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Aspen Plus simulation of biomass integrated gasification combined cycle systems at corn ethanol plants

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ABSTRACT

Biomass integrated gasification combined cycle (BIGCC) systems and natural gas combined cycle (NGCC) systems are employed to provide heat and electricity to a 0.19 $hm^3\ y^{-1}$ (50 million gallon per year) corn ethanol plant using different fuels (syrup and corn stover, corn stover alone, and natural gas). Aspen Plus simulations of BIGCC/NGCC systems are performed to study effects of different fuels, gas turbine compression pressure, dryers (steam tube or superheated steam) for biomass fuels and ethanol co-products, and steam tube dryer exhaust treatment methods. The goal is to maximize electricity generation while meeting process heat needs of the plant. At fuel input rates of 110 MW, BIGCC systems with steam tube dryers provide 20–25 MW of power to the grid with system thermal efficiencies (net power generated plus process heat rate divided by fuel input rate) of 69–74%. NGCC systems with steam tube dryers provide 26–30 MW of power to the grid with system thermal efficiencies of 74–78%. BIGCC systems with superheated steam dryers provide 20–22 MW of power to the grid with system thermal efficiencies of 53–56%. The life-cycle greenhouse gas (GHG) emission reduction for conventional corn ethanol compared to gasoline is 39% for process heat with natural gas (grid electricity), 117% for BIGCC with syrup and corn stover fuel, 124% for BIGCC with corn stover fuel, and 93% for NGCC with natural gas fuel. These GHG emission estimates do not include indirect land use change effects.

1. Introduction

Process energy in the form of heat and electricity is the largest energy input to the corn ethanol production process [1]. The most common fuel used to provide process heat is natural gas, although some plants burn coal [2]. Electricity purchased by ethanol plants is often generated with coal. Analyses of second generation, cellulosic biofuels suggest improved energy balances and reduced greenhouse gas (GHG) emissions compared to corn ethanol [3]. Some of the technologies proposed for the production of cellulosic biofuels can also be applied to the current corn ethanol production process, specifically the production of heat and power from biomass, an alternative renewable source of energy for ethanol plants. Dry-grind corn ethanol plants produce biomass co-products that contain a significant amount of energy when used as a fuel. These corn ethanol plants are usually located in corn growing areas where corn stover could be available for fuel.

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Biomass powered dry-grind fuel ethanol plants could generate the electricity they need for their own use as well as electricity to sell to the grid. The use of biomass replaces a large amount of fossil fuel input with a renewable source, which will significantly improve the renewable energy balance for dry-grind corn ethanol [4,5].

De Kam et al. [6] used Aspen Plus simulation modeling to study several technology options using biomass to produce heat and power at dry-grind fuel ethanol plants. They showed significant improvements in the renewable energy balance by using biomass fuels with increasing improvements as the amount of electricity produced increased. Their results suggested that even greater amounts of electricity could be produced while satisfying the process heat needs if biomass integrated gasification combined cycle (BIGCC) technology were applied. BIGCC has been extensively studied for producing both heat and electricity using wood chips and herbaceous biomass materials [7–9]. De Kam et al. [10] developed a BIGCC model for steam gasification of corn cobs and syrup at dry-grind ethanol plants. Another study evaluated corn stover fired BIGCC systems using air and steam as the gasifying agent [11]. Because syngas produced with pure steam as a gasifying agent has a larger heating value per unit of gas than gas produced using air and steam, the performance of BIGCC systems using steam gasification is evaluated in this paper following the initial work of De Kam et al. [10]. This paper focuses on corn stover and a mixture of corn stover and syrup fuels as well as the impact of alternative drying processes and configurations at the ethanol plant on the overall BIGCC system performance.

The objectives of this study are to:

1) develop Aspen Plus simulation models for integrating combined cycle systems fueled with biomass or natural gas at a 0.19 $hm^3\ y^{-1}$ (50 million gallon per year) dry-grind corn ethanol plant with the goal of maximizing electricity generation while meeting process heat needs of the plant;
2) study the overall system performance for three different fuel combinations (syrup and corn stover, corn stover alone, and natural gas), two levels of syngas compression for the gas turbine (1 MPa with 2-stage compression and 2 MPa with 3-stage compression), two different dryer technologies (steam tube dryer and superheated steam dryer), and three different steam tube dryer exhaust treatment methods (sending exhaust to combustor, sending exhaust to gas turbine, and sending exhaust to a duct-burner); and
3) evaluate potential reductions in life-cycle greenhouse gas emissions for corn ethanol due to integration of BIGCC, and natural gas combined cycle (NGCC) systems at corn ethanol plants.

2. Methodology

2.1. System overview

We developed a model of a 0.19 $hm^3\ y^{-1}$ (50 million gallon per year) dry-grind corn ethanol plant that uses biomass to produce process heat and generate electricity. The process heat is used for the ethanol production process including co-product drying, and for fuel drying when the fuel used is a mixture of corn stover and syrup. Some of the electricity generated is used by the plant with the excess power sent to the grid. The goal is to evaluate alternatives that maximize power sent to the grid.

The ethanol part of the process is based on an Aspen Plus model of a dry-grind plant obtained from the USDA Agricultural Research Service [12–14]. Our modeling adds biomass gasification and combustion to produce syngas following the approach of De Kam et al. [10]. It includes syngas cleanup prior to the gas turbine as well as stack gas treatment. The power generation model is based on a combined cycle gas turbine and steam turbine. The biomass gasification/combustion and power generation comprise the power island at the biomass fueled ethanol plant.

A conventional dry-grind ethanol plant uses a direct-fired natural gas dryer for co-product drying. A thermal oxidizer destroys volatile organic compounds (VOCs) in the dryer exhaust air. To accommodate biomass fuels, either a steam tube dryer or a superheated steam dryer is substituted for the direct-fired dryer. In the case of the steam tube dryer, dryer exhaust is directed to the twin fluidized bed combustor, the gas turbine, or a duct-burner following the gas turbine to destroy VOCs. In the case of the superheated steam dryer, water vapor removed from the product is collected in the superheated steam. A portion of the superheated steam is removed and condensed to reduce energy use and recover water. Aspen Plus models are developed for both of these drying systems. Schematic diagrams illustrating the overall configuration of the BIGCC systems with syrup and corn stover as fuel are shown for the steam tube drying and the superheated steam drying systems in Figs. 1 and 2, respectively. The steam tube dryer schematic (Fig. 1) shows the configuration where ambient air is preheated in a heat exchanger using stack exhaust then mixed with dryer exhaust prior to the inlet of the gas turbine.

2.2. Aspen Plus model

The implementation of various components of the BIGCC systems in Aspen Plus 2006 software (AspenTech, http://www.aspentech.com) is detailed below. The Aspen Plus model of the NGCC system is similar to that of the BIGCC model. The key difference is that the NGCC model does not include a twin fluidized bed gasification/combustion system.

2.2.1. Biomass fuels

De Kam et al. [10] modeled syrup and corn cobs as fuel in their BIGCC model. Syrup is the solubles portion of the dried distillers grains with solubles (DDGS). However, the amount of corn cobs is limited, so we studied the other biomass fuel sources — syrup and corn stover, and corn stover alone — along with natural gas for comparison purposes. For the use of corn stover alone as fuel, there is no need to dry it, since the moisture content of corn stover received is about 13%. When the fuel is a mixture of syrup and corn stover, it needs to be dried before being sent to the gasifier since the moisture content is approximately 43%. Because we need to dry the fuel