facility. In addition by means of thermodynamic modelling, projected results from different scenarios will be presented. The model is developed in a MATLAB/ Cantera environment. Modelling is a faster and a lesser-risk method in comparison to the real life applications and if applied correctly they can provide valuable results.

2. Methods

The type of the gasifier that was used as comparison for the framework of this paper along with the data that are utilized for the analysis and the extrapolation of results have can be found in the literature and are accessible [6, 8]. The composition of the input parameters for producer gas, flue gas and char can be found on Figure 3.

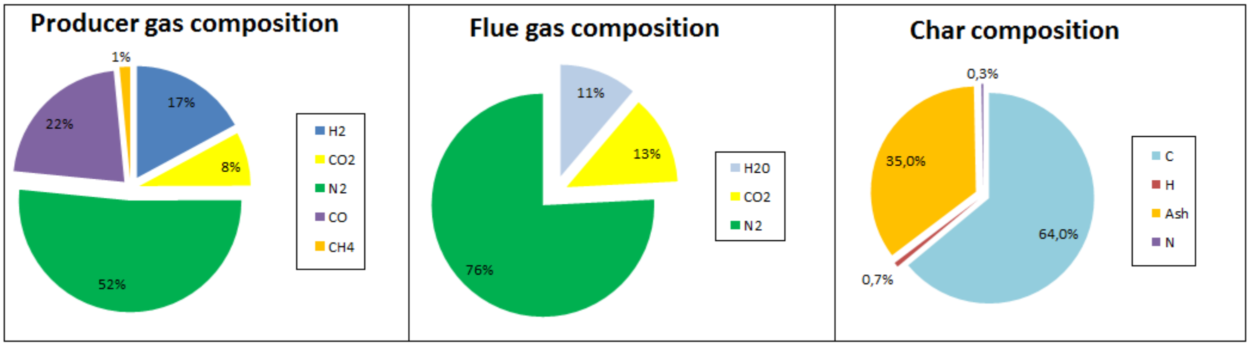

Figure 3. Input parameters for gaseous and char streams.

The current model is developed in Matlab - Cantera environment and uses the method of element potential minimization and the Villars–Cruise–Smith (VCS) algorithm. The initial inputs pass through multiple stages of equilibrium that are defined by the different conditions in the gasifier. Although no model can be perfect and can only serve the cause of describing a specific case, the model returns values that are close to operating downdraft gasifiers. It is significant to point out that the composition of the inputs is a highly influential factor for the case of thermodynamic modelling. Hence, the implementation of mass and elemental balances is crucial for the extrapolation of reliable results [9-11].

In the present work an equilibrium model (gas–solid), based on the minimization of the Gibbs energy, has been used in order to estimate the theoretical yield and the equilibrium composition of the reaction products (flue gas and char) of biomass thermochemical conversion processes (pyrolysis and gasification). The data obtained from this model have also been used to calculate the heating value of the fuel gas, in order to evaluate the overall energy efficiency of the thermal conversion stage. The proposed model has been applied for different operating temperatures from 700 K to 1300 K.

Finally, in order to assess the thermodynamic behavior of the system, an analysis of the net energy flows is performed and several different scenarios are presented for different temperatures of operation and different energy recovery scenarios.

3. Theory

In the framework of this manuscript, an apparatus for the utilization of gasification by-products in a downdraft gasifier is introduced. The apparatus utilizes the flue gases from the Internal Combustion Engine and the Char which is created as a by-product from the process of gasification.The apparatus may be applied in all types of small scale gasifiers, but the optimal condition is when it is applied on a downdraft gasifier. An indicative scheme of the addition of this secondary reactor can be found on Figure 4.

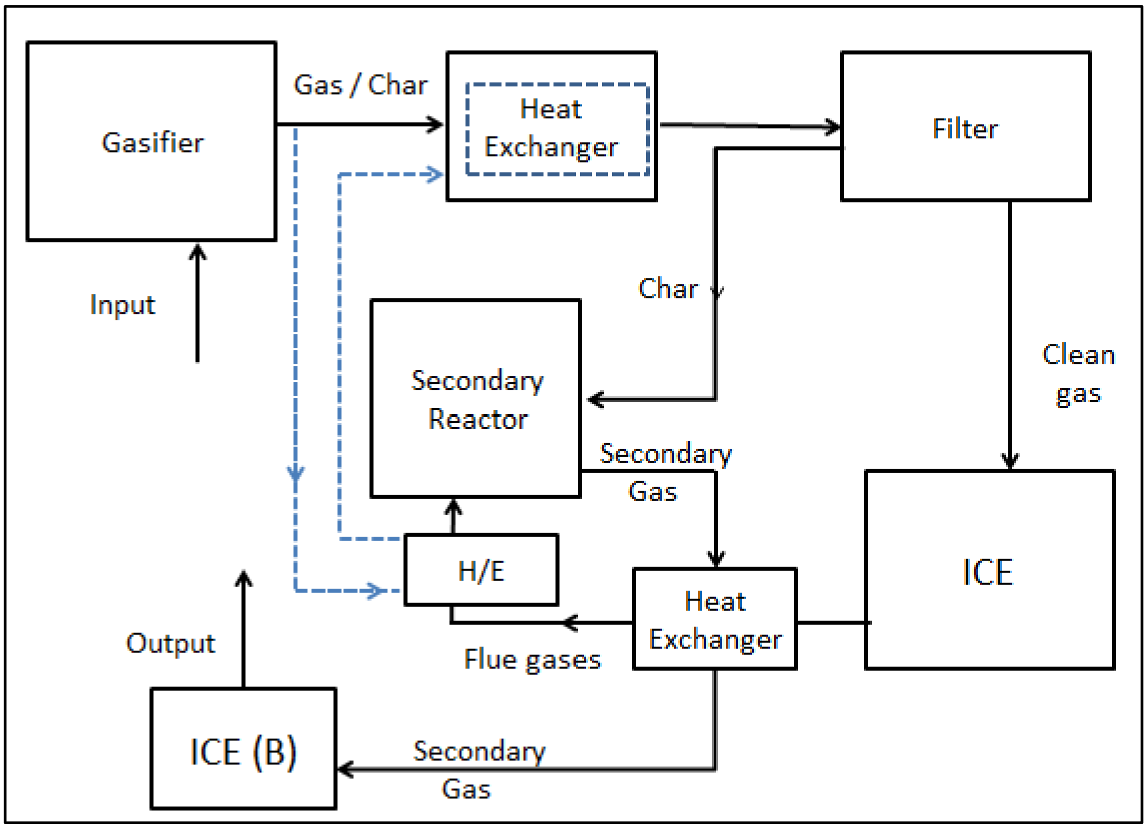

Figure 4. Indicative scheme of the addition of a secondary reactor to a standard small scale gasifier unit

The reactions that primarily take place are the Boudouard and the Water-gas reaction, although the full reaction mechanism is rather complicated. The apparatus converts the input streams into a gaseous fuel mainly consisted of Hydrogen and Carbon Monoxide, Carbon Dioxide and Nitrogen. This fuel can be utilized for electricity production in a smaller internal combustion Engine, as shown on Figure 4 as 'ICE (B). A change in the setup of the heat exchangers optimized the heat recovery. The apparatus can optimally be operated as fluidized bed and thus a blower (0.25 kW) for fluidizing the bedding material is taking into consideration.

This gaseous fuel has a lower energy density than the producer gas that is initially produced mainly due to the high fraction of nitrogen and carbon dioxide. These two gases are knocking suppressors, thus higher compression ratios can be utilized in order to increase the thermal efficiency of the engine.The temperature of the apparatus plays a significant role in the propagation of the reactions and the final thermodynamic equilibrium.

The apparatus is enclosed in a bigger vessel which works as an output buffer for the producer gas from the gasification process. The high temperature of the gas ensures a high temperature inside the apparatus and less energy has to be utilized in order to raise the temperature in the optimal range.

4. Results and discussion

On Figure 5 is shown the changing composition of the produced gas from the apparatus along different possible temperatures of operation. Primarily the combine composition of hydrogen and carbon monoxide are responsible for the heating value of the gas. The composition of the carbon monoxide continuously increases with increasing temperature. On the other hand after an initial increase in the composition of hydrogen until 800 K, a slow decrease is observed until 1200 K.

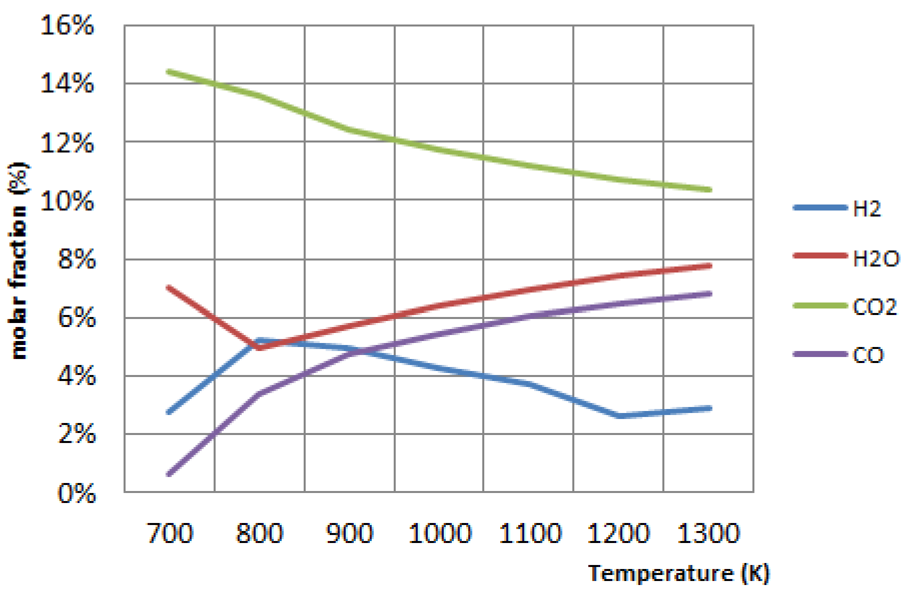

Figure 5. Molar fraction of hydrogen, steam, carbon monoxide and carbon dioxide in the produced gas

Finally, it has to be mentioned that Nitrogen is the dominant compound with a composition over 72% for all the above presented cases.

In Figure 6 is shown the heating value of the produced gas on dry basis. Although the highest heating value is observed for an operation mode at 1300 K, between 900 K and 1100 K only a marginal change in the heating value is observed at the range of 15 kWh.

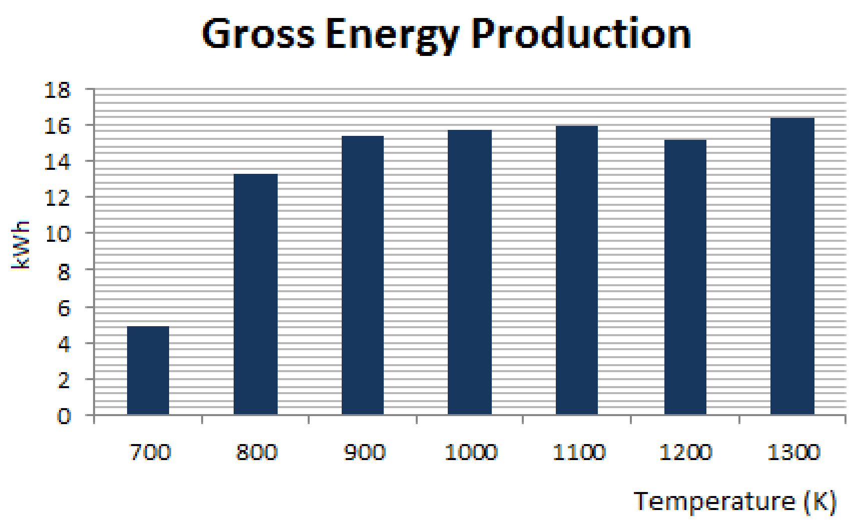

Figure 6.Heating value of the produced gas on dry basis.

But, no matter the heating value of the produced gas, an issue of high significance is the efficiency of conversion of the Internal Combustion Engine. Figure 7, shows all the different scenarios for efficiencies between 30 and 47 %. It is rather typical for these units to have efficiencies between 30 and 35%. Nonetheless the high presence of nitrogen acts as a knocking suppressing factor and higher compression ratios could be utilized which would result to higher engine efficiencies.

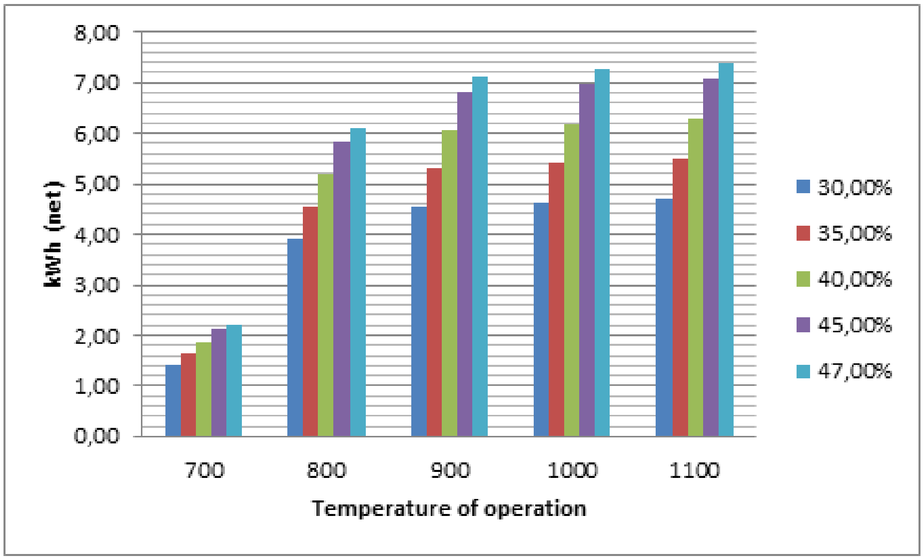

Figure 7. Net electrical production for different scenarios of engine conversion efficiencies

Finally what is shown from Figure 7 is that the investigated facility, with a nominal power output of 45 kW_e and an actual of 42 kW_emay have an additional 5 kWh of electricity on average which represents 11% of the energy. For very high compression efficiencies, i.e. over 45%, the produced electricity would be enough to cover the necessary power for the operation of the auxiliaries.

Conclusions

To sum up, some main aspects should be highlighted.

- Char residue from gasification and emissions from ICE for syngas production are by-products that are underutilized and no satisfactory management strategies have been developed.
- In the framework of this paper an apparatus is introduced that utilizes char residue from gasification and emissions from ICE for the production of a gaseous fuel
- Although the highest heating value is observed for an operation mode at 1300 K, between 900 K and 1100 K only a marginal change in the heating value is observed at the range of 15 kWh.
- The additional electricity produced by this apparatus would on average increase 11% the energy production of the facility. For very high compression efficiencies, i.e. over 45%, the produced electricity would be enough to cover the necessary power for the operation of the auxiliaries.

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