

# New concepts for large-scale integration of biomass gasification with concentrated solar energy for renewable energy carriers

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*Abstract*— The interest and possibilities of conducting steam gasification of biomass (SGB) assisted by concentrated solar energy (CSE) at high temperature as external heat source for applications at large scale is studied. First the different options to conduct SGB to produce syngas and hydrogen are analyzed. Thereafter the possibilities of integrating CSE in SGB are investigated, including the ways to transfer the heat to the reactor, as well as methods to increase fuel conversion efficiency and the solar share in the gas produced. Finally, some original ideas to conduct SGB with solid particles as energy carriers heated by CSE are proposed.

*Keywords*—gasification, solar, biomass, fluidized-bed, hydrogen, syngas, hybridization

## I. INTRODUCTION

Production of fuels and chemicals using solar energy to gasify biomass and waste is a promising technology for CO<sub>2</sub> reduction and energy storage. Steam gasification of biomass into renewable syngas/H<sub>2</sub> is highly endothermic, and the concepts proposed until now are either autothermal (the heat is supplied by partial burning of the fuel) or just laboratory studies where the heat is supplied by electrical heaters. The use of solar energy as external heat source for steam reforming of fuels has been recognized as highly attractive method [1]. However, it is yet to be determined how to supply the solar heat to industrial scale reactors. In this paper we propose a new concept to conduct allothermal gasification/reforming of biomass using solar energy that might be implemented at large scale to produce either syngas or H<sub>2</sub> enriched gas..

## II. TYPES OF STEAM GASIFICATION PROCESSES

Figure 1 shows schematically different gasification options that have been suggested for solid fuels: allothermal steam gasification, heated by an external source (Fig. 1 (a)), and autothermal gasification, in which part of the fuel is burnt to generate the necessary heat Fig. 1 (b), whether using pure oxygen (Fig. 1 (b.1)) or air (Fig. 1 (b.2)).

In autothermal gasification (Fig. 1 (b)) (pure) oxygen is used for the production of nitrogen-free syngas, but an air separation unit (ASU) must be used to supply the oxygen. ASUs are energy intensive and can be costly. In order to produce a similar syngas quality in autothermal gasification using air (Fig. 1 (b.2)), a dual fluidized bed (DFB) reactor system must be used, hence trading the cost and energy penalty of an ASU for a more complex gasification

In allothermal gasification (Fig. 1 (a)), a heat source at the gasification temperature or higher, in the range of 700-1000 °C depending on the fuel and reactor type, must be available to support the endothermic reactions. The external heat source would ideally carry out by transferring all the energy available in the fuel into the produced syngas, instead of burning some to provide the heat, hence raising the yield significantly and improving the overall energy efficiency of the process. In turn, on the one hand, the steam gasification transforms heat into chemical energy in the syngas with higher exergy, and thus acts as a chemical heat pumping. On the other hand, allothermal gasification can be seen as a way to reduce the water (water splitting) using the carbon in the fuel as reducing agent, generating additional hydrogen from the fuel during its reformation (so H<sub>2</sub> comes from water and fuel).

The representations in Figure 1 are simplified schemes and hide some key process design details. In the gasification reactor of Figure 1(a) several processes take place: the pyrolysis of biomass, the reforming of volatiles and the gasification of char. These processes can take place in one single reactor or in several reactors. For instance, the gasification process can involve three different reactors: biomass pyrolyzer to generate volatiles and char, reformer to convert the volatiles into syngas with steam, and gasifier to convert the char into syngas with steam and O<sub>2</sub>. Under this concept, there are two streams of syngas from the volatiles and that from the char than can be merged for cleaning and upgrading. This design has never been applied yet but constitutes a reasonable separation from the efficiency point of view, since it enables proper thermal utilization of the heat (external heat utilization and heat process integration) and fuel conversion. If O<sub>2</sub> is used as in autothermal gasification of Figure 1(b), feeding of more oxygen enables more feeding of biomass and steam at a given reactor temperature, or

otherwise, higher reactor temperature at a given steam/O<sub>2</sub> or steam/biomass ratio, while more loss of chemical energy of the original fuel is inevitable.

Practical implementation of indirect autothermal includes a dual fluidized bed gasification (DFBG) systems (Figure 2), where the biomass is gasified/devolatilized with steam in a bubbling FB, which is heated by the circulating hot material from the circulating FB combustor (where the char transported from gasifier and an additional fuel, if necessary, are burnt and heat the sand material). The bubbling FB gasifier is allothermal (provided no additional fuel is added, which is usually the situation in practice) since the energy (heat from sand and chemical energy from char) comes from an external device, although the system (gasifier+combustor) is “autothermal”.

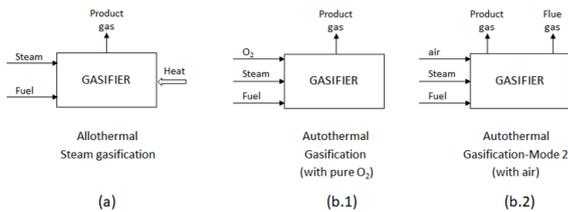


Fig. 1. Gasification options: (a) Allothermal gasification (use only steam as gasification agent and solar energy as the heating source). (b) Autothermal gasification: (b1) using O<sub>2</sub>/steam as gasification agent, (b2) using air/steam as gasification agent.

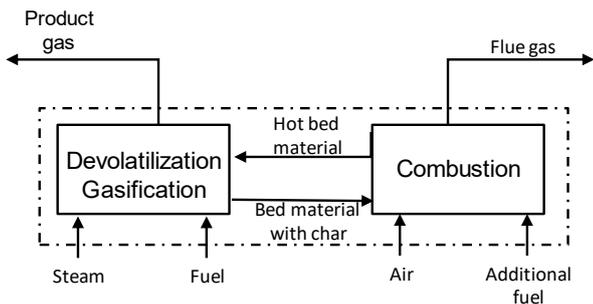


Fig. 2. Steam gasification in a dual fluidized bed (DFB).

### III. OPERATIONAL MODES OF DFB

There are two types of steam gasification process to be analyzed for the purpose of this work: single stage allothermal gasification (Fig. 1) and air-steam gasification carried out in an DFB. We first analyze the latter, since several operational modes are possible and need to be understood for the use of solar energy in it, and then the former is dealt with as a limiting case of DFB.

In Fig. 3 the possibilities of DFB of Fig. 2 are extended by considering: the use of external heat and additional fuel in the combustor and in the gasifier. Colors in Fig. 3 outline the main aspects to be discussed in the following which make different from one operational way to another. Taking this picture in mind, there are, in principle, various operation regimes in a DFB.

Case 1: Partial Allothermal Operated PALO gasifier (some external energy, not all, comes from a source other than the biomass):

- Case 1.a: the system is thermally balanced by providing some external heat to the gasifier (from the concentrated solar system)
- Case 1.b: the system is thermally balanced by providing external fossil fuel to the combustor (natural gas, coal or other fossil fuel)

Case 2: Complete autothermal operated CATO gasifier (all the energy comes from the biomass, i.e. no external heat is supplied (neither to the gasifier nor to the combustor))

- Case 2.a: the system is thermally balanced by burning part of the biomass in the combustor (no syngas recirculation)
- Case 2.b: the system is thermally balanced by burning part of the syngas produced in the combustor (all the biomass is fed in the gasifier)
- Case 2.c: the systems operates in such a way that the autothermal operation is achieved by burning the char generated (and not completely converted) in the combustor without any additional burning of biomass or recycle syngas.

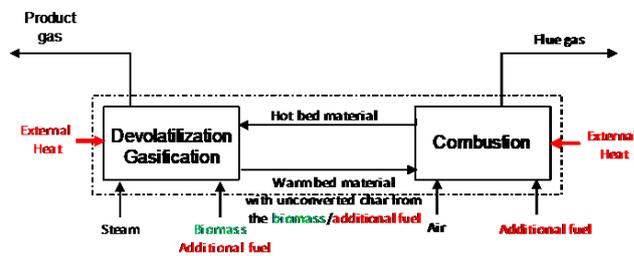


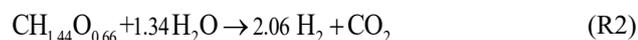
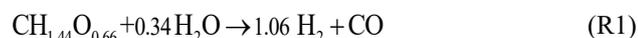
Fig. 3. Indication of various fuel operational modes of gasification in a dual fluidized bed (DFB)

The CALO gasifier the most interesting case from the perspective of this work, since all the energy from the fuel, plus that of the external renewable (solar), is transfer to the syngas. The PALO gasifier is the second most interesting case since it is just the “natural” solution to be applied when it is impossible to sustain the gasifier with external heat only; two streams are generated syngas and flue gas, instead of one single syngas. A remarkable point is that the oxygen provision is through air to the combustor so that the syngas is neither diluted with oxygen nor contaminated with CO<sub>2</sub>. The CATO gasifier is the usual way to operate the DFBG as developed by TUV, ECN or some universities in Sweden, China, Japan, France and Spain (and probably more places), although sometimes these DFBGs are operated burning some natural gas to elevate the combustion temperature and formally, it would belong to PALO. In any case, this seems to be the current superior mode of fuel utilization (and the simplest way from the hardware point of view) and the only technical development that has reached commercial scale. This design is, however, not presently prepared for external heat supply. The other types of CATO gasifiers are not so interesting: syngas recirculation are not exergetically efficient (and probably not that easy to be implemented), and the use of fossil fuel burned with air does not provide a feasible way to carbon capture, in addition that the use of pure oxygen for this application seems to be not feasible for these scales. Therefore, the analysis that follows is focused on the most interesting cases, CALO and PALO. CATO will be analyzed as the reference case since is the only DFB with

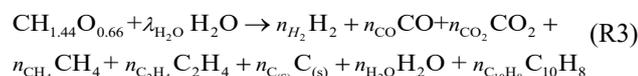
extensive operation experience at large scale in (Austria, Germany and Sweden).

#### IV. MODELLING OF THE PROCESSES

The steam gasification of biomass (general formula  $\text{CH}_{1.44}\text{O}_{0.66}$ ) to yield syngas ( $\text{H}_2/\text{CO}$ ) or  $\text{H}_2$  (with  $\text{CO}_2$ ) fed can be stoichiometrically represented by the reactions (R1) y (R2)



The stoichiometry of reactions R1 and R2 establishes the amount of reactants involved (steam per unit of biomass or SBR) and products ( $\text{H}_2$  and  $\text{CO}/\text{CO}_2$ ) generated provided the reactions are complete and stoichiometric. This is usually far from the actual case in practice since thermodynamic and kinetic limitations make the product distribution very different from the complete conversion indicated by the stoichiometry in R1 and R2 [1]. A more realistic way to represent the product gas from a gasifier is R3



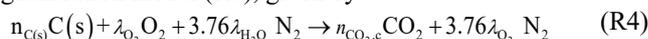
where besides  $\text{CO}$  and  $\text{H}_2$  other components are present in the product gas, such as hydrocarbons (mainly  $\text{CH}_4$ , and other light hydrocarbons, here lumped into  $\text{C}_2\text{H}_4$ ) and tars (lumped into naphthalene  $\text{C}_{10}\text{H}_8$  as tar model) as well as solid carbon (char). It should also be kept in mind that there it is always unconverted steam even feeding it stoichiometrically for either reaction R1 or R2.

If gasification temperature (or heat addition to gasifier) and steam to biomass fed,  $\lambda_{\text{H}_2\text{O}}$ , as well as the temperature at which gasification agent is fed to the gasifier are specified, there are 9 unknowns (heat addition (or temperature), and the 8 molar yield of all species in the product gas  $n_i$ , expressed per mol of biomass). There are 4 balance equations, CHO, and one heat balance. In principle 5 additional equations are needed.

Three approaches can be applied to provide the additional relations: (i) The assumption of equilibrium (EM); (ii) application of kinetics models (KM), taking into account chemical and fluid-dynamics rate considerations; (iii) a combined approach, sometimes called pseudo-equilibrium (PEM), which are models applying the equilibrium frame but supported by semiempirical inputs to take into account kinetic- and flow- rate limitations. EM is the most universal way to close the calculations but also it fails in predicting real gas composition (especially  $\text{C(s)}$ ,  $\text{CH}_4$  which above  $750^\circ\text{C}$  are almost zero, overestimating the  $\text{H}_2$  production and steam conversion). Though equilibrium calculations can be easily made and it is a good approach as a first step to calculate roughly the heat requirements for different fuels when there is not much specific data of the gasifier. The gas composition may differ significantly from the that of a real unit, greatly misleading the conclusions. KM gives better representation of the process for a specified system (geometry, type of biomass, etc) but a great deal of inputs is required and the conclusions are system-dependent. Although it is the most complete and reliable approach for the design of a particular device, it is not very useful for system and conceptual analysis and so for the purpose of our

study. The PEM is a reasonable compromise to be applied if some empirical, but still general, knowledge of the process is available.

The model for steam gasification in dual fluidized bed (DFB) gasifier (Figure 1b2 or Figure 2) is in principle the same as the stand-alone allothermal gasifier (Reaction R3), but the model need to consider the separate combustion equipment producing the heat which is carried to the gasifier by solids circulation. Then, the combustion model is added to the gasification model (R3), given by



where the char is burned, alone or with additional heat supply (by means of additional biomass feeding, burning recirculated syngas or another fuel (solid or gas), or by supplying heat from external source). As seen the gasification process is represented by the same reaction (R3), since the gasifier is allothermal and steam gasification takes place. The difference is the heating medium/carrier, which was not defined above (only the heat need was defined but not the way in which the heat is provided). The heat necessary for gasification comes from the combustion.

The analysis of an autothermal gasifier using steam and oxygen (Figure 1(b).1) is simply Reaction R3 adding  $\text{O}_2$  as gasification agent. Since very substoichiometric conditions (referred to complete combustion) is added, defined as oxygen equivalence ratio, in the order of 0.15-0.25, the fed oxygen is virtually converted in the gasifier and from the modelling point of view there is no additional unknown (only one additional specification, the  $\text{O}_2$  to biomass ratio).

In any of the gasifiers to be studied, simulation of char conversion is a key step. In steam allothermal stand-alone gasification (Fig.1) the main effort must be concentrated to fully converted the carbon with steam, for instance by operating at high temperature, high solid residence times or by catalytic addition. In DFG, in contrast, the char generated after fuel devolatilization is barely converted, but it is directed to the char combustor. Even in this case, it is necessary to calculate the char available for combustion since the gasifier heat needs must be satisfied by the combustion heat, and the amount of char converted in the gasifier establishes the additional fuel needed to be supplied in the combustor to balance the system energetically. The char conversion in the gasifier depends on the carbon-steam gasification rate of the char particles ( $\text{CO}_2$ -carbon rate is much slower) and the residence time of the char particles in the reactor. On the one hand, the rate of reaction depends on the temperature, the species concentration (mainly steam, but hydrogen can be also important as it inhibits the carbon-steam reaction rate), the intrinsic reactivity of the char (fuel type and form of char generation) and the quality/extent of gas-solid contact. On the other hand, the residence time of the char particles depends on the rate of solids removal, that can be (i) intentionally made by gas-solid entrainment and elutriation and/or by removing the solids in the case of DFBG to carry the solids to the combustor, or (ii) unintentionally as carbon losses by entrainment of elutriated particles from the bed in a stand-alone gasifier. Theoretically, in a gasifier with not char removal of any kind, the residence time of char is infinite and the char conversion is complete, but also the volume of the reactor is very high (infinite for an infinite time of complete conversion for a single particle). The model of char conversion developed in [3] for a FB is applied.

## V. ANALYSIS OF ALLOTHERMAL GASIFICATION (CALO)

Figure 4 shows the heat balance over the system (including the steam generation) of a CALO for steam equivalence ratio  $ER_{H_2O}$  (stream fed/stoichiometric steam to produce syngas) of  $ER_{H_2O}=1$  (calculated by equilibrium model. It is concluded that if equilibrium conversion is attained, about 105 kJ per mol of daf biomass ( $2.6 \text{ MJ/kg}_{dafb}$ ) is necessary to be supplied to the gasifier even if the system is energetically integrated (i.e. steam is produced and superheated at  $700^\circ\text{C}$  by heat exchange with the syngas). This is an important consideration because the heat in the gasifier should be provided at high temperature ( $900\text{-}1000^\circ\text{C}$ ) whereas steam generation and superheating can be made with lower temperature heat source (and using the sensible heat of the syngas). Only for high steam to biomass ratio and high steam temperature at the gasifier inlet, there is some heat (about 65 kJ/mol) that has to be externally supplied in the steam generator at relatively low-medium temperature.

The amount of heat necessary in the gasifier depends much on the fuel. In Figure 5 the heat necessary for different fuels is calculated according to equilibrium. The region of biomass (marked in green) is well below that for char from wood (blue) and pure carbon (represented as C in black). Obviously the higher the carbon to hydrogen ratio the larger the heat necessary and also more water is split. However, on the basis of heating value of the fuel, the ratio to be supplied to the gasifier ( $\text{MJ/kg}_{fuel}$ ) is approximately the same, in the order of  $0.20\text{-}0.30 \text{ MJ/kg}_{fuel}$ .

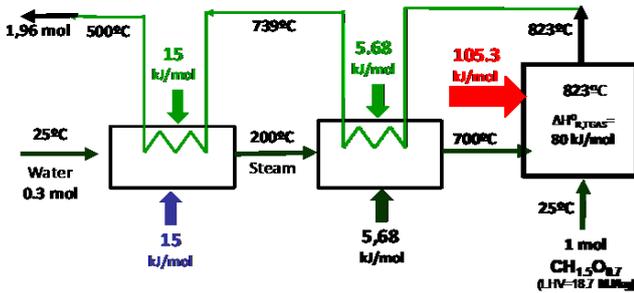


Fig. 4. Analysis of the heat integration for  $ER_{H_2O}=1$  ( $SBR=0.22 \text{ kg/kg}$ ) with indication of main temperature of streams and gasifier, as well as heat rates needed

## VI. ANALYSIS OF AUTOTHERMAL DFB GASIFIER (CATO)

In Figure 6(a) the solids circulation rate (per unit of  $\text{kg}_{dafb}$ ) required to maintain the system autothermal (neither fuel nor heat externally provided) is plot as a function of combustion temperature for three gasification temperatures. For a fixed gasification temperature, the solids circulation rate decreases rapidly with combustion temperature (i.e. higher difference of temperature between the two reactors,  $\Delta T$ ). It is concluded that for keeping solids circulation rates under reasonable values,  $\Delta T$  should be in the order of  $50^\circ\text{C}$  and above. In figure 6(b) the corresponding conversion as a function of the residence time of the char in the gasifier is presented for the same three gasification temperatures of Figure 6(a). As shown, the residence time of the char in the gasifier decreases (so it does the char conversion) with gasification

temperature, since more char yield has to be produced in the gasifier to be burned in the combustor. Note that although the char reactivity is higher as gasification temperature is increased, the char conversion in the gasifier decreases because of the significant reduction in the char residence time.

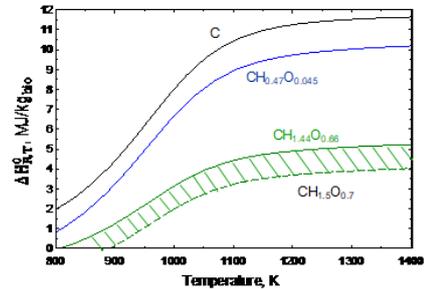


Fig. 5. Heat to be supplied to the gasifier (per kg of fuel) for different fuels: carbon, char and biomass

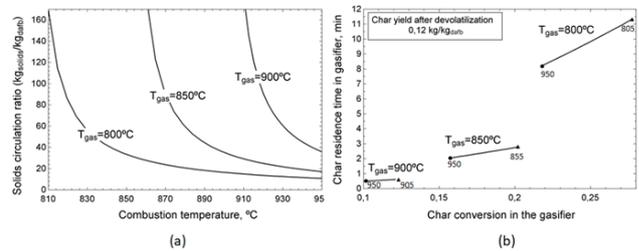


Fig. 6. (a) Solids circulation ratio (flow rate of solids/flow rate of biomass) as a function of combustion temperature for three gasification temperatures (b) Corresponding residence time vs conversion of the char (the numbers indicated below the lines are the two extreme combustion temperatures simulated for each gasification temperature)

It observed in Figure 6(b) that, for a given gasification temperature, the higher the combustion temperature, the lower the degree of char conversion, especially at lower gasification temperatures, but the influence is small. The reason is that more sensible energy escaped with the flue gas as the combustor is operated at higher temperature, so a little bit more char is necessary to be burnt for equal gasification temperature. Although not shown in the figure, the corresponding cold gasification efficiencies for the simulations made in Figure 6 decrease slightly with temperature, from 71 ( $800^\circ\text{C}$ ) to 68 ( $950^\circ\text{C}$ ), and the lower heating value of the dry syngas ranges between  $12.8$  and  $13 \text{ MJ/Nm}^3$ .

## VII. ANALYSIS OF PARTIAL ALLOTHERMALLY-OPERATED GASIFIER (PALO)

Now the discussion is made to understand the performance of a DFBG gasifier where some of the heat required by the gasifier is externally supplied, i.e. PALO-DFBG. It is modelled by taking the model developed above but now the restriction that the heat required in the gasifier is provided by the heat from char oxidation in the combustion zone is liberated, since some external heat addition to the gasifier. The sum of the heat from the combustion and that from the external source is that necessary for the gasification process.

Figure 7 shows a DFBG with various levels of % of external heat added, from 0 (CATO-DFBG) to 1 (CALO-FBG) at constant gasification and combustion temperature, and steam to biomass ratio. The solids circulation between the reactors is seen to decrease significantly, whereas  $\tau_{\text{bio}}$  (larger mass inventory or reactor size for a given throughput) increases with % of external heat added. Logically no circulation is necessary when all the heat required in the gasifier is externally supplied. For that case full char conversion has to be achieved in the reactor and very long residence times of the char are necessary, quantified in Figure 7(b). It is seen in Graph 7b that significant char conversion is reached for reasonable long residence time (80% of char conversion is attained in the gasifier with residence time of 40-50 min) but higher char conversion requires excessive long residence times and thus reactor volumes per unit of biomass feeding rate (see  $\tau_{\text{bio}}$  in Graph (a)). Although not indicated, the gas composition improves considerably (hydrogen yield increases roughly linearly from 40 to almost 70 g/kg) as a result of higher steam-char conversion, decreasing substantially the steam concentration in the syngas as the % of external heat to the gasifier is higher.

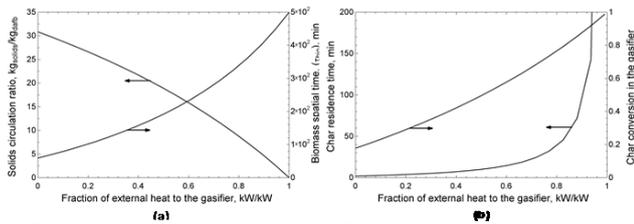


Fig. 7. Performance of a DFBG operating with different % of external heat at constant temperature in the gasifier (850°C) and combustor (905°C), and steam equivalence ratio  $ER_{\text{H}_2\text{O}}=2$  (Steam to Biomass mass ratio,  $SBR=0.44$ ) (a) Solids circulation ratio (flow rate of solids/flow rate of biomass) and biomass spatial time (b) Char residence time and conversion of the char in the gasifier. Simulations are made for char yield after devolatilization of 0.12 kg/kg<sub>dafb</sub>.

The fraction of energy supplied to the gasifier normalized to the heating value of the fuel and also to the syngas produced (solar share) is presented in Figure 8(a). It is seen that the solar share (solar energy in the produced gas) is around 16%, when all the energy is supplied to the gasifier (around 75 kJ/mol or 3 MJ/kg) (in Figure 8(b)). If the equilibrium is reached the solar share can be increased to the values indicated in Figure 5.

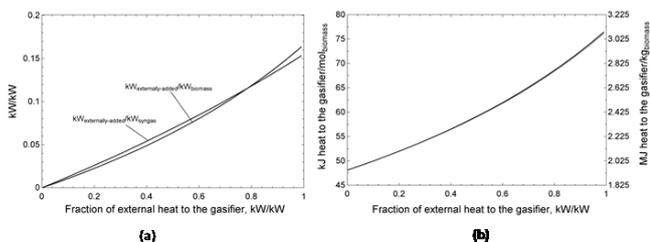


Fig. 8. Heat supplied to the gasifier (a) referred to the energy of the incoming fuel and produced gas as a function of % of external heat; and (b) on the basis of mol (kJ/mol) and mass (MJ/kg) of biomass. Values for the simulation are: temperature in the gasifier 850°C; in the combustor 905°C;

steam equivalence ratio  $ER_{\text{H}_2\text{O}}=2$  (Steam to Biomass mass ratio,  $SBR=0.44$ ); char yield after devolatilization of 0.12 kg/kg<sub>dafb</sub>)

## VIII. IMPLEMENTATION OF BIOMASS GASIFICATION WITH CONCENTRATED SOLAR ENERGY

A key aspect of the process is to know how the external heat transfer is implemented [2]. In this paper we propose to conduct the gasification/reforming of biomass using solar energy. The essential idea is based on the use of solid particles to carry the solar energy to the gasification process (Figure 9). The solid particles capture the concentrated solar energy in a central particle receiver (tower), carrying the energy to a hot storage tank. The gasification system is continuously fed by hot solid particles, providing the necessary heat for reaction. Then the particles are conveyed to a warm tank, where they are stored and will be sent to the central receiver, closing the solar-particle loop.

The use of solids particles as a thermal energy carrier, circulating cyclically between the solar receiver and the gasification system enables the separation of the receiver and the reactor, with minimum heat loss. Solids particles are excellent thermal energy storage medium because of their low cost and high operating temperature. In addition, accommodation of solar intermittency by hot solids storage is relatively easy: fluidization and circulation of solids can be achieved with state-of-the-art technology, and temperatures in the receiver in the range of 700-900 °C is realizable using existing solar collectors/concentrators. These characteristics ensure continuous operation of the biomass conversion system despite the unsteady and intermittent nature of the solar radiation.

In an idealized scenario, the heat transfer is carried out by hot solid particles from the receiver at  $T_{\text{rec}}$ , and it is completely mixed in the gasifier at  $T_{\text{gas}}$ . Figure 10 plots the circulation of solids from the hot storage (receiver) to the gasifier necessary to maintain the process for several % of external heat as a function of the difference of temperature  $T_{\text{rec}} - T_{\text{gas}}$ . It is seen that for operation with full external heat from the solar receiver solids circulation between 50 and 30 kg/kg<sub>dafb</sub> are necessary for temperature differences between 50 and 100°C. Obviously small difference of temperature is more interesting from the solar receiver perspective but it results in more solid circulation. This simplified scenario does not take into account how to separate the ash/char from the solid particles circulating through the receiver loop. Several possibilities are possible and must be defined by further investigation.

Another gasification concept towards  $\text{H}_2$  production based on Calcium Looping (CaL) assisted by solar energy is presented in Figure 11. The biomass (and some minor addition of limestone to compensate the loss of sorbent activity with time) is converted into two streams, one with high  $\text{H}_2$  content of and another with high content of  $\text{CO}_2$ . There are several possibilities to carry out the operation under this concept.

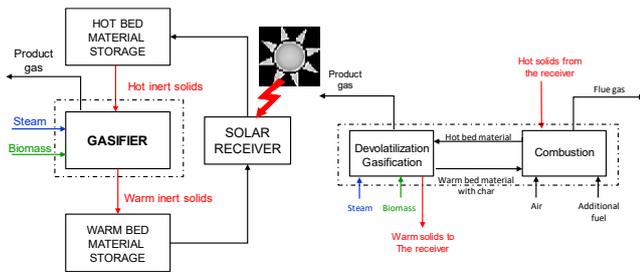


Fig. 9. Integration of biomass gasifier in the solar particle loop (left) and detail of the DFBG of Figure 3 working in solar mode (right)

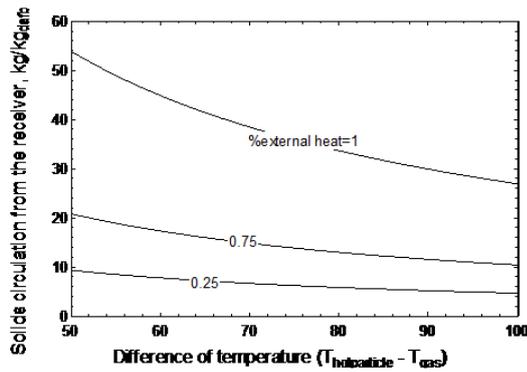


Fig. 10. Circulation of solids from the hot storage (receiver) to the gasifier as a function of the difference of temperature  $T_{rec} - T_{gas}$  for several % of external heat

- Option 1: The most immediate way to carry out the process is as it has been used up to now for biomass gasification with in-situ  $CO_2$  capture in one FBG (carbonator) and regeneration of  $CaCO_3$  to  $CaO$  in a separated CFB calciner, i.e. SEG [4] but by providing the heat in the gasifier externally: the hot solid transfer the heat in the calciner by heat exchangers. This can be made by fluidized tubes as being developed for indirect receivers. The design can be done in one or two-stages as has been applied in classical FB calciners. The flue gas contains water and  $CO_2$  and then the  $CO_2$  can be captured because there is not nitrogen. This advantage is penalized by lowering the heat efficiency because of the water condensation. The calcination is made by steam and  $CO_2$  mixtures and then it can be carry out between 800-900°C depending on the composition. The calcination temperature has strong influence on the  $CaO$  activity and has been discussed in the literature review. The activity of the  $CaO$  resulting from this process could behave differently compared to that from SEG applied till now and the ability of this sorbent to enhance char reactivity,  $CO_2$  capture and tar reforming have to be studied. A challenging variant of this option is to conduct direct heating of solids, which avoid the heating surfaces but add several challenges issues like the need of solid separation and contamination of the solar-particle loop.
- Option 2: another approach is to carry out the gasification at relatively high temperature (800-850°C) compared to other CaL (non-solar) processes, while the calciner (regenerator of  $CaCO_3$ ) and the carbonator ( $CO_2$

capture using  $CaO$ ) are operated at lower temperature than the gasifier. This thermal operation profile through the conversion system is potentially achieved by the use of solar energy at high temperature, carried by the hot particles. The improved technical performance with respect to other gasification and CaL systems rests on both temperature and spatial time. For instance, the lower temperature in the calciner can be achieved by using steam as fluidization agent along with energy supply using solids at high temperature. This resulting in a lower deactivation of the  $CaO$  sorbent with time (number of cycles) compared to typical operating conditions investigated up to now (more severe conditions), therefore, minimizing the makeup of sorbent and generation of waste (deactivated sorbent). In addition, the higher temperature achieved in the gasifier allows the increase of char and tar conversion. This concept proposes to address the three major issues of the CaLG: 1) supply of external heat, 2) loss of sorbent activity and 3) poor char and tar conversion in the gasifier.

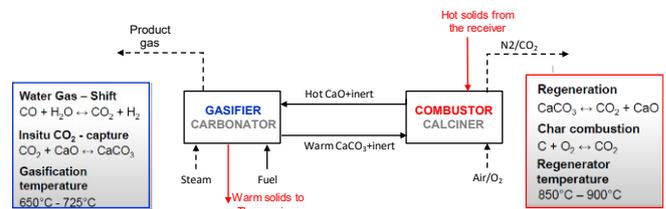


Fig. 11. Solar biomass gasification Calcium Looping

## IX. CONCLUSIONS

Allothermal steam gasification with external heat from concentrated solar energy (CS) energy is extremely interesting but complete fuel conversion and heat supply to the reactor are challenging so it is still at lab-scale state. Solar gasifiers are still at conceptual and lab-scale. Promising results are envisioned by using solid particles receivers but further research is necessary. Various new solar gasification concepts for large scale applications have been presented here with promising potential.

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