



Technical Paper

ADVANCED BIOMASS GASIFICATION FOR THE PRODUCTION OF BIOPOWER, FUELS, AND CHEMICALS

**Mark A. Paisley, PE
Taylor Biomass Energy**

Presented at



November 5 - 9, 2007

ADVANCED BIOMASS GASIFICATION FOR THE PRODUCTION OF BIOPOWER, FUELS, AND CHEMICALS

*Mark A. Paisley, Taylor Biomass Energy, LLC, 350 Neelytown Road, Montgomery, NY 12549
Phone: (614) 893-7312, Fax: (614) 459-8579, Email: mark.paisley@taylorbiomassenergy.com*

ABSTRACT: Recent price increases for various forms of energy along with projected shortages of supply have resulted in renewed interest in alternative fuels. Biomass gasification provides a renewable basis for supplying not only direct energy products such as gaseous and liquid fuels, and electric power, but also a broad suite of chemicals such as Fischer-Tropsch liquids as well as hydrogen. A medium calorific value (MCV) gas is necessary to achieve the full potential of biomass gasification for fuels, chemicals, and hydrogen production. The Taylor gasification process, being developed by Taylor Biomass Energy is a biomass gasification process that produces a MCV gas. The Taylor gasification process provides improvements over currently available gasification processes by integrating improvements to reduce issues with ash agglomeration and provide in-situ destruction of condensable hydrocarbons (tars), an essential element in gas cleanup. The gas conditioning step integrated into the Taylor Gasification Process provides a unique method to convert the tars into additional synthesis gas and to adjust the composition of the synthesis gas to significantly increase its hydrogen to carbon monoxide ratio. Testing has shown that approximately 90% of the tars can be removed by the gas conditioning step providing a synthesis gas suitable for a variety of applications.

Keywords: gasification, integrated gasification combined cycle, biomass conversion

INTRODUCTION

Biomass resources currently supply over 3 quads to the nation's energy supply and are projected to provide between 17 and 55 quads of the nation's energy needs in the future. A primary benefit of this growth is the potential to increase energy supplies with a renewable, environmentally attractive feedstock. This benefit coupled with the potential to offset recent price increases for various forms of energy and help to impact projected shortages of supply have resulted in renewed interest in alternative fuels from biomass.

Much of the emphasis on biomass supplies has been focused on the production of dedicated biomass crops such as switch grass, woody feedstocks, and other agricultural based materials. To actively pursue commercial scale biomass based systems, however, an adequate, sustainable supply of appropriate biomass material is necessary. Biomass as a fuel source is widely obtainable throughout the United States, but, in many locations, is prohibitively expensive due to transportation costs, seasonality, or local supply issues.

Biomass is an underutilized, renewable resource that can potentially reduce fossil fuel dependency as a part of the primary energy supply. Historically, biomass has merely been used for heating. Today's developing energy technologies are broadening the uses of biomass

well beyond simple combustion for heating. The flexibility of biomass as an input to conversion processes provides the ability to generate a wide range of energy products. These include gaseous products that can substitute directly for natural gas or liquid products such as ethanol or Fischer-Tropsch liquids. In addition other products ranging from fuel gas to steam, electric power, and, through synthesis applications, a suite of chemical intermediates and products, or hydrogen can readily be produced from gasification-generated synthesis gas.

To actively pursue commercial scale biomass based systems, however, an adequate, sustainable supply of appropriate biomass material is necessary. Biomass as a fuel source is widely obtainable throughout the United States, but, in many locations, is prohibitively expensive due to transportation costs, seasonality, or local supply issues.

However, if an appropriate biomass feedstock could be recovered from the abundant, primarily biomass, residues from construction and demolition (C&D) and municipal solid waste (MSW) the resources for available, cost competitive biomass could be greatly expanded and, therefore, the supply of bioproducts derived from this resource. Reasonable supplies of such post-sorted MSW and C&D material with all the non-biomass components removed can be derived from the residual materials discussed above, but conventional approaches to energy recovery from these wastes result in environmental problems due to the inherent properties of the technologies themselves.

A FLEXIBLE CONVERSION TECHNOLOGY

Biomass gasification provides a renewable basis for supplying not only direct energy products such as gaseous and liquid fuels, and electric power, but also a broad suite of chemicals such as Fisher-Tropsch liquids as well as hydrogen. Biomass provides the only non-fossil fuel route for renewable hydrogen production. A number of biomass gasification processes have been developed by the US Department of Energy and as well as foreign industry and governments. However, most of these gasification processes are not well suited for the wide range of applications needed to fully exploit the potential of biomass gasification due to their production of a nitrogen diluted, low calorific value product gas.

A medium calorific value (MCV) gas is necessary to achieve the full potential of biomass gasification for fuels, chemicals, and power production. MCV gas can be used directly as a substitute for natural gas in combustion devices such as boilers or turbines but, unlike LCV gas, has the added advantage of being useful for synthesis applications for the production of liquid fuels or hydrogen as shown in Figure 1.

The Taylor gasification process being developed by Taylor Biomass Energy is a biomass gasification process that produces a MCV gas. MCV gas, unlike the low calorific value gas produced in air blown gasifiers, provides the ability to achieve the goal of a true biomass refinery capable of producing not only a fuel gas or power but a range of other products by using the gas as input to a synthesis reactor.

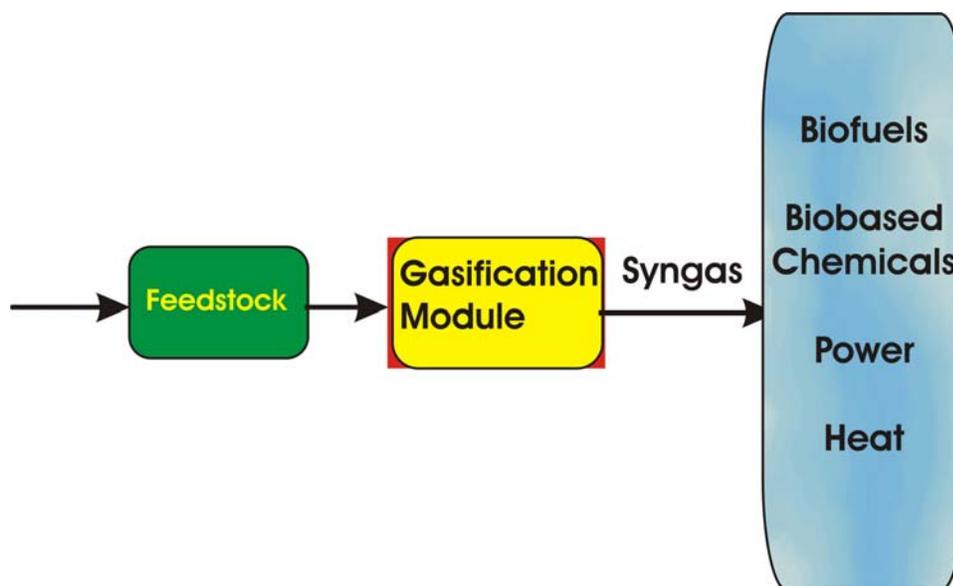


Figure 1. Medium Calorific Value Gas Provides Bioenergy Product Flexibility

BACKGROUND

Of significant concern are supplies of the premium fuels such as natural gas and distillate oil as these fuels both provide environmental advantages to end users as well as convenience for residential use as heating fuels. Importation of both petroleum and natural gas from foreign countries is rapidly increasing. Such imports contribute to the increasing negative balance of trade in the United States. Furthermore, such dependence increases the risk of a foreign nation holding the U.S. hostage as energy security declines.

Biomass provides a means to address these issues when converted in a gasification process, such as the Taylor gasification process, by providing a range of flexible energy products. When a non-nitrogen diluted gas is produced, the options for end use of the synthesis gas greatly expand as illustrated in figure 1 above. The primary emphasis during development of biomass gasification technologies, however, has been toward fuel gas or power. Such emphasis, however, ignores a much broader applicability of the technology.

There are a number of technical issues that must be overcome in order to realize this potential. Many of these issues must also be addressed in order to implement gasification as a part of advanced power systems such as integrated gasification combined cycle (IGCC) cycles. These include, primarily, gas cleanup and conditioning and biomass fuel flexibility. For end use as a synthesis gas, the additional issue of hydrogen content (or the ratio of hydrogen to carbon monoxide in the synthesis gas) must be addressed.

Medium calorific value gas is uniquely suited for use as a synthesis gas for the production of chemicals or hydrogen. By eliminating nitrogen from the synthesis gas, downstream reactor systems to produce these products can approximate their counterparts in petroleum refineries. Even with a medium calorific value gas, the contaminants contained in

the synthesis gas produced, consisting of, primarily, condensable hydrocarbons (tars) must be removed. These materials restrict heat recovery from the gases and can cause fouling of downstream equipment or poisoning of synthesis catalysts. One method for avoiding this problem has been to use the gas hot in a boiler or other similar combustion device. Such end use, however, restricts the potential efficiency of such systems and virtually eliminates both the use of high efficiency power production via gas turbines and the use of the gas for synthesis. Other established methods, used for many years in the gas making industry, use wet scrubbing systems that can remove solid particles, soluble gases, soluble salts, and condensable liquids, to produce high levels of fuel purity. These systems, however, in order to achieve high removal efficiencies, utilize solvents to dissolve the aromatic organics present. This then leads to disadvantages related to disposal of contaminated water. These systems also introduce additional heat losses which can adversely affect overall system efficiencies.

Taylor Biomass Energy has developed an advanced, indirectly heated gasification process that effectively converts the tars in the gas to non-condensable, lower molecular weight species. This removal allows a higher level of the sensible energy contained in the synthesis gas to be recovered while simplifying any secondary conditioning of the gas that might be necessary. By building on the success of other indirectly heated gasification processes, the Taylor Gasification Process provides a means to utilize the broad range of biomass feedstocks that are available while simplifying the process of converting these biomass feedstocks into economically viable energy products.

THE TAYLOR GASIFICATION TECHNOLOGY

The Taylor Gasification Process, being developed by Taylor Biomass Energy is a biomass gasification process that produces a medium calorific value gas having a higher heating value approximately half that of natural gas. This gas, unlike the low heating value gas produced in air blown gasifiers, provides the ability to directly substitute for natural gas or be used as a synthesis gas for the production of ethanol or, alternatively, for the production of power, chemicals, or hydrogen.

Indirectly heated gasification has been demonstrated to be a flexible and reliable method for efficiently producing a medium heating value gas from biomass based feedstocks. A number of technologies have been successfully demonstrated at commercial scale that utilize this type of conversion process. These include the FICFB gasifier in Gussing, Austria; the SilvaGas gasifier in Burlington, VT; the ENSYN pyrolysis process; and the Thermochem process along with other processes at earlier stages of development at various institutions in Europe and China. The Taylor gasification process, with a patent pending, builds upon the results of these technologies. Taylor's process, however, provides improvements in operation by integrating innovative improvements to the technologies to reduce issues with ash agglomeration and in-situ destruction of condensable hydrocarbons, an essential element in gas cleanup and environmental performance of the process. By providing in-situ removal of the condensable hydrocarbons, subsequent gas cleanup is greatly simplified as the gas may be cooled prior to final cleanup thus reducing the size of the cleanup equipment. Such cooling improves overall process efficiency by providing a means to more effectively recover sensible energy in the product gas stream.

In the Taylor Gasifier, a circulating heat carrying material is used to rapidly heat the incoming biomass and convey unconverted materials from the gasification reactor into an associated combustion reactor, as shown in figure 2 below.

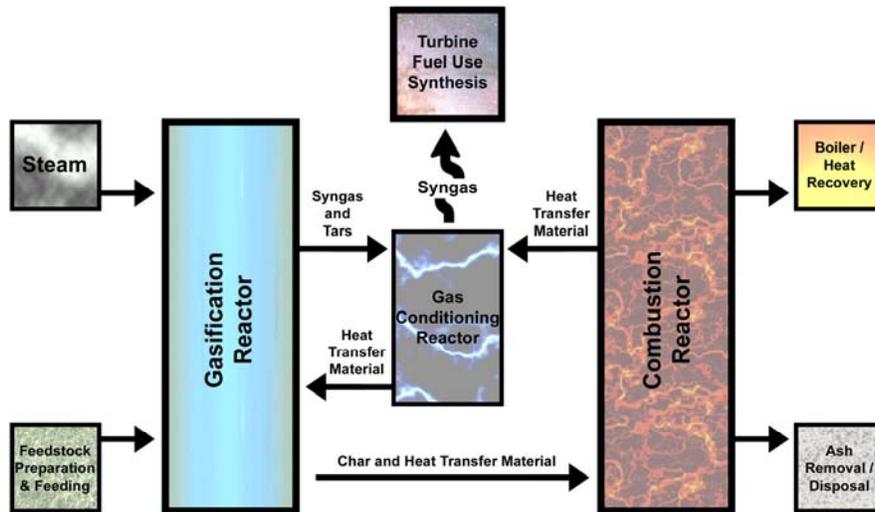


Figure 2. Block Diagram of the Taylor Gasification Process

In the gasifier, biomass is contacted by the heated heat carrying material, and steam. No air or oxygen is added so there are no combustion reactions taking place, providing environmental advantages. The biomass is rapidly (less than one second) converted into medium calorific value gas (14-17 MJ/Nm³) at a temperature of approximately 850C. Any unconverted material along with the cooled heat transfer material, pass through the gasifier and then are separated from the product gas. The product gas continues on to the gas conditioning step prior to any final gas cleanup that might be needed while the solids are conveyed into the process combustion reactor.

In the combustion reactor, air is introduced which consumes the char and, in the process, reheats the sand to approximately 1000C. In the combustion reactor all remaining carbon is consumed, resulting in a carbon-free ash. Due to the combustion conditions and the fact that the unconverted material is essentially carbon, emissions are low from this step in the process. The reheated solids are separated from the flue gas and returned to the gasification reactor. Ash is removed from the flue gas, resulting in a high temperature (1000C), clean gas stream available for heat recovery.

The gas conditioning reactor is the key element of the Taylor Process that provides enhanced gas compositions along with the improved heat recovery potential. Within the gas

conditioning reactor, the product gas contacts the high temperature solids (1000C) providing an optimum environment for steam reforming of the tars. The tars are converted to lower molecular weight compounds that augment the quantity of synthesis gas produced.

The additional residence time provided by the gas conditioning reactor in the presence of a catalytic medium (the hot circulating solids) allows the synthesis gas to reach water gas shift equilibrium. As a result the hydrogen content of the synthesis gas is enhanced compared to other biomass gasification processes as shown in Table 1 below. The steam reforming reactions and the water gas shift reaction are balanced thermally so no cooling of the circulating solids takes place.

Table 1. Comparison of Taylor Syngas Compositions With Other Indirect Gasification Processes

Component, o/v	Taylor	FICFB	SilvaGas [®]
Hydrogen	45-48	37.7	20.7
Carbon Monoxide	15-20	29.1	46
Methane	10-13	10.4	15.6
Ethylene	1-3	2.8	5.3
Carbon Dioxide	18-20	19.6	11.1
Ethane	0-1	0.3	0.7
Nitrogen	trace	0.1	0.6

As an additional benefit, the syngas exits from the process at a higher temperature (1000C) and, because of the significant reduction in condensable materials, can be cooled to a much lower temperature resulting in an increase in heat recovery of nearly 40% when compared to syngas generated by other indirectly heated gasification processes.

DEVELOPMENT OF THE PROCESS

An extensive data base exists on indirectly heated gasification processes. This data was generated by Repotec in Gussing, Austria, by Battelle in Columbus, Ohio, by the National Renewable Energy Laboratory in Golden, Colorado, and by other research laboratories throughout the world. Because of the information and data on both the gasification and combustion reactors in the process contained in this data base, only the performance of the unique gas conditioning reactor had to be investigated by Taylor Biomass. To confirm the performance of this gas conditioning step, a series of tests were conducted at the National Renewable Energy Laboratory in their Thermochemical Users Facility (TCUF).

This unit, while not in the exact configuration of the Taylor gasification process can be used to accurately simulate the process to allow determinations such as those for this study to be conducted. A description of the facility follows:

Thermochemical Process Development Unit

The Thermochemical Process Development Unit (TCPDU) is an integrated system of unit operations designed to investigate biomass thermochemical conversion to gaseous and liquid fuels and chemicals. The individual unit operations were designed to permit multiple equipment configurations. The ability to reconfigure the TCPDU permits operation over a wide range of conditions.

In the process configuration for gasification, the first and primary reactor in the process is an electrically heated 20.3 cm diameter fluidized bed reactor with a 40.6 cm (16") diameter freeboard. Product gas, entrained char, and bed material flow from the reactor through a pipe into a thermal cracker. The thermal cracker ensures that the raw composition of the product gas along with tars and other contaminants is appropriate for the gasification process being examined. Downstream of the thermal cracker are two cyclone separators in series that remove solids from the gas. The gas leaving the cyclones moves quickly into a "full stream tar reformer."

The Full Stream Reformer (FSR) shown in figure 3 below, is an electrically heated, 35.6 cm (14") diameter fluidized bed reactor with a 61 cm (24") diameter freeboard. Process gas from the gasification system is mixed with superheated steam or nitrogen as required and is then heated up to or near bed temperatures in a preheater. The reformed gas exits the FSR via an internal 11.4 cm (4.5") diameter cyclone. Entrained solids from the catalyst bed are collected by the cyclone and returned to the bed through a 4 cm (1.5") diameter dip leg. For this series of experiments, the full stream tar reformer was used to evaluate the Taylor "gas conditioning reactor".

This experimental system is outfitted with extensive analytical measurement devices. These include on-line gas chromatography and a transportable molecular beam mass spectrometer (TMBMS) to provide a continuous measurement of the process performance including concentrations of tar species present before and after the tar cracking operation.

Overview of the TMBMS

The TMBMS was used to provide continuous, real-time chemical analysis of the hot syngas at the inlet and outlet of the full-stream reformer. The hot process gas arrives at the entrance of the instrument by means of a heated sampling system, which will be described below. A molecular beam forms as the gases are extracted through a heated 300- μm critical-flow orifice into a three-stage, differentially pumped vacuum system. The gases then undergo a free-jet expansion, essentially halting chemical reactions and preventing condensation. Components of the molecular beam are then ionized by 22.5 eV electrons before passing through a quadrupole mass analyzer. The ions are then detected with an off-axis electron multiplier and mass spectra are generated according to the molecular weight of the ions. TMBMS data collection and the mass spectrometer were automated using a PC-based data acquisition and control system. Mass spectra were recorded for $m/z=3$ to $m/z=400$ along with auxiliary pressure data at the rate of 36 scans/min with 1 minute averages stored. A schematic of the TMBMS system is shown in figure 4.

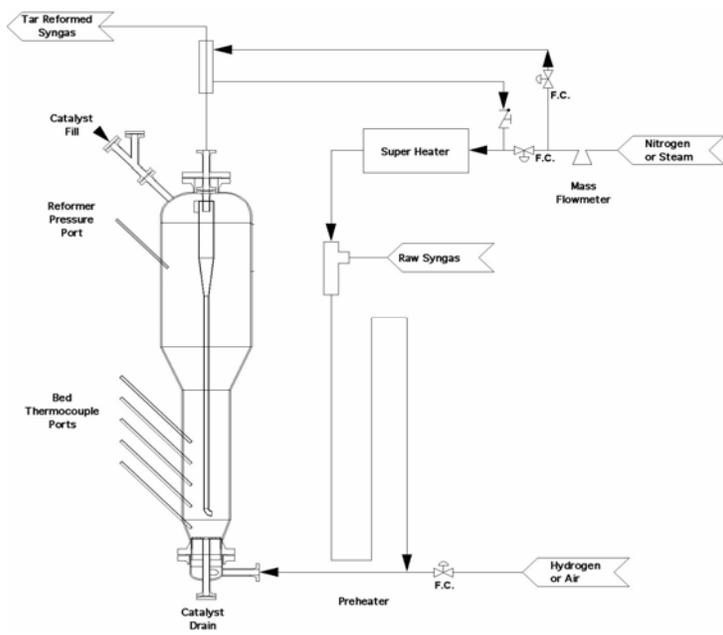


Figure 3. Full Stream Tar Reformer

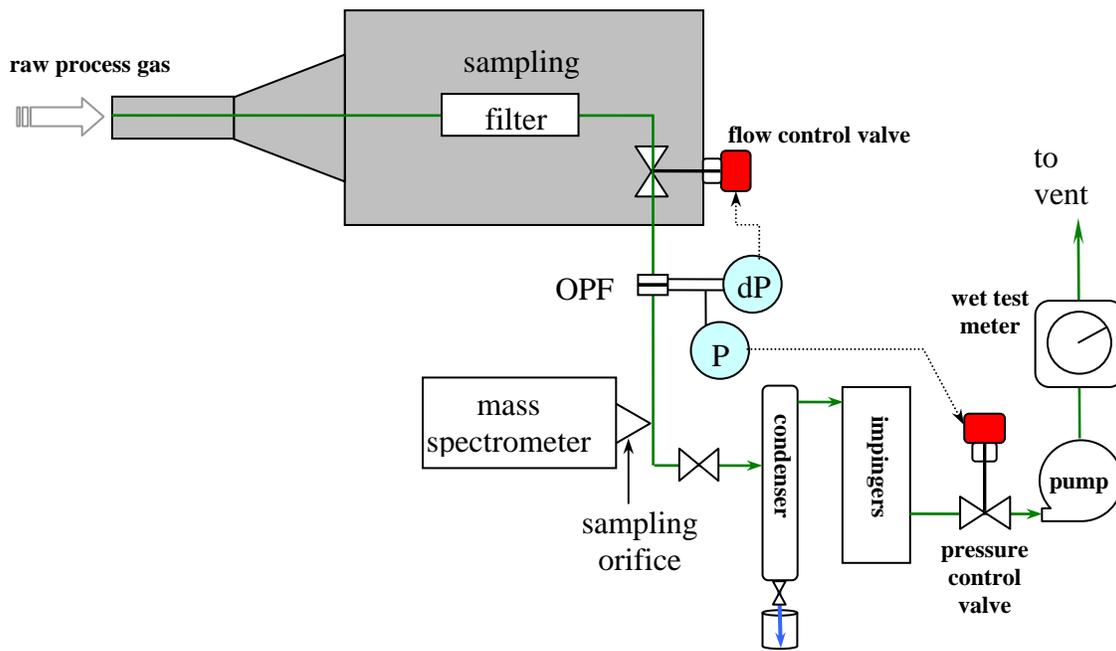


Figure 4. Schematic of TMBMS System

For these tests, NREL's TCPDU was operated in indirect gasification mode using steam and nitrogen as the fluidizing gas/oxidizer to produce a medium calorific value synthesis gas from the incoming biomass feedstock. In order to provide process stability, all critical process parameters for the TCPDU, including temperatures, pressures and flow rates, are automated by a PC-based data acquisition and control system. These parameters were generally stable to within a few percent over a given experimental run. In the full stream reforming reactor, the temperature in the fluidized bed was maintained at 925°C.

EXPERIMENTAL RESULTS

Based on data measured using the TMBMS and on-line gas chromatography, tar conversion results showed between 80 and 90% conversion of nearly all species present. An increase in benzene was noticed, indicating that a portion of the tars was converted to this stable compound. This is not an unexpected result as the tars are primarily aromatic in nature and benzene is a very stable aromatic molecule. Figures 5 and 6 illustrate the tar compounds found in the inlet and outlet of the full stream tar reformer.

Water Gas Shift Results

As discussed above, an additional benefit of the gas conditioning reactor, is the resulting increase in hydrogen content due to water gas shift equilibrium and the conversion of the tars into additional syngas. Table 2 shows the inlet and outlet composition of the synthesis gas illustrating this desirable result.

Such a change in composition allows the syngas from the Taylor gasifier to be used directly for a much broader range of applications including the use for synthesis applications or for the direct recovery of hydrogen as an end product.

Table 2. Comparison of Gas Compositions at the Inlet and Outlet of the Gas Conditioning Reactor

Component, o/v	Inlet	Outlet
Hydrogen	29.5	47.2
Carbon Monoxide	30.1	17.4
Methane	14.4	12.2
Ethylene	3.9	2.6
Carbon Dioxide	20.7	20.1
Ethane	0	0.1
Nitrogen	trace	trace

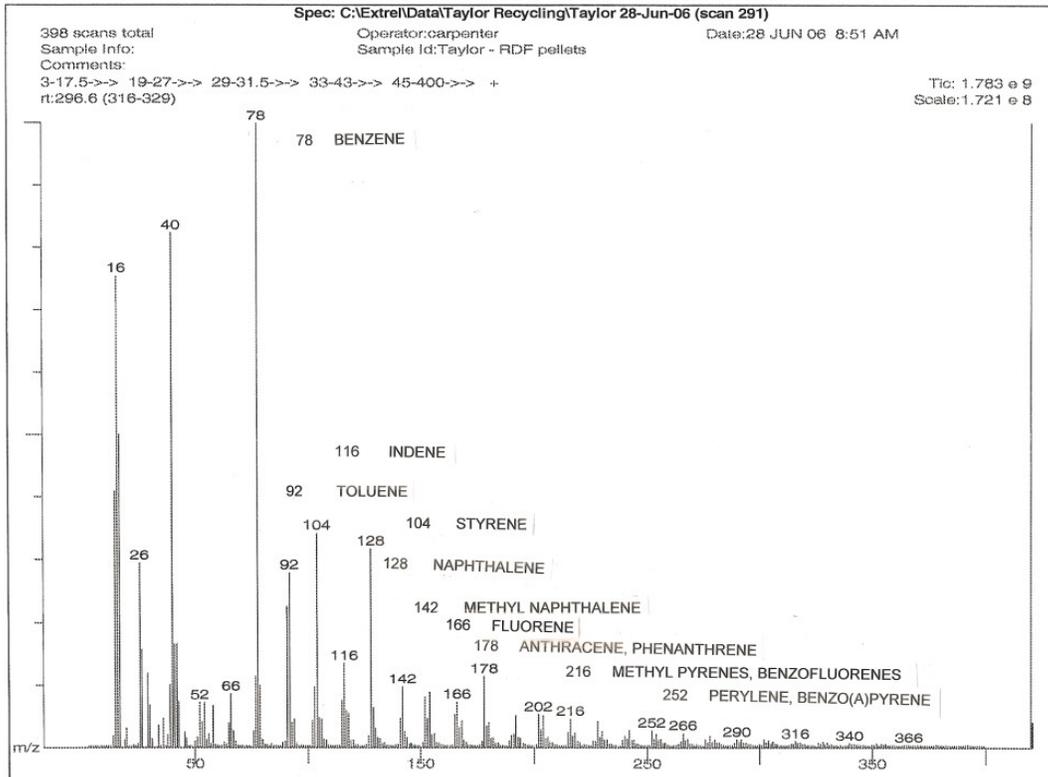


Figure 5. TMBMS Trace Showing Inlet Concentrations of Tar Compounds

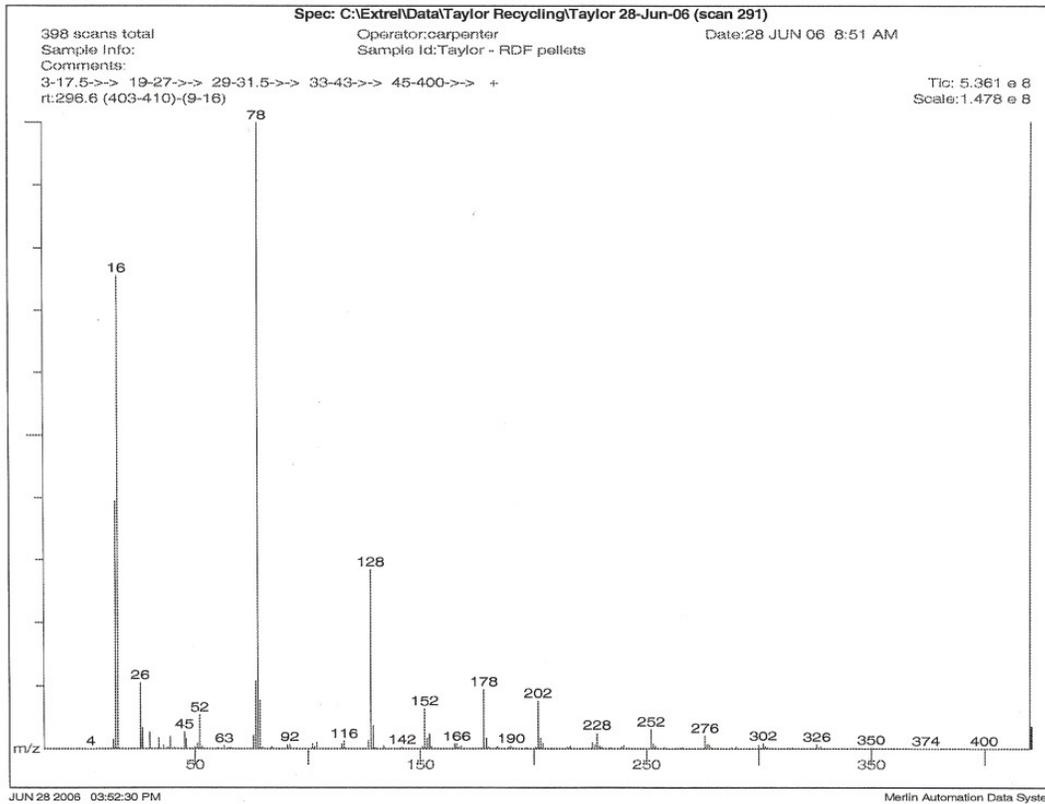


Figure 6. TMBMS Trace Showing Outlet Concentrations of Tar Compounds

Lifetime of Catalytic Performance

When applications rely upon the catalytic performance of a material, as in the Taylor gas conditioning reactor, there is always a question about the expected lifetime of the catalyst material. One primary cause of this deactivation in steam reforming type of reactions is the formation of carbon deposits on the catalyst surface. As the catalytic material in the Taylor Gasification Process is the circulating heat transfer material, such deactivation can not occur as the material passes alternately through an oxidizing regime and a reducing regime. This allows for in-situ regeneration of the catalyst thereby virtually eliminating the problem of catalyst deactivation.

During the testing at NREL, this “regeneration” of the material was evaluated. The “regenerated” material showed essentially the same tar conversion activity as the “virgin” material. This is illustrated in Figure 7 which shows the conversion performance on two consecutive days of operation. A “regeneration” of the material had taken place between the two testing periods.

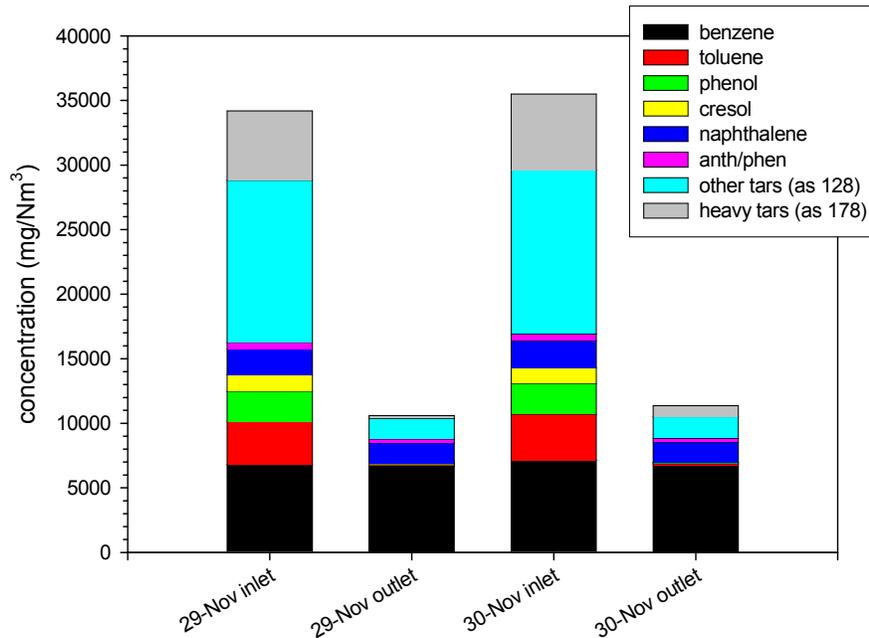


Figure 7. Consistent Performance of the Gas Conditioning Step

COMMERCIAL APPLICATION OF THE TAYLOR GASIFICATION PROCESS

To actively pursue commercial scale biomass based systems, an adequate, sustainable supply of appropriate biomass material is necessary. Biomass as a fuel source is widely obtainable, but, in many locations, is prohibitively expensive due to transportation costs, seasonality, or local supply issues.

The disposal of MSW is becoming an increasingly serious problem throughout the United States. In the period 1990 to 2000, MSW generation rates have increased by 13 percent. When compared to 1980 levels, generation rates have increased over 50 percent. Large quantities of other solid wastes, commonly referred to as construction and demolition wastes (C&D) are also generated annually further increasing the problem.

Taylor Biomass Energy is constructing a facility at its site in Montgomery, NY to utilize biomass recovered from these plentiful and sustainable materials and convert them into green bioproducts. This integration of the Taylor sorting, separating, and recycling process along with the Taylor Gasification Process is underway.

At the site currently, approximately 275 tonnes per day of C&D material along with 90 tonnes of wood residues (stumps and similar materials) are sorted and a significant portion of biomass that would be suitable input to the gasification process is recovered. This existing operation will be expanded by approximately 50% and a sorting operation to handle approximately 450 tonnes per day of municipal solid waste is being added. The combined operation will produce, on a sustainable basis, approximately 275 tonnes per day (dry basis) of a "processed biomass fuel" for the gasification process.

A schematic showing the process arrangement for the Taylor gasifier is found in figure 8. In the diagram, the flow of the hot solids through the gas conditioning reactor on their return to the gasification reactor can be clearly seen. The cleaned gas is then directed to heat recovery to enhance the overall process efficiency.

The Taylor gasifier will be constructed in a modular fashion rather than being completely assembled on site. This fabrication technique will provide much tighter control of the assembly as well as provide capital cost savings during construction. Completed modules will be delivered to the site and erected with a minimum of installation necessary on site. A 3-D rendering of the assembled gasification process is found in Figure 9.

Syngas generated from the incoming biomass will be cleaned of particulates, compressed and used as fuel for a gas turbine based combined cycle power system. Approximately 20 MW will be exported from the facility to a local utility substation located on the site.

In addition, the facility will be constructed to provide a development platform where additional feedstocks and / or downstream unit operations such as chemical synthesis or hydrogen production can be readily demonstrated.

The Montgomery facility is underway with the Class A design package completed, permit documents in review, project financing in place, and initial site preparations completed. Detailed design is underway and construction of the gasification modules is expected to start shortly.

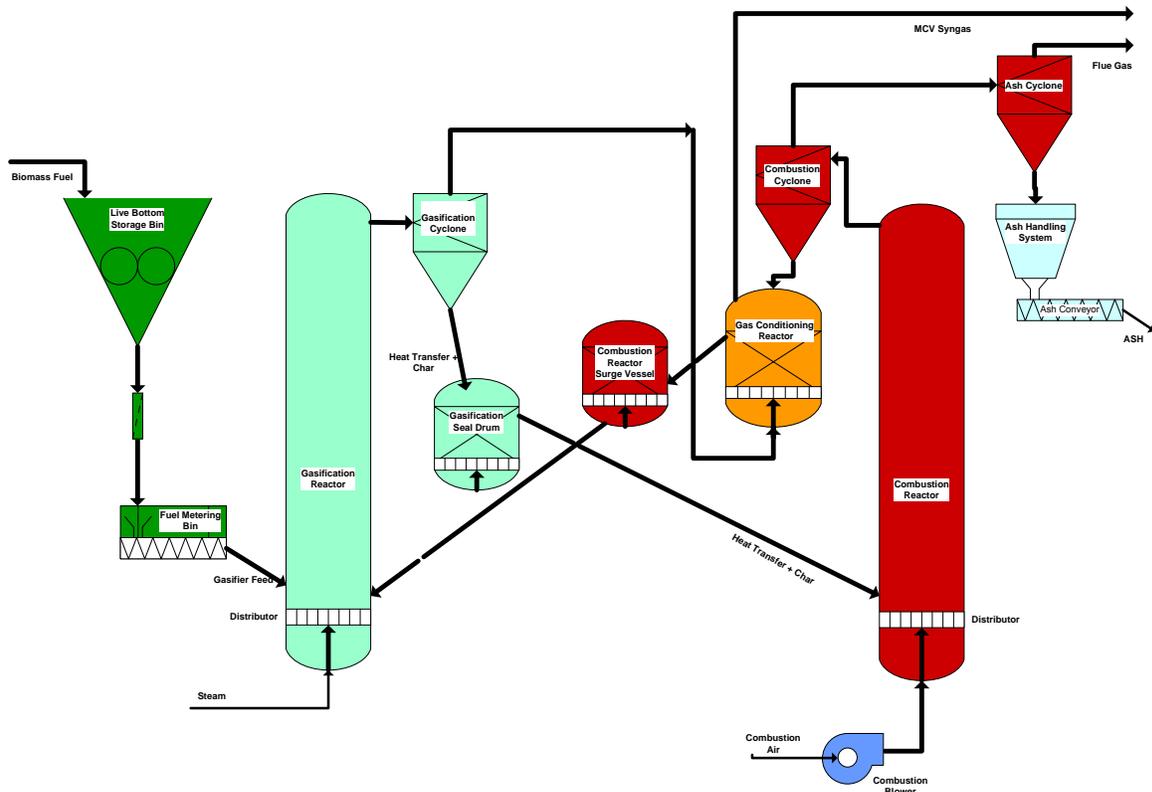


Figure 8. Schematic Diagram of the Taylor Gasification Process Showing Process Arrangement

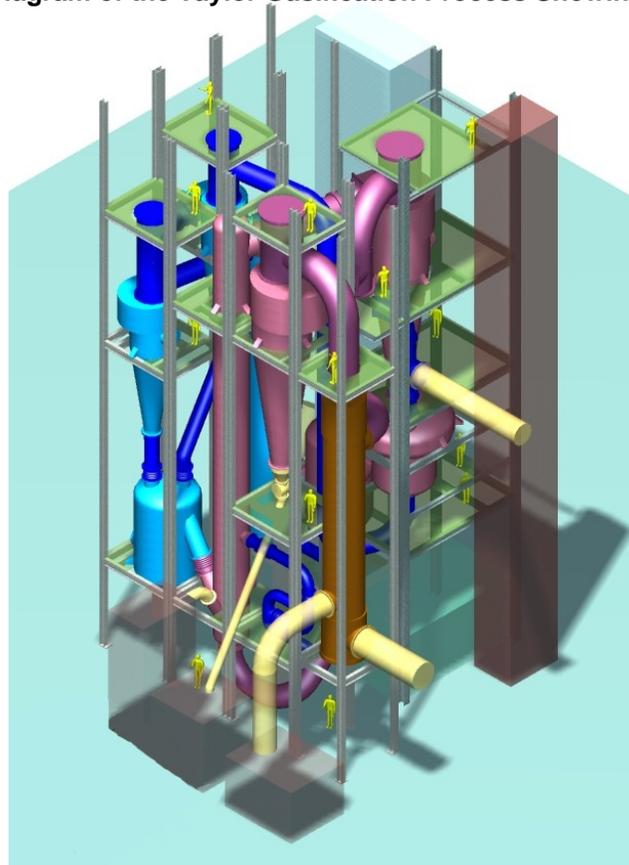


Figure 9. Layout of the Taylor Gasification Process Modules

PROCESS ECONOMICS

The installed capital cost for the gasification island has been estimated to be between \$550 and \$600 per installed kW. Final costs for the power island have not been determined, but are expected to be consistent with state-of-the-art combined cycle facilities based on natural gas firing.

The facility at the Montgomery site will provide approximately 20 MW of power to the New York grid. This power is anticipated to be considered “renewable power” and therefore will be able to take advantage of various incentives available at the State and National level.

Additional income to the project will accrue based on the sale of recyclable materials recovered from the incoming C&D and MSW streams and from tipping fees associated with the handling of these materials at the site.

Overall, the project is expected to be profitable in the very early years of the project life.

CONCLUSIONS

The Taylor gasification process has been shown to provide enhanced conversion of condensable organics by the integration of a unique gas conditioning step within the process. This step has been experimentally verified through testing at NREL and shows significant advantages when compared to downstream unit operations.

The commercial demonstration of the integrated Taylor sorting, separating, and recycling process with the Taylor gasifier has also shown that:

- A viable biomass resource can be supplied from residues including C&D materials and MSW
- Incorporation of these residue based biomass resources can be a key element in economical biomass energy projects
- A high quality synthesis gas can be produced from biomass without the need for multiple downstream process steps
- Biomass gasification can provide a route to a wide range of energy products including power, liquid fuels, chemicals, and hydrogen

Additional projects employing the Taylor gasifier and the Taylor sorting, separating, and recycling processes are in various stages of development. These projects are expected to be “on-line” within one year after the completion of the Montgomery, NY project.

REFERENCES

1. Marquard-Mollenstech, T., et al, "New Approach for Biomass Gasification to Hydrogen," 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, 10-14th May 2004
2. Reed, T., and Gaur, S., "A Survey of Biomass Gasification 2000," BEF Press, 2001
3. Paisley, M.A., and Overend, R., "Verification of the Performance of Future Energy Resources' *SilvaGas*® Gasifier Operating Experience in The Vermont Gasifier", Pittsburgh Coal Conference, 2002
4. Paisley, M.A., "Biomass Energy," Kirk-Othmer Encyclopedia of Chemical Technology," John-Wiley and Sons, 2003