ENERGY INTEGRATION OF CELLULOSE HYDROLYSIS REACTORS AND CHP SYSTEMS

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ABSTRACT

Plant biomass is composed mainly of cellulose, hemi-cellulose and lignin. Production of glucose through hydrolysis from these raw materials is of interest because it can be used as starting point in the production of chemicals, materials and bio-fuels. Cellulose hydrolysis can be performed in supercritical water with a high selectivity of soluble sugars. This reaction yield can be achieved using a continuous reactor with instantaneous heating and cooling methods that allow the precise control of the residence time. Operation can be carried out by adding a stream of supercritical water to the cellulose stream and by cooling the reactor outlet by sudden decompression. With this technology it is possible to greatly decrease the temperature in a fraction of a second. The process produces a high pressure steam that can be integrated, from an energy point of view, with the global biomass treating process. This work investigate the integration of cellulose hydrolysis reactors with commercial Combined Heat and Power (CHP) schemes, with special attention to reactor outlet streams. Temperature of the flue gases from CHP around 500 ºC and the use of direct shaft work in the process offer adequate energy integration possibilities for feed preheating and compression. The wide range of commercially available GT sizes allows widespread process scaling.

INTRODUCTION

The annual biomass growth on the continents is estimated to be 10,000 dry tons·ha^{-1} [1]. Taking into account the crude oil production and the energy equivalence between biomass and oil (2.5 times higher than oil), less than 10% of the annual growth of vegetal biomass is needed to replace the petroleum production. Biomass is composed of 34-50% cellulose, 16-34% hemi-cellulose and 11-29% of lignin. Cellulose hydrolysis can be performed in supercritical water with a selectivity of soluble sugars as high as 98% w/w [2]. This reaction yield can be achieved using a continuous reactor with instantaneous heating and cooling methods that allow the precise control of the residence time [3]. Operation can be carried out by mixing the cellulose steam with supercritical water and by cooling the reactor outlet by sudden decompression of the stream [2,3]. Proceeding in this way it is possible to decrease the temperature from 400ºC to 100ºC in a fraction of a second. The use of supercritical water requires high pressures and temperatures. Water as a liquid, can be compressed using a pump with affordable costs. It is necessary to supply heat of high quality (≈ 400ºC) in order to the hydrolysis to proceed. For this reason it is necessary to work out reasonable solutions which are able to solve this part of the process with an affordable efficiency.

ENERGY INTEGRATION

A possible solution would be the integration of supercritical processes with energy production in CHP cycles, where the engine or prime mover produces shaft work that can be used to generate primary electrical power whereas thermal energy in the exhaust gases is converted into steam in the heat recovery boiler [4] or could be used to directly preheat process streams. Nowadays, CHP processes are frequently implemented using gas turbines, being natural gas the most extended fuel. Energy recovering in this kind of turbines present good flexibility and high efficiency, use compact engines, lower manpower operating needs and ready availability [5]. Also, the gas turbine is further recognized for its better environmental performance manifested in curbing of air pollution and reducing the greenhouse effect [7]. Over the last two decades, the gas turbine has seen tremendous development and market expansion, claiming approximately forty percent of new capacity additions [8]. As mentioned above, the biomass hydrolysis process at supercritical conditions produces a high pressure steam. This stream can be thermally integrated if there is a necessity of heat in other parts of the global process. If there are no other heat requirements, it is possible to implement a mixing of the stream into the gas turbine flue gas path, which will improve the shaft work production of the engine. This mechanism links the process of cellulose hydrolysis with the CHP process. Steam employ in gas turbines is a technique which can increase the ability of a plant to generate extra power without burning extra fuel and requiring moderate capital investment. Furthermore a decrease in NO_x emissions from the gas turbine is produced and also the electric generation efficiency of the simple and regenerative cycles is improved [9], if the global efficiency of the process is taken referred. Steam Injected Gas Turbines (STIG) systems operate as an enhancement to the Brayton cycle. High quality steam (35 bar) is used to increase the power output and improve operating efficiency of the basic Brayton cycle. In general, the amount of steam injected can vary at a rate of between 2% and 10 % related to the compressed air [8]. The site at which this steam is injected differs according to the design of the particular gas turbine; however, mainly, high pressure steam is injected into the high-pressure sections of the gas turbine via the combustor fuel nozzles [8]. In its most basic form, steam injection works by increasing general mass flow through the gas turbine without increasing the mass of air compressed. This increase in the expanded mass flow generates an increase in the rotational torque and power output. Steam injection technology offers a clear improvement over the Brayton cycle while providing a fully flexible operating cycle. For all these reasons it has been selected to be implemented in the process of hydrolysis. As a consequence of the extended and frequent use of these procedures, equipment vendors often offer steam injection as an option or as extra equipment for transformation of non-injected GT. The wide range of commercially and readily available GT sizes enables process scaling. Apart the production of electricity, normally employed for in house consumption, high outlet temperature of GT flue gases –around 500 ºC– and use of direct shaft work offer diverse energy integration possibilities, e.g., feed preheating and compression for the reactor unit, or steam generation at various levels up to 80-100 bar, among other possibilities.

METHODS - ASPEN simulation of biomass hydrolysis plant

Nowadays, the biomass hydrolysis under hydrothermal conditions is starting to be applied in an industrial scale. Energy integration of processes is greatly influenced for the specific process flow diagram and layout of the plant. Process throughput, dimensions and type of utilities, location, waste treatment costs and various other considerations can lead to very different energy integration schemes even for similar processes, so the convenience and profitability of a hydrolysis unit integration can not be accurately assessed but for a specific process. For the preliminary, general study carried out in the present work, calculations for three different scenarios using the AspenTech Aspen Plus® simulation software were performed. Two alternatives deal with the integration of the hydrolysis process to a process of electrical energy production using a gas turbine with or without steam injection. The other alternative was supposed to be fossil fuels independent, using a biomass burner to obtain the heat requirements. The GT was modeled as different compression, combustion chamber and expansion units, characterized by regular, conservative efficiencies. For the simulations, Peng-Robinson property package has been selected. It has been necessary to introduce the interaction parameter between glucose and water, which constitute the main raw materials in the simulation. This parameter was experimentally analyzed and calculated by Abderafi et al [10,11] at 1 bar of pressure and temperatures between 100 and 113 ºC. The vapor-liquid equilibrium of system glucose-water should be measured at the range of 1.5 MPa to 3.5 MPa in order to obtain the accurate interaction parameters of glucose and water. The three analyzed options are: (1) Hydrolysis + Gas Turbine + Vapor injection; (2) Hydrolysis + Gas turbine and; (3) Hydrolysis + Biomass Burner. When gas turbine was used in the process, the flows have been adjusted to similar values than used in commercial gas turbines (e.g. SGT-100).

RESULTS

The gas turbine + steam injection setup consumes 73 tons$\cdot h^{-1}$ of air, 1.23 tons$\cdot h^{-1}$ of natural gas and 13.68 tons$\cdot h^{-1}$ of water. The process produces 520 kg$\cdot h^{-1}$ of sugars (from cellulose hydrolysis) with a concentration of 35% $w\cdot w^{-1}$ and 8.9 tons$\cdot h^{-1}$ of available steam at 245ºC and 3.5 MPa. In addition, the gas turbine produces 5.15 MW of work. The gas turbine without injection setup consumes 73 tons$\cdot h^{-1}$ of air, 1.1 tons$\cdot h^{-1}$ of natural gas and 12.6 tons$\cdot h^{-1}$ of water. The process produces 480 kg$\cdot h^{-1}$ of sugars (from cellulose hydrolysis) with a concentration of 37% $w\cdot w^{-1}$ and 11.8 tons$\cdot h^{-1}$ of available steam at 245ºC and 3.5 MPa. In addition, the gas turbine produces 4 MW of work. About the flash unit, the relationship between the outlet stream of liquid and the outlet stream of vapor in the flash is L/V = 0.1. The liquid stream has a mass concentration of glucose of 37% $w\cdot w.^{-1}$ In this stream it is recovered the 91.5 % $w\cdot w^{-1}$ of the glucose fed to the flash. The biomass burner setup consumes 1.66 Gcal$\cdot h^{-1}$ of burnable biomass (the mass of required biomass will depend on the heat capacity and humidity of the biomass) and 3.6 tons$\cdot h^{-1}$ of water. The process produces 137 kg$\cdot h^{-1}$ of sugars (from cellulose hydrolysis) with a concentration of 37% $w\cdot w^{-1}$ and 3.3 tons$\cdot h^{-1}$ of available steam at 245ºC and 3.5 MPa. In this case there is not production of work. Table 1 summarizes these results.

Process	**Work requirement / kg of product ($kW\cdot kg^{-1}$)**	**Work production / kg of product ($kW\cdot kg^{-1}$)**	**Work balance / kg of product ($kW\cdot kg^{-1}$)**
Gas turbine & steam injection	20.60	30.44	9.84
Gas turbine no steam injection	22.46	29.50	7.05

Table 1. Work comparative of the three simulated alternatives.

CONCLUSIONS

The integration of cellulose hydrolysis in supercritical water with the electrical power generation by gas turbines with steam injection showed to be a promising alternative for the production of sugars from a renewable raw material, using compacts equipment and energetically efficient processes. In this work, it was thermodynamically calculated that cellulose hydrolysis could be done selectively (98% $w \cdot w^{-1}$) without any energy demand if the process is linked to a gas turbine with steam injection. In addition the production of work by a gas turbine is enhanced (≈10%) by injecting the steam produced in the process of cellulose hydrolysis. In addition, the use of a flash chamber after the reactor allows the concentration of the products from 0.04% $w \cdot w^{-1}$ to 0.37% $w \cdot w^{-1}$.

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