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Estimation of the Energy Efficiency of a Wood Gasification CHP Plant Using Aspen Plus

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The simultaneous combined heat and power (CHP) production via biomass gasification is considered as one of the main alternatives to fossil energy. Yet, a major obstacle in the development of this advanced technology lies in the presence of tars in syngas that are responsible for clogging downstream process equipment. Mathematical modelling and simulation studies are powerful tools to predict the performance of new processes. Baratieri et al. (2009), Pérez-Fortes et al. (2011) or Damartzis et al. (2012) develop comprehensive models of integrated biomass gasification plant, but based on thermochemical equilibrium approach that do not take into account the formation of tars. Recently, extensive models of Dual Fluidised Bed (DFB) gasifier demonstrate the possibility of accurately predict the formation of tars in syngas (Abdelouahed et al., 2012). The work presented in this paper consists in integrating a rigorous model of a DFB gasifier capable of predicting tar and contaminants in a global biomass CHP process. Our model includes the steps of wood drying, wood gasification, syngas cleaning, and power production in gas engine. Heat integration is considered all over the process for intern consumption and extern district heating. The model is set in Aspen Plus® and external Fortran user-subroutines are used to precisely describe complex phenomena in gasification reactor and gas engine. The energey efficiency of the CHP plant is evaluated. Simulation results highlight the strong impact of the syngas cleaning step in the overall performance of the CHP plant.

1. Introduction

The use of biomass renewable source in advanced energy technology is considered as one of the main alternatives towards fossil energy systems. Biomass gasification in Combined Heat and Power (CHP) plant has recently received considerable attention for its potential high electrical efficiency – around 25 % – compared to conventional combustion unit. Yet, a major barrier for the development of biomass gasification plant resides in the presence of tars and inorganic compounds in the produced syngas. These components are responsible for damaging downstream equipment and require syngas cleaning. At the Güssing biomass CHP demonstration plant, an electrical production of 2 MW from 8 MW of input biomass is achieved through a biomass gasifier coupled with an Internal Combustion (IC) gas engine (Hofbauer et al., 2003). Mathematical modeling and simulations are powerful tools for optimizing processes. Regarding biomass gasification, numerous models have been proposed. Most

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often modeling approaches are based on thermodynamic equilibrium (Hannula and Kurkula, 2010; Nikoo and Mahinpey, 2008). However, this method is not able to predict tars composition and yields. Hence power generation in IC engine (Baratieri, 2009; Damartzis, 2011) or in combined cycle gas turbine (Baratieri et al., 2009; Pérez-Fortes et al., 2011) has been evaluated through comprehensive, yet simplified models that do not account for tars formation in gasifier nor downstream removal. Extensive approaches have been recently developed based on gasifier decomposition in reaction modules such as pyrolysis and char combustion (Biagini et al., 2009; Sadhukhan et al., 2009), and lately including tars production and conversion (Abdelouahed et al., 2012). The aim of our study is to integrate an extensive biomass gasification model that determines tars and inorganic components in a whole CHP plant including drying, syngas cleaning and syngas combustion steps as well as heat recovery for district and intern process/stream heating. The detailed model allows an accurate prediction of the energy efficiency of the CHP plant. Syngas cleaning performance is also estimated along with the major emissions of the plant.

2. Materials and methods

2.1 Model settings and validation

The model of the biomass gasification CHP plant is implemented on Aspen Plus® simulation tool. External Fortran files are used in Aspen Plus® user subroutine for complex mechanisms description (Abdelouahed et al., 2012). RK-Aspen is used as base property method for the whole system, excepted for the wet scrubber where ELECTRNTL property method is preferred. Wood and char components are defined as non-conventional components based on their ultimate analysis including C, H, O, N, S; Cl and Ash elements, and proximate analysis.

Parameters of the gasifier model are adjusted to match the characteristics of the Tunzini Nessi Entreprises d'Equipments (TNEE) biomass gasifier pilot developed in France in the 80's (Deglise et al., 1985). This process was successfully operated during more than 2000 h with 500 kg.h^{-1} of wood. The TNEE gasifier is an atmospheric Dual Fluidized Bed (DFB) constituted of a dense Low Velocity Fluidized Bed (LVFB) and a High Velocity Pneumatic Riser (HVPR) interconnected with a circulating sand bed fluidized by direct recycling of 14 % of raw syngas. Simulation results regarding raw syngas composition in permanent gases including H_2, CO, CO_2, CH_4 and H_2O as well as total amount of tars are consistent with syngas composition results measured at the TNEE pilot. Syngas cleaning unit and IC engine parameters are adjusted based on literature data.

2.2 Process modelling

The Biomass gasification CHP plant is composed of a drying unit, a gasification unit, a syngas cleaning and cooling arrangement, and an IC gas engine for power production. Heat is recovered at different stages of the plant for district heating but also for intern processes and streams heating. An overview of the whole integrated process is provided in Figure 1. To the best of our knowledge, it is the first time that such a detailed Aspen Plus model is developed including tars, minerals, N, S compounds and heat recovery integration.

The drying unit is composed of a screw conveyer and a rotary dryer. The electrical consumption is estimated based on NREL correlations (2005). Wood is dried with a mix of flue gas and air at 200 °C from 40 to 28 %. Wood exits the dryer at 75 °C while flue gas – air – steam mixture exits at 110 °C. Inlet air is pre-heated with a part of the heat recovered from syngas cooling (cf. syngas cleaning unit). Under Aspen Plus, the rotary dryer is modeled as a combination of Heater and Flash 2 blocks. Vapor fraction in Flash2 block is set to have a wood moisture content of 28 % as specified in the TNEE pilot configuration.

The gasification unit consists of a DFB reactor composed of two distinct compartments as shown in Figure 1. Raw syngas and char are produced in the gasifier compartment. In the combustor compartment, char is oxidized in presence of O_2 (from air) to indirectly supply heat to the gasifier compartment through sand bed circulation. Clean syngas and tar sludge are also burned in the combustor as additional fuel for heat production. The gasifier model implemented in Aspen Plus is detailed in Figure 2 (Abdelouahed et al., 2012). Two main mechanisms occur in the gasifier compartment that are wood pyrolysis in the dense zone of the reactor and wood gas thermal cracking

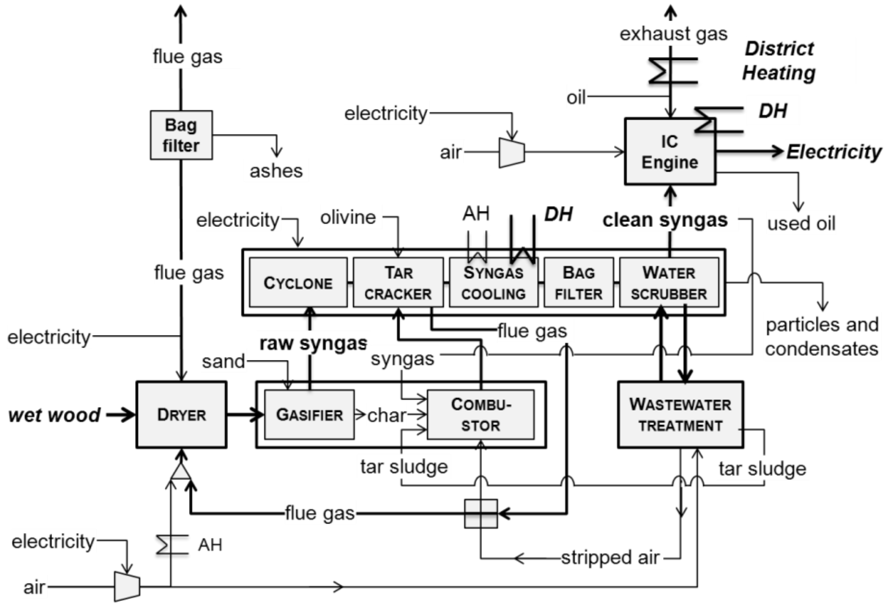

Figure 1: Overview of the modelled biomass gasification CHP plant

in the upper zone. In the simulation, the two mechanisms are separated in two distinct modules that are respectively PYROLYSER and FREE-BOARD as depicted in Figure 2. The PYROLYSER module is modeled with a RYield block associated to an external Fortran subroutine in which pyrolysis products yields are predicted depending on the temperature in the dense zone. The FREE-BOARD module is modeled with an RPlug block where kinetic reaction schemes are implemented including hydrocarbons (CH_4 and higher) thermal cracking and water gas shift reaction. Both modules predict syngas composition in permanent gases (H_2, CO, CO_2, CH_4, C_2H_4, C_2H_6), steam (H_2O), lumped tar compounds (phenol C_6H_6O, benzene C_6H_6, toluene C_7H_8, naphthalene $C_{10}H_8$), and inorganic compounds (NH_3, H_2S, HCl) as well as entrained solid particles. A TAR COMPOSITION IMPROVMENT block is added to increase the “number” of tars in syngas. Initially, tars composition is simplified (PYROLYSER) to allow the implementation of a kinetic approach in the FREE-BOARD. However, measurements at the Güssing CHP demonstration plant have revealed the presence of styrene C_8H_8, indene C_9H_8, acenaphthylene $C_{12}H_8$, anthracene $C_{14}H_{10}$, phenanthrene $C_{14}H_{10}$ and pyrene $C_{16}H_{10}$ in addition to the modeled components (Pfeifer and Hofbauer, 2008). As heavy polyaromatic ($C_{16}H_{10}$) and light polyaromatic with 2 or 3 rings ($C_{10}H_8 \rightarrow C_{14}H_{10}$) largely contribute to high tar dew point hence having a major influence on the downstream process equipment functioning (Rabou et al., 2009), the initial $C_{10}H_8$ mass flow stream is then split in the additional tar species according to the measured amounts of each specie. The combustion reactor – COMBUSTOR in Figure 2 - is decomposed in two modules. A RYield block coupled with a Fortran file is implemented for describing char combustion while a RStoic block is used to oxidize each component contains in syngas and tar sludge. Flue gas is then composed of O_2, N_2, CO_2, CO, NO, N_2O, HCl and SO_2 and also contains entrained fly ashes, unburnt char and sand particles. Sand is circulated from PYROLYSER to COMBUSTOR, from COMBUSTOR to FREE-BOARD and is then sent back to PYROLYSER. The amount of sand circulated is set to maintain a temperature of 760 °C in the PYROLYSER (adiabatic reactor) with a COMBUSTOR temperature fixed at 980 °C. In this condition, the temperature in the FREE-BOARD reaches 950 °C (adiabatic reactor).

The syngas cleaning unit consists of a cyclone, a catalytic tar cracker, a cooling step, a bag filter and a water scrubber. Conventional biomass syngas purification arrangement suggests the implementation of cyclone and bag filter for particles and condensates removal and wet scrubber for N, Cl and tarry species removal (Göransson et al., 2011). Water is most commonly used as scrubbing agent (Zwart, 2009) despite its known poor absorbing efficiency regarding tertiary tars. In our model, a catalytic tar cracker with pre-treated olivine is added upstream the water scrubber to increase tars conversion (Devi et al., 2005a,b). Cyclone and bag filter are modelled with Sep blocks with efficiencies according to Hasler and Nussbaumer (1999). Catalytic tar cracker is modelled with a REquil block including steam, dry and thermal reforming reactions. Conversion degrees for the reforming reactions at 900 °C are fixed and based on Devi et al. empirical results (2005a,b). The water scrubber is modelled with a Flash2 block. The amount of water supplied to the scrubber is set to sufficiently reduce the NH_3 content in syngas. Tars removal efficiencies are based on experimental results (Rabou et al., 2009). Clean syngas exiting water scrubber is compressed to 1 bar at 40 °C to compensate for pressure losses along upstream process equipment. Wastewater from wet scrubber is purified from its tars content in a settling tank. Inorganic contaminants and traces of tarry compounds are removed from water in an air stripper. Clean water is directly reused in water scrubber while stripped air is sent to the combustor. Gas engine is modelled as a black box under Aspen Plus® with characteristics based on the GE's Jenbacher wood gas engine type (GE's Jenbacher documentation) with electrical efficiency of 42 %, thermal efficiency of 43 %, an exhaust gas temperature of 180 °C and an oil service life of 2,000 h. The exhaust gas composition is defined from the syngas combustion equation encoded in an external Fortran files with CO and NOx emissions from Herdin et al. (2003) measurements on GE's Jenbacher wood gas engine and $C_{10}H_8$ and Polycyclic Aromatic Hydrocarbons (PAH) emissions from Teislev (2000) report.

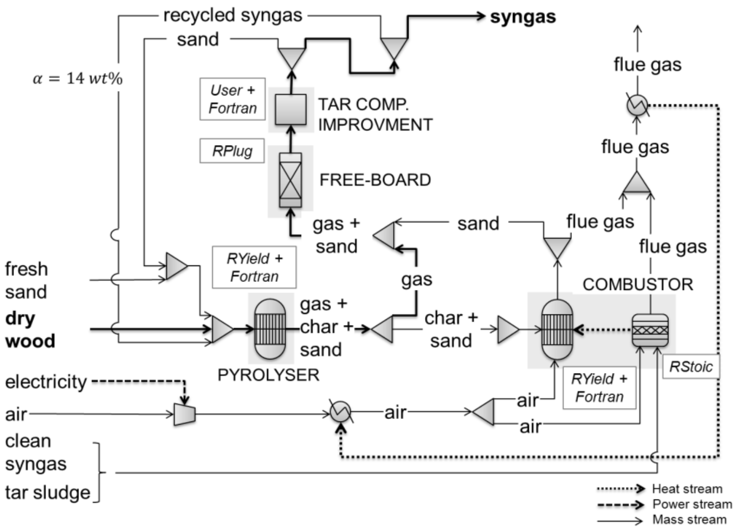

Figure 2: Aspen Plus detailed model of the DFB gasifier

3. Results

3.1 Energy efficiency

The overall energy performance of the biomass gasification CHP plant is illustrated on Figure 3. A production of 10 MW of electrical power (W_{engine}) and 13.4 MW of thermal energy for district heating (Q_{DH}) is achieved from 34 MW of wood with reference to anhydrous basis ($m_{anhy.wood}$) and Lower Heating Value ($LHV_{anhy.wood}$). The plant requires an electricity input (W_{input}) of 0.9 MW for operating air compressors, water pump, syngas compressor, screw conveyer and dryer. The net electrical efficiency obtained is then of 27 % (Eq. 1).

$$\eta_{el} = \frac{W_{engine} - W_{input}}{LHV_{anhy.\ wood} \times m_{anhy.\ wood}} \tag{1}$$

Heat is recovered at different stages of the process. Heat from flue gas (at 980 °C) is entirely used for internal needs: maintaining tar cracker temperature at 900 °C, pre-heating combustor air to 650 °C and wood drying. A part of the heat recovered from syngas cooling is used for heating dryer air to 200 °C. The remaining heat from syngas cooling is used for district heating and so is heat recovered from gas engine and exhaust gas (from 180 to 110 °C). The net thermal efficiency obtained is of 40 % (Eq. 2).

$$\eta_{th} = \frac{Q_{DH}}{LHV_{anhy.\ wood} \times m_{anhy.\ wood}} \tag{2}$$

And the net global energy efficiency of the biomass plant reaches 67 %. Exergy analysis and optimization are currently under progress.

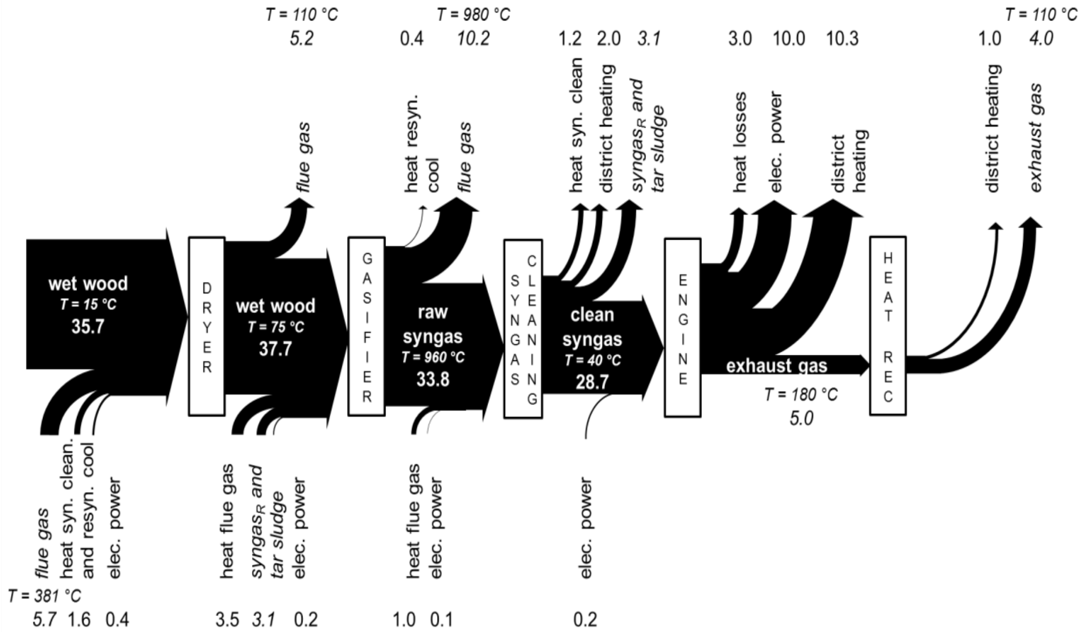

Figure 3: Sankey diagram of the energy performance of the CHP plant (heat stream unit: MW)

3.2 Overall performance of the biomass CHP plant

Internal heat recovery is optimized to avoid any fossil fuel input. 13 % of clean syngas is then directly used as fuel in combustor. The use of a catalytic tars cracker upstream wet scrubber limits hazardous emissions to scrubbing agent and increase the yield in syngas from tars conversion. Besides, the use of water instead of a more efficient solvent, as scrubbing agent allows the implementation of a simple wastewater purification system (settling tank and air stripper) hence preventing serious polluting emissions to the environment and limiting fresh water consumption. Tar sludge and stripped air originating from wastewater treatment are burned in the combustor with positive impact on the overall emissions. Nevertheless, the use of water shows limitations to properly reduce tar dew point. Thus, at the outlet of the cleaning unit, a tar dew point of 70 °C is obtained instead of 35 °C as recommended for syngas use in IC engine (GE's Jenbacher documentation). The major pollution arises from flue and exhausts gases that release CO, NOx, SOx, PAH and fine particles to the atmosphere with potential consequences to the environment, ecosystem and human health.

4. Conclusion

Our work provides a detailed model of a biomass DFB gasification unit coupled with an IC engine for the simultaneous production of heat and power. The model is implemented on Aspen Plus® and extern Fortran files are used to encode for complex reaction mechanisms in gasifier, combustor and engine systems. The DFB reactor is modeled as three distinct reactors (Abelouahed et al., 2012). This approach allows the prediction of an accurate syngas composition including tars, inorganic and particulates contaminants. Simulation results are validated with experimental measurements at pilot scale (Deglise et al. 1985, Pfeifer and Hofbauer, 2008). A conventional wet syngas cleaning unit is implemented at the outlet of the gasifier, and syngas is then burned in gas engine. A net electrical efficiency of 27 % is reached. Heat is recovered for district heating from engine, exhaust gas and syngas cooling with a thermal efficiency of 40 %. Heat contained in flue gas is entirely used for process needs. The overall energy performance of the CHP plant is 67 % which is quite promising for further gasification development. Further process optimization on energy, exergy and environmental basis can be performed thanks to this model.

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