ALFALFA STEM FEEDSTOCK FOR IGCC POWER SYSTEM FUEL

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ABSTRACT: A feasibility study was completed for an integrated gasification combined cycle (IGCC) electric power generation plant to operate in conjunction with an alfalfa processing plant that provides the gasification feedstock and a mid-level protein animal feed co-product. Alfalfa stem material was evaluated as a gasification feedstock. The leaf material was evaluated as a mid-level protein animal feed supplement. The alfalfa leaf-stem separation and power generation operations have dual and/or synergistic functions which contribute to a technically and economically compatible combination.

The pressurized biomass gasification process selected is the IGT RENUGAS™ system licensed to Tampella Power Corp. Adaptation of the air-blown gasification process to alfalfa stems results in low-Btu fuel gas suitable for combustion turbines. The gasification process is expected to obtain very high carbon conversion with low tar production, overcome ash agglomeration, and provide for control of volatile alkali species. A hot gas clean-up system removes particulate matter with a ceramic filter system. The collected ash residues are expected to be returned to the land that grew the alfalfa.

The physical and chemical properties of the alfalfa feedstock were evaluated for the gasification process. The alfalfa char carbon-steam reaction, which is the slowest step in the complete conversion of biomass to gases, was measured and the char proved to have a high reactivity. Ash components were measured and evaluated in terms of agglomeration within the gasifier. Using this information, the alfalfa gasification conditions were predicted. A subsequent preliminary gasification test confirmed the alfalfa gasification conditions. To complete the engineering design of the IGCC system, additional testing is required, but the results to date are positive for a successfull process.

INTRODUCTION: In response to a solicitation by USDOE, through the National Renewable Energy Laboratory (NREL), with co-sponsorship by the Electric Power Research Institute (EPRI), Northern States Power Company (NSP) formed a team with the University of Minnesota, The Institute of Gas Technology, Tampella Power Corp.and Westinghouse Electric Corp. to perform a feasibility study of alfalfa crop production coupled to a gasifier/hot gas clean-up/gas turbine/steam turbine power generation system. Figure 1 presents a block diagram of the combined electrical power and alfalfa co-product concept. In accordance with the solicitation by NREL, the study investigated economic development through biomass systems integration, and emphasized: 1) sustainable biomass energy crop production, 2) efficient power generation, and 3) co-product value from alfalfa-leaf meal.

This system concept uses alfalfa from a dedicated feedstock supply system (DFSS); namely, biomass material planted specifically for an energy production facility. The proposed cropping plan involves planting alfalfa in a seven year cycle with 4 years of alfalfa followed by 2 years of corn and one year of soybeans. This seven year rotation is in contrast to the often used current rotation system of corn and soybeans being continously alternated. Alfalfa is a crop that can be grown on a long term basis by a group of farmers with coordination through a closed-end cooperative arrangement (i.e., membership is offered only to producers). The co-op carries on a value added processing and marketing function for the farmer.

Alfalfa provides real benefits for other agricultural crops in the rotation and the land. These benefits result from the inclusion of a perennial (nitrogen-fixing) legume in the crop rotation. The need for external inputs of fertilizers, fossil fuels, herbicides and insecticides are reduced while distinct environmental benefits including reduced soil erosion, improved soil tilth, increased soil organic matter levels, and reduced potential for nitrate leaching are realized. Alfalfa was chosen as a feedstock because it has been sucessfully grown in NSP's service territory including the region surrounding the plant site of the feasibility study, NSP's Minnesota Valley Generating Plant at Granite Falls, MN. Additional acreage of the crop would enhance the regions ability to continue progress towards achieving a sustainable agricultural (i.e., preservation of long term productivity and no adverse environmental impact). The knowledge base, expertise and production capability for producing the crop is well established in the region.

ALFALFA FRACTIONATING PROCESS: The alfalfa fractionating (separating) plant diagram shown in Figure 2 receives sun-cured alfalfa in a conventional round bale package; reduces the particle size of the alfalfa material; dries it to a suitable moisture content for fractionation, storage or further processing. A dual air path (radially and axially) hammermill separates the leaf from the stem material. The separation of leaf from stem enhances the quality of the stem material as fuel, because the leaf fraction has the higher proportion of ash, fuel bound nitrogen and sulfur. Also, the stem material after fractionation has lower particle-to-particle friction and a higher bulk density than a mixture of the two fractions. The leaf fraction benefits from separation because the resulting crude protein concentration is raised, and the subsequent power for pelletizing is reduced as a result of the removal of the fibrous stems. Gas turbine exhaust heat can be used to assist in drying the incoming alfalfa. Low grade steam from the power cycle can be used to roast the leaf fraction to improve the digestibility and value of the crude protein.

ALFALFA FEEDSTOCK PROPERTIES: The alfalfa stem feedstock was analyzed chemically and physically. The analyses were compared with similar biomass feedstocks, namely bagasse and wood chips that have been successfully gasified in the RENUGAS™ fluidized-bed gasifier. The initial results were positive. The alfalfa stem feedstock is expected to be as good as the bagasse feedstock, in terms of gasification operating conditions and feed handling operations.

Important physical properties of alfalfa include its particle shape, particle size distribution, and bulk density. Handling characteristics relate to biomass particle-to-particle friction and biomass particle-to-wall friction factors that are important in solids handling considerations. Tests showed that sized and dried alfalfa should handle and feed well.

Also included with the physical properties is an assessment of the tendency of the ash constituents to combine and form agglomerates within the gasifier or in downstream equipment. Alkali elements such as potassium and sodium can combine with silica to form agglomerates in the gasifier. Unlike woody biomass feedstocks, which tend not to form agglomerates, alfalfa contains amounts of potassium, sodium, and silica that may form a eutectic mixture with a melting point near the expected gasification temperature. Furthermore, alkali compounds may exit the gasifier with the product gases as aerosols. These could potentially pass through the barrier filter and eventually deposit on the blades of the combustion turbine.

The important chemical properties of alfalfa include its moisture level, ultimate analysis, calorific value, and the elemental composition of the ash. Another chemical property important for gasification is char reactivity with steam. Reactivity of the biomass char carbon with steam is a measure of the slowest reaction step in the complete conversion of biomass into gases. After the very rapid devolatilization step, about 5% to 15% of the initial biomass weight remains as char carbon. The char carbon reacts with steam in the gasifier to complete the gasification process forming additional carbon monoxide and hydrogen. The rate of this reaction determines the char residence time in the fluidized bed, hence, is related to the size of the gasifier. Figure 3 shows the measured char reactivity or the steam-char gasification rate for the char of alfalfa stems compared to chars measured previously from a similar agricultural residue, namely, corn stover, and a silvicultural residue, maple wood chips. Also shown in comparison to the three biomass species are the slower char gasification rates measured for peat and bituminous coal. The base carbon entity plotted in the figure is the weight of char carbon that remains after completion of the rapid devolatilization step minus the weight of the ash in the material.

The char reactivity measurements were made in a pressurized thermobalance operating at expected gasification conditions of 1600°F and 300 psig. The composition of the gas in the thermobalance was representative of the gasifier product gas with respect to steam and hydrogen: namely, 45% steam, 5% hydrogen, and 50% nitrogen. Hydrogen is a product of the steam-char reaction, thus the design char gasification rate is measured under similar hydrogen concentration.

As seen in the Figure 3, the alfalfa char reacted at essentially the same rate as the corn stover and the maple chars under similar conditions. Therefore, it is expected that the alfalfa char should gasify at least at the same rate as char from wood chips that have been successfully gasified. In terms of the process design, the alfalfa throughput rate over the same cross-sectional area of the gasifier should be at least equal to that of the maple wood chips, which have been extensively tested in the PDU.

ALFALFA EVALUATION RESULTS: The moisture, ultimate analysis, and heating value results for the alfalfa feedstock are presented in Table 1 for samples of alfalfa obtained from three counties with different soil classifications surrounding the Granite Falls plant site. The alfalfa samples received were separated into stem and leaf fractions and were analyzed individually. The alfalfa stems are intended to be the gasification feedstock. The leaves are to be separated and processed into value-added leaf meal products, although the gasifier system does not preclude the leaves being sent to the gasifier along with the stem material.

The alfalfa compositions shown in Table 1 are within the expected range of most biomass feedstocks considered for gasification. The major distinctions seen in Table 1 are that the leaf fraction has more ash and also a higher nitrogen content than the stems. The higher nitrogen content of the leaves is related to the animal protein feed value. If the leaf fraction is to be gasified along with the stems, then the higher ash and fuel-bound nitrogen levels have to be considered in the design of the plant.

Table 2 presents the ash analyses of the stem and leaf fractions of alfalfa from the three county samples. The leaf fraction is up to 47 wt % of the dried alfalfa plant. The amounts of potassium, sodium, and silicon are important. These elements can combine to form a eutectic that have a melting temperature below the normal gasification temperature. Possible combinations of the oxides of these elements are well known in coal combustion systems and in iron-making. The presence of these species is a concern in combustion boilers with an oxidizing atmosphere which favors the formation of agglomerates that foul the boiler internals. There is a concern that even at lower temperatures and in the reducing atmosphere of a fluidized-bed gasifier these agglomerates may form.

A coal agglomeration test used at IGT was modified for biomass agglomeration to assess the degree of agglomeration under non-oxidizing conditions (the IGT boat test). The general test procedure involves reducing the size of the biomass to 200 mesh and then pyrolyzing the mass in a 3/8-inch by 3-inch ceramic boat under nitrogen at 1800°F followed by cooling under nitrogen to room temperature. The residue is then evaluated in terms of agglomeration strength. The mass of biomass char carbon and ash that remains in the boat after cooling is described in terms of varying degrees of agglomeration ranging from a very strong adhesive mass to completely free-flowing particles.

The boat test conducted with the alfalfa stems alone showed a very weakly agglomerated mass of char and ash. Just the weight of a pencil point could break up the mass and it also could not be extracted intact from the boat. It was weakly held together by the adhesion due to some tar pyrolysis products and ash components. The bagasse feedstock that was successfully gasified in the RENUGAS process development unit (PDU) at IGT showed a more strongly agglomerated mass in the boat test compared to the alfalfa. However, the subsequent PDU bagasse gasification test at 1600°F (871°C) did not show any evidence of agglomeration with the agitation and mixing with the inert material in the fluidized-bed gasifier. Bagasse, however, is washed of most of the potassium and sodium elements in the sugaring process, so a precaution is recommended for initial alfalfa gasification tests.

One possibility for preventing agglomeration in the gasifier is to add small amounts of certain additives that contain magnesium, which is known to combine with alkali and prevent the formation of the lower melting temperature agglomerates. Two such additives were tested in the boat tests. These additives were magnesium oxide and a high magnesium carbonate content dolomite. The amount of these materials that were added to the alfalfa was kept to a minimum and was calculated as a one-to-one weight ratio of the amount of potassium that was measured in the ash of the samples, i.e., 4 wt % magnesium oxide and 8 wt % dolomite.

All of the boat tests conducted with these two additives showed that the char-ash residue became completely free flowing, just like dry sand. Hence, if the alfalfa fluidized-bed gasifier is designed to operate with dolomite as the fluidized-bed media, then alfalfa ash agglomeration will be controlled and not a concern. Furthermore, conditions for alkali capture or removal from the product gas stream should be enhanced with the collection of the dolomite fines by the hot gas filter.

BASIC GASIFICATION PROCESS CONDITIONS: The specification of the basic conditions for the air-blown, fluidized-bed gasification process include the gasification temperature and pressure, and to a lesser degree, the acceptable limits for feed moisture and the amount of steam addition to the fluidized bed. The gasification temperature is the most important operating variable in terms of achieving the highest carbon conversion efficiency, namely, conversion of the feed carbon to gases along with the lowest amount of oil and tar species in the product gas. The incoming feed moisture will affect the amount of air needed to maintain a selected gasification temperature. Hence, the heating value of the product gas is affected due to feed moisture and the additional air that is required to maintain the gasification temperature.

Based on data in Figure 3 from the thermobalance test of the alfalfa char gasification rate at pressure and 1600°F, and from the previous gasification test experience in the IGT RENUGAS™ 10 ton per day process development unit (PDU) with the Hawaiian bagasse feedstock at 1580°F, which yielded 96% bagasse feed carbon conversion, it is expected that an alfalfa gasification temperature near 1600°F should yield similar or greater feed carbon conversions.

PDU TESTS WITH ALFALFA: In a concurrent DOE program, the IGT RENUGAS process development unit (PDU) gasifier system was modified to evaluate the hot gas cleanup for the 100 ton per day bagasse demonstration gasifier being built in Hawaii. One alfalfa gasification test was conducted in that program. The alfalfa was successfully reduced in size with a forage harvester with an increase in the bulk density to about 10 lbs per cubic foot and fed smoothly to the PDU gasifier at the rate of 7.7 tons per day for an 8-hour test duration. The entire alfalfa plant was gasified, including the leaves and stems.

The PDU gasifier results showed that the alfalfa carbon conversion to gases and condensible liquids at the 1470°F gasifier temperature was about 98%, and the product gas composition was similar to bagasse gasification. The alfalfa test in the PDU was conducted with about 8 wt % dolomite added with the alfalfa to the fluidized bed of the inert alumina bead material used for alfalfa gasification. However, in this limited test, the test conditions were not optimized for the alfalfa according to the conditions identified in this feasibility study, but overall, the test indicates alfalfa can be successfully gasified. Additional alfalfa gasification performance testing at the PDU or larger scale is needed to obtain detailed engineering design information. Alfalfa exhibits some variation in the amount and type of ash components between the stem and leaf fractions and also between the different growing regions around the proposed plant site. It is expected that these differences will not impact the proposed alfalfa gasification scheme, but this also needs to be evaluated with gasification tests. The gasification of alfalfa stems in a fluidized bed of dolomite is expected to control ash agglomeration tendencies.

Table 1. ALFALFA ANALYSIS: FROM THREE COUNTIES NEAR THE PLANT SITE

County	Olivia		Montevideo		Clarkfield		Average	
Moisture and Ash Analysis, wt %	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
Moisture	9.99	6.65	8.40	6.91	9.73	6.42	9.37	6.66
Ash	5.18	11.01	4.62	7.37	4.69	9.03	4.83	9.14
Ultimate Analysis, wt %								
Ash	5.65	11.43	4.98	7.68	5.14	9.48	5.26	9.53
Carbon	47.15	47.11	47.47	48.22	46.96	47.02	47.19	47.45
Hydrogen	5.84	5.89	5.94	6.10	5.93	5.92	5.90	5.97
Nitrogen	2.14	4.76	2.07	4.80	1.98	4.53	2.06	4.70
Sulfur	0.08	0.29	0.08	0.28	0.08	0.21	0.08	0.26
Oxygen (by diff.)	39.14	30.52	39.46	32.92	39.91	32.84	39.5	32.09
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Higher Heating Value, Btu/lb (dry)	8030	8230	8140	8660	8080	8360	8083	8417

Table 2. ELEMENTAL ASH ANALYSIS OF ALFALFA: THREE COUNTIES NEAR THE PLANT SITE

County	Olivia		Montevideo		Clarkfield		Average	
Ash Element, wt % of Ash	Stems	Leaves	Stems	Leaves	Stems	Leaves	Stems	Leaves
Silicon	0.23	0.56	0.26	0.25	0.80	1.21	0.43	0.67
Aluminum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Titanium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphorus	0.95	0.76	1.84	1.13	1.57	1.93	1.45	1.27
Calcium	5.67	5.77	6.33	11.40	13.80	11.20	8.60	9.46
Magnesium	1.46	1.18	2.09	1.69	1.65	2.29	1.73	1.72
Sodium	0.56	0.49	0.70	0.37	0.32	0.42	0.53	0.43
Potassium	10.50	7.40	12.60	9.59	6.23	10.50	9.78	9.16
Sulfur	0.52	0.50	0.62	1.24	2.04	1.54	1.06	1.09

Figure 1 Power And Co-Product Plant Concept

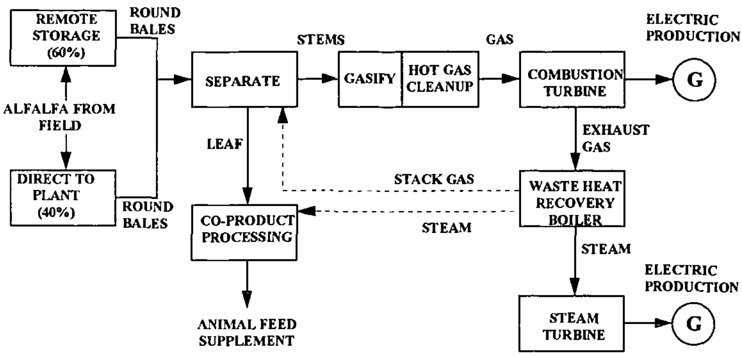

Figure 2 Processing Plant

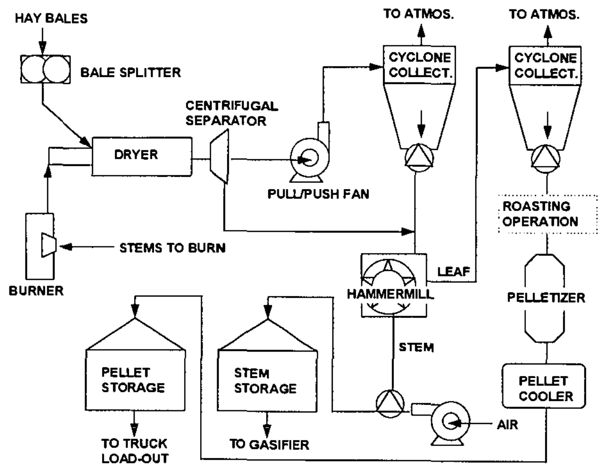

Figure 3. Comparison of Char Gasification Rates