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A Two-stage Approach for the Design of Biomass Conversion Processes

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Abstract

This paper presents an approach to find process alternatives that can transform biomass feedstock into value-added products given the properties of the biomass material such as ultimate analysis and product requirements such as the amount of desired electricity.
The proposed methodology firstly identifies main processing technologies based on feedstock and product constraints. Subsequently, a process synthesis method is applied to generate flowsheet alternatives.

Keywords: process synthesis, biomass processing, waste management

1. Introduction

The term biomass applies to the category of any non-fossil organic substances with high energy content. Biomass can be converted into value-added products including compost, wood pellets, charcoal, methanol, ethanol, biodiesel, stream and electricity. Typically raw materials should be transported and preprocessed. In order to process biomass feedstock, the decision maker must select and design a process from a number of physical, chemical and biological processing technologies that are available. Feedstock can be converted by using processing technologies such as combustion, gasification, pyrolysis, plasma arc, anaerobic digestion. However, feedstock preparation may include operations such as size reduction, drying, pelleting, storing, sorting, washing and grinding.

Furthermore, a specific product may require additional processing such as filtering, scrubbing or the application of other of processing technologies to meet product specifications or environmental requirements.
In addition, as in traditional chemical processes each processing technology has a number of design parameters that add complexity to the generation of process design alternatives. This paper describes the development to date of an approach for the conceptual design of biomass processes which allows the user to identify a set of good alternative designs chosen on the basis of multiple competing criteria. The proposed methodology firstly identifies main processing technologies based on feedstock and product information. Subsequently, a process synthesis method is applied to generate flowsheet alternatives. Much research is reported in the literature on process synthesis of chemical systems. However, the area of computer-based process synthesis of biomass conversion systems is relatively new. Few papers have been reported in the literature dealing with the conceptual design biomass processes. Sánchez et al. [1] report the automated design of ethanol processes using Jacaranda [**Error! Bookmark not defined.**], an object oriented computational framework for automated design. Brown et al. [2] discuss a superstructure-based method for gasification energy conversion systems.
Firstly, the two-stage methodology is presented. Then the material and unit models are explained. Finally, a case study for electricity generation from woody biomass is used to evaluate the performance of the proposed approach.

2. Methodology

The objective of the proposed methodology is to find process alternatives that can transform biomass feedstock into electricity or a value-added substance given the properties of the biomass material such as ultimate analysis and product requirements such as the amount of desired electricity.
In the first stage a matchmaking approach is carried out to screen for chemical or biological conversion technologies from a given set of product specifications and product requirements.
In the second stage, biomass unit modeling and design methodologies have been developed and incorporated within a synthesis algorithm implemented in the Jacaranda object-oriented framework for automated design.

2.1. Matchmaking

In this stage, software agents use process specific knowledge to propose possible processing technologies to the decision maker. A software agent is a software entity that functions continuously and autonomously in a particular environment where agents can cooperate and communicate [3]. The matchmaking architecture is made up of a number of software agents. The system architecture is shown in Figure 1.

An agent that provides main chemical or biological processing services such as gasification, anaerobic digestion, etc. may also function as a broker to find additional processing services needed downstream or upstream to satisfy the requirements. The decision maker specifies feedstock and product requirements using the process requester (PR). Then the PR submits this information to process agents (PAs). In order for the PR to find process agents, PAs advertise their services with the Directory Facilitator who manages the yellow pages of all the agents of the environment. The prototype was programmed in Java using the JADE library for distributed agent applications and the JTP inference system [4].

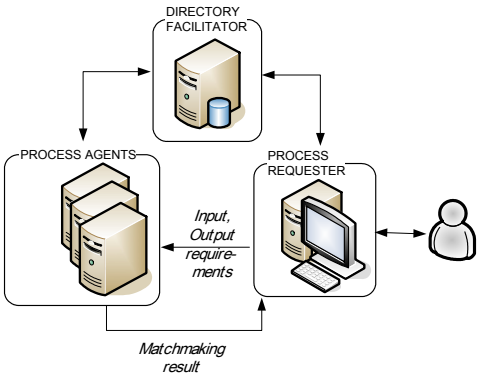

Figure 1 System architecture of the matchmaking

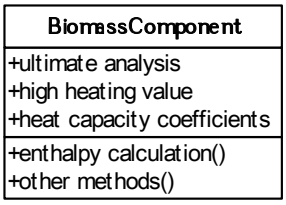

Figure 2. Data structure for the biomass component

2.1.1. Process synthesis

Biomass unit models and their design methodologies have been developed to be used by the synthesis algorithm implemented in the Jacaranda object-oriented framework for automated design [5]. Jacaranda is based on an implicit enumeration algorithm that generates the best *n* flowsheet alternatives for a number of criteria, providing the necessary insight to modify or adapt the synthesis problem for further refinement [6]. Jacaranda is implemented in Java and it is easy to extend and add new capabilities. Because of the distinctive characteristics of biomass substances and processing technologies, new classes were added for physical properties, biomass solid streams and models of processing technologies.

3. Physical properties

Due to the heterogeneous nature of biomass and the broad variability in chemical composition, a generic albeit representative set of thermophysical properties is needed. In order to evaluate mass and energy balances, a biomass

component data structure is used to accommodate information about the ultimate analysis, the high heating value, heat capacity and proximate analysis (Figure 2).
The ultimate analysis provides the elemental composition in terms of carbon, hydrogen, nitrogen, chlorine, oxygen, sulfur obtained from laboratory analysis of the gases that result after complete combustion. A representative chemical formula (pseudo-formula) of the biomass is obtained from these values.
The high heating value (HHV) is the combustion energy when water vapor is condensed. HHV is necessary as an estimation of the biomass formation enthalpy. Experimental values of HHV are available from the literature and from online databases. However, in the absence of data HHV can be estimated from the ultimate analysis data using well-known correlations.
The proximate analysis reports volatile matter, fixed carbon, moisture content, and ash present in a fuel as a percentage of dry fuel weight. Fixed carbon is the solid residue other than ash obtained by prescribed methods of heating a biomass sample.
Moisture content is the amount of water in the feedstock. This amount of water is modeled as a water liquid phase. Biomass is modeled as a stream containing solid and liquid phases with at least one biomass component.

4. Modeling

A number of models have been developed including a dryer model, an air-based gasifier, a steam-driven gasifier, compressor, combustor, gas turbine and an anaerobic digester model. These are lumped-parameter models based on the literature and first-principles. In all cases where chemical reactions are present, chemical equilibrium was assumed. The models were validated by comparing the predicted values of gas composition and generated electricity against those in the Batelle gasifier [7]. Some of these models are described below.

4.1. Gasifiers

Models were developed for air-gasification (air as a reaction agent) and for steam-gasification extending the model in [8]. Four reaction zones can be distinguished in any gasifier, namely drying, pyrolysis, reduction, and oxidation. In the drying zone, biomass is heated and consequently water evaporates. In the pyrolysis zone, biomass decomposes into hydrocarbons, gas products and char. Char further reacts with gases in the oxidation zone. The overall reaction assuming that the gasification agent is either air or steam can be represented as

$$CH_aO_b + wH_2O_{(g)} + sH_2O_{(l)} + mO + nN_2 \leftrightarrows x_1H_2 + x_2CO + x_3CO + x_4H_2O_{(g)} + x_5CH_4 \quad (1)$$

Mass and energy balances are formulated in terms of the equilibrium relations for the reduction and oxidation reactions, the stoichiometric relations derived from (1), and the respective enthalpies and Gibbs energies. The high heating value is used as formation enthalpy of the biomass molecule.

4.2. Gas turbine

Fuel gases from the gasification process can be combusted in a gas turbine. Gas turbines are modeled as a combination of compressor, combustor, turbine, and generator. Shaft work and energy consumption are calculated assuming isentropic changes and specified thermodynamic efficiencies. Electric efficiencies are used in the electricity generation.

5. Economics

The process synthesis is guided by optimization criteria based on capital cost evaluations of the unit designs. Costs of individual units depend on the size of the equipment and are calculated by scaling from known correlations and data in literature. Specifically, the cost of the gasifiers was obtained using the volume and cost information of the Battelle gasifier using the scaling factors of a reactor found in [9].

6. Case study

This case study evaluates the alternatives for generating more than 6 MW of electricity out of woody biomass (20% of moisture) with an ultimate analysis consisting of carbon (50.88 %w), hydrogen (6.04 %w), nitrogen (0.17 %w), oxygen (41.9 %w), ash (0.92 %w) and a HHV of 474008.72 kJ/kmol. In preparation of studying CO_2 sequestration for green-house reduction the amount of CO_2 in each alternative is also evaluated. This data was obtained from [10] for the Battelle gasifier. The first step is to identify those processes that meet these requirements before the process synthesis. The matchmaking agents suggest the use of fluidized-bed gasifiers in which case no drying is necessary or the use of an updraft gasifier with dryer.

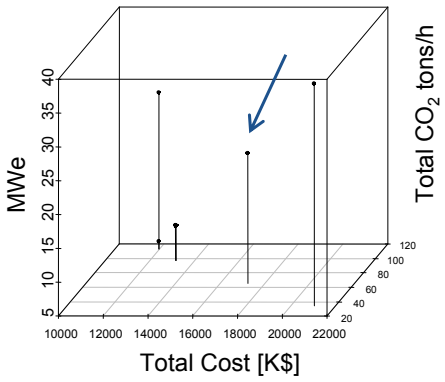

Figure 3. Process design alternatives

The synthesis produces a number of alternatives which are shown graphically in Figure 3. It can be seen that best multi-criteria solutions can be obtained around

the alternative pointed by the arrow which corresponds to a flowsheet with a dryer, steam-based gasifier and gas turbine. This alternative can produce around 24 MW with a capital cost of 17 M$. A comparison against the other alternatives suggests that steam is preferred over air and that the design is particularly sensitive to the steam/biomass ratio, as well as the pressure ratios in the compressor and turbine. The electricity compares in magnitude against that of the FERCO gasifier (31 MW). The gas compositions are similar although the models under-predicts methane and over predicts the conversion into carbon monoxide which can be understood for the equilibrium assumptions regarding the pyrolysis reactions.

7. Conclusions

This paper discussed an approach for designing a biomass conversion processes using a combination of cognitive agents and process synthesis. More work is required for the design of biological processes such as fermentation and anaerobic digestion. Ongoing work in the context of multi-criteria design includes the development of models for absorption processes (e.g. Selexol) that will be incorporated in the model library.

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