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Comparison of Biomass to Bio-oils Reactor Systems: Direct Conversion vs. Companion Coal Gasification

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Biomass to Bio-oils

Alexandra Eicher

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2013 AIChE Contest Problem
University of New Hampshire

COMPARISON OF BIOMASS TO BIO-OILS REACTOR SYSTEMS:

DIRECT CONVERSION VS. COMPANION COAL GASIFICATION

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MAY 8, 2013

2013 AIChE DESIGN PROBLEM

UNIVERSITY OF NEW HAMPSHIRE

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SUMMARY

It is well known that the United States' dependence on crude-oil negatively affects its economy, safety, and environment. To alleviate these negative consequences, a more economical and environmentally-friendly source of fuel, such as biomass, should be explored. The conversion of biomass to bio-oils involves the pyrolysis of biomass at about 500°C, thus requiring a great deal of heat. This heat source could be the excess waste heat from a coal gasifier.

As such, this report specifies the design of an industrial plant that produces bio-oils from biomass by using the waste heat from a coal gasifier. It is designed to produce 2.24×10^{8} kg/yr of bio-oil that can be sold at $0.79/kg. This plant involves coal and biomass solids handling, a coal gasification reactor, a biomass pyrolysis reactor, and a series of separation units to remove waste products from the syngas and isolate the bio-oil. The syngas contains methane, hydrogen, and carbon monoxide and is sold as a by-product credit. The plant is expected to run on feeds of $1.5\text{x}10^{11}$ kg/yr of coal and $5.4\ \text{x}10^{8}$ kg/yr of raw biomass.

The coal gasification reactor was sized based on the heating duty of steam at 273000 kJ/s and the biomass pyrolysis reactor was sized based on a heating duty of 7026 kJ/s. The plant's operating factor (POF) is 0.9 at 7884 hrs/yr running 24 hrs/day and 328.5 days/yr. The total bare module equipment cost, including all pumps, heat exchangers, grinders, separators, absorber, and reactors is $93 million.

The safety considerations include:

- Insulation on gasification product lines due to high temperatures.
- Spring loaded relief values and bursting discs on all vessels to prevent built up pressure and on storage vessels to prevent backflow.
- Pressure relief valves on the discharge side of pumps, compressors, and turbines .
- Double block and bleeds on feed lines and cool lines exposed to heat.
- Control system, with PID controls, on gasification and pyrolysis reactor to monitor and control their pressure and temperature by adjusting the cooling water to reactor jackets and the feed flow rates.
- Additional temperature and pressure gauges on the reactor for manual monitoring by the operator.

The key, innovative design features include:

- Waste heat, in the form of steam, from the gasifier used to heat the biomass.
- Bio-char from the pyrolysis of biomass recycled to the gasifier to decrease the amount of raw coal fed and, consequently, the cost of raw materials.
- Bio-gas from the pyrolysis of biomass used to dry the raw biomass to a moisture content of 10% as well as to blow the biomass up through the fluidized bed.

The total capital investment of the plant is $173 million. The DCFRR and NRR are 12.59% and 20% respectively.

Given that selling price of bio-oil ($0.79/kg) associated with this plant is about six times more expensive that the average cost of bio-oil ($0.13/kg), it is not recommended that a Class – 1 Estimate be conducted. Before a Class – 1 Estimate can be conducted, the unnecessary costs associated with this proposed plant must be addressed and reduced. Specific attention must be paid to the following two heat exchangers, E-127 and E-129. Additionally, attention should be given to discover a cheaper source of industrial, liquid oxygen.

INRODUCTION

It is well known that the United States is heavily dependent on crude-oil; annually, Americans consumes 180 billion gallons of gasoline and diesel (Ackerson, 2012). Due to the shortage of crude-oil that can be found and harvested in America, our heavy dependence on crude-oil forces the United States to import vast quantities of it. This results in three major, negative consequences: 1) the United States' economy becomes tied to the price of crude-oil, which it controlled by foreign nations; 2) the United States must trade with nations that, traditionally, do not hold America in very high regard; and 3) the carbon dioxide emissions, produced from consuming crude-oil, accumulates in our atmosphere and greatly contributes to global warming (Ackerson, 2012).

To alleviate these negative consequences, a more economical and environmentally-friendly source of fuel that does not necessitate importation should be explored. One abundant resource found in the United States is biomass. "It is estimated that there are at least 500 million dry tones of biomass available in the U.S. annually in the form of forest residues, mill residues, potential dedicated energy crops, urban wood wastes, and agricultural residues" (Ackerson, 2012). While using biomass as a source of fuel would be more economical and environmentally-friendly than using crude-oil, the technical specifics of industrial conversion of biomass to bio-oil has yet to be fully explored.

The conversion of biomass to bio-oils involves the pyrolysis of biomass at about 500°C (Ackerson, 2012). This requires a great deal of heat. One source of heat is hot sand. Another is waste heat from a separate reaction, such as coal gasification to generate syngas. To yield syngas with an acceptable amount of CO as compared to CO_2, a coal gasifier must be operated at high temperatures, thus producing a significant amount of waste heat and low thermal efficiencies. Utilizing the waste heat from coal gasification to drive the pyrolysis of biomass would not only increase the thermal efficiency of the coal gasifier, but also allow for a maximum conversion of energy to liquid fuels (Ackerson, 2012). As such, this report proposes an industrial plant that follows this "married" process for the conversion of biomass to bio-oils using the waste heat from coal gasification.

The primary reaction for this plant is the pyrolysis of biomass. There are three different pyrolysis processes: slow pyrolysis, fast pyrolysis, and flash pyrolysis (Goteti, 2010). Fast pyrolysis produces the most bio-liquid of all three processes, and, as such, is the most common thermal process for converting biomass to bio-oil (Ackerson, 2012). Fast pyrolysis yields 75% bio-liquid, 12% bio-char, and 13% bio-gas and is characterized by moderate temperatures of about 500°C and short residence times of less than 2 seconds (Goteti, 2010). To ensure that fast pyrolysis occurs, there must be a very high heat flux to the biomass (i.e. a high heat transfer rate to the biomass) and a very short residence time (i.e. the heat transfer rate must occur in a very short amount of time) (Ringer, 2006). For these reasons, the pyrolysis reactor in the proposed married process is a fluidized bed reactor. This ensures direct contact with the biomass, and thus, a high heat transfer rate to the biomass.

Immediately after the pyrolysis reaction, the resulting gaseous mixture must be quenched to prevent the compounds from further cracking into permanent gases or polymerizing into char (Ringer, 2006). In this process, quenching is accomplished through fractional condensation using a series of shell and tube heat exchangers. The bio-oil that condenses is a mixture of more than 100 chemical species that have a wide range of molecular weights (Ackerson, 2012). "A typical elemental composition shows 44-47% carbon, 6-7% hydrogen, 46-48% oxygen, and 0-0.2% nitrogen" (Ackerson, 2012).

The secondary reaction for this plant is the pyrolysis of coal. Since the United States has over 273.6 billion short tons of coal reserves (the largest in the world), there is no shortage of raw material for this married process (Ackerson, 2012). This proposed process follows the Texaco process because it is the most widely used and the most economically preferred (Ackerson, 2012). Additionally, "the low capital investment for this process makes it ideal to integrate it with a coal and biomass production" (Ackerson, 2012). For the Texaco process, coal is feed as a slurry into the gasifier. For combustion to occur properly, this slurry must have a high enough coal concentration so that the reactor operates at the appropriate temperature but a high enough water concentration so that the slurry's viscosity is low enough to ensure an ease of transport. Since the major hazard for the pyrolysis of coal is the high gasification temperature, the coal concentration in the slurry was set around 60% to ensure a low flow rate of water entering and vaporizing in the gasifier. The pyrolysis of coal ultimately produces synthesis gas, or syngas, which is a fuel gas mixture consisting hydrogen, carbon monoxide, and methane.

The following report gives a detailed description of a plant that uses the married process to produce 2.24×10^8 kg/yr of bio-oil. There are three main, novel features of this plant: 1) waste heat, in the form of steam, from the gasifier is used to heat the biomass; 2) bio-char from the pyrolysis of biomass is recycled to the gasifier to decrease the amount of raw coal fed and, consequently, the cost of raw materials; and 3) the bio-gas from the pyrolysis of biomass is used to dry the raw biomass to a moisture content of 10% as well as to blow the biomass up through the fluidized bed. The major objective of this married process design is to determine its economic feasibility, i.e. the selling price of crude bio-oil: $0.79/kg.

CONCLUSIONS

To produce bio-oil from biomass, safety, environmental, process, and economic issues must all be addressed.

First, to ensure the safety of the operators and the surrounding area, the plant was designed with numerous safety features. The key safety features include the use of safety relief valves, temperature and pressure gauges for manual monitoring, and control systems for automatic vessel and reactor monitoring. Safety relief valves were placed on all vessels to inhibit pressure build up. These valves were also placed on storage vessels to prevent back flow. Safety valves were also included on all pumps, compressors, and turbines on the discharge side to release pressure in case of excessive pressure caught between the compressor and valve. A double block and bleed system, which involves two valves with a relief valve in between, is in place on all feed lines and lines exposed to heat. The double block and bleed prevents pressure build up in the line. A control system, in place on the reactor, monitors and adjusts its temperature and pressure. The supply of cooling water to the reactor jacket is varied by the control system to control the reactor temperature. Feed flow is varied by the control system to control the reactor pressure. Additional pressure and temperature gauges are in place on all units for manual monitoring by the operator. Manual monitoring is an extra level of safety in case of control system malfunction.

A key environmental consideration tied to this project is reforestation. The only way to avoid carbon dioxide accumulation when burning bio-oils is to ensure the growth of more biomass. As biomass grows, it absorbs carbon dioxide from the atmosphere. If fact, if the amount biomass grown equaled the amount of bio-oil burnt, the whole process would be carbon-neutral.

This plant design features a few key, innovative systems. First, steam from the gasifier is used to heat the biomass. This takes advantage of excess heat, in the form of steam, from the coal gasifier. Not only does this increase the thermal efficiency of the gasifier but it also provides a convenient method to heat the biomass. Second, bio-char from the pyrolysis of biomass is recycled to the gasifier. This decreases the amount of raw coal needed to be fed to the coal gasifier, thus, decreasing the cost of raw materials. Third, the bio-gas from the pyrolysis of biomass is used to dry the raw biomass to a moisture content of 10% as well as to blow the biomass up through the fluidized bed. This decreases waste steams leaving the plant.

There are a few other noteworthy features. The MEA stream loop has no inlet and outlet streams because all of the MEA is assumed to be recycled though the process. It is regenerated on a yearly basis. This keeps the costs of solvents and, thus, manufacturing costs down. It also minimizes MEA waste. Also to minimize consumption and cost, the process water used by the Venturi scrubber to remove slag from the product stream is recycled with only a minimum of water being released and wasted. Before the product stream is cleaned of its waste gases by the MEA absorber the temperature of the stream is lowered though use of scrubber. This scrubber was used instead of a heat exchanger to take advantage of direct contact with water. This allows for a more efficient cooling of product gases, when compared to that of a heat exchanger, and, therefore reduces cost of equipment and electricity consumption.

Given a typical cost of bio-oil of $44 per barrel equivalent and a higher heating value for bio-oil of 7,554 Btu/lb, the average cost of bio-oil is $0.13/kg. The selling price of bio-oils derived from this study is $0.79/kg. This price is about six times more than the average cost of bio-oil. Therefore, it does not seem economically sound to produce bio-oil from biomass given the proposed plant.

RECCOMENDATIONS

The recommendations for this Class – 4 Estimate are the following:

1. This plant should not be constructed as specified.
2. Means of cutting cost need to be considered.
3. Specific attention should be paid to E-127, the heat exchanger designed to cool down the scrubber recycle water, and to E-129, the heat exchanger designed to cool down the recycled MEA to the absorber while heating up the saturated MEA to the stripper. Both of these heat exchangers are designed with higher-than-anticipated surface areas, which necessitate the use of multiple heat exchangers. This drastically increases the Total Bare Module Cost and, consequently, all other costs associated with it.
4. Another large source of expense is the cost of raw materials, specifically, the cost of liquid oxygen. Attention should be given to discover a cheaper source of industrial, liquid oxygen.
5. Given that selling price of bio-oil is about six times more expensive that the average cost of bio-oil, it is not recommended that a Class – 1 Estimate be conducted until the unnecessary costs associated with this proposed plant are addressed.

PROJECT PREMISES

1. **Start and Completion Dates**
   a. Effective Start Date: May 18, 2014
   b. Mechanical Completion Date: May 18, 2017

2. **Feed Specifications**
   a. Coal
      i. Proximate Analysis (wt%): 8.9% Moisture, 10.7% Ash, 32.5% Volatiles, 47.9% Fixed Carbon (Zheng, 2005)
      ii. Ultimate Analysis (wt%): 69.71% Carbon, 4.8% Hydrogen, 0.82% H/C, 1.4% Nitrogen, 3.64% Sulfur, 7.83% Oxygen, 11.8% Ash (Zheng, 2005)
      iii. Higher Heating Value (HHV): 29.4 MJ/kg (Zheng, 2005)
      iv. Heat Capacity: 31400 kJ/kg
      v. Temperature (°C): 25
      vi. Pressure (bara): 1
      vii. Mass Flow Rate (kg/s): 52.04
   b. Water
      i. Concentration in Slurry (wt%): 40%
      ii. Heat Capacity (kJ/kg/K): 4.181 (Goteti, 2010)
      iii. Heat of Vaporization at 75 °C (kJ/kg): 2322.87 (Goteti, 2010)
      iv. Temperature (°C): 25
      v. Pressure (bara): 16
   c. Liquid Oxygen
      i. Mass flow rate: 0.97% of coal mass flow rate (Zheng, 2005)
      ii. Temperature (°C): -183
      iii. Pressure (bara): 16
   d. Biomass
      i. Heat Capacity at 298 K (assuming the heat capacity in the given temperature range does not change significantly): 1.2 KJ/kg/K (Goteti, 2010)
      ii. Temperature (°C): 25
      iii. Pressure (bara): 1

   Product Specifications and Quality Considerations
   e. Bio-oil
      i. Mean Specific Heat Capacity (kJ/kg/K): 2.435 (Goteti, 2010)
      ii. Mean Heat of Vaporizaiton (kJ/kg): 609.9 (Goteti, 2010)
      iii. Temperature (°C): 352.2
      iv. Pressure (bara): 12.5

3. **Manufacturing Costs**
   a. Capital Expenses
      i. Fixed Capital: $144,000,000/yr.
      ii. Working Capital: $28,800,000/yr.
   b. Manufacturing Expenses
      i. Direct
         1. Raw Materials: $697,000,000/yr.

            2. By-product Credits: $841,000,00/yr.0
            3. Solvents: $49,400/yr.
            4. Operating Labor: $1,260,000/yr.
            5. Supervisory and Clerical Labor: $251,000/yr.
            6. Utilities
                a. Steam: $301,000/yr.
                b. Electricity: $12,30,000/yr.
                c. Cooling Water: $679,000/yr.
                d. Waste Disposal: $4,210,000/yr.
            7. Maintenance and Repairs: $14,400,000/yr.
            8. Operating Supplies: $2,880,000/yr.
            9. Laboratory Charges: $252,000/yr.
            10. Patents and Royalties: $8,440,000/yr.
        ii. Indirect
            1. Overhead, Packaging, and Storage: $11,100,000/yr.
            2. Local Taxes: $4,310,000/yr.
            3. Insurance: $2,880,000/yr.
    c. General Expenses
        i. Administrative Costs: $2,780,000/yr.
        ii. Distribution and Selling: $14,100,000/yr.
        iii. Research and Development: $7,040,000/yr.

4. **Product Selling Price**
    a. Bio-oil: $0.79/kg

5. **Economic Parameters**
    a. Project Life: 10 years
    b. Depreciation Schedule: $14,400,000/yr.
    c. Total Expenses: $141,000,000/yr.
    d. Net Annual Profit: $35,400,000/yr.
    e. Income Taxes: $12,400,000/yr.
    f. Net Annual Profit After Taxes: $23,000,000/yr.
    g. Revenue from Sales: $176,000,000/yr.
    h. Net Rate of Return (NRR): 20%
    i. Payback Period (PBP): 4.25 years
    j. Discounted Break-even Point (DBEP): 11.5 years
    k. Discounted Cash Flow Rate of Return (DCFRR): 12.59%

6. **Environmental Requirements**
    a. De Minimis Emission Levels
        i. Carbon Monoxide: 100 tons/year (*De Minimis* Levels, 2013)

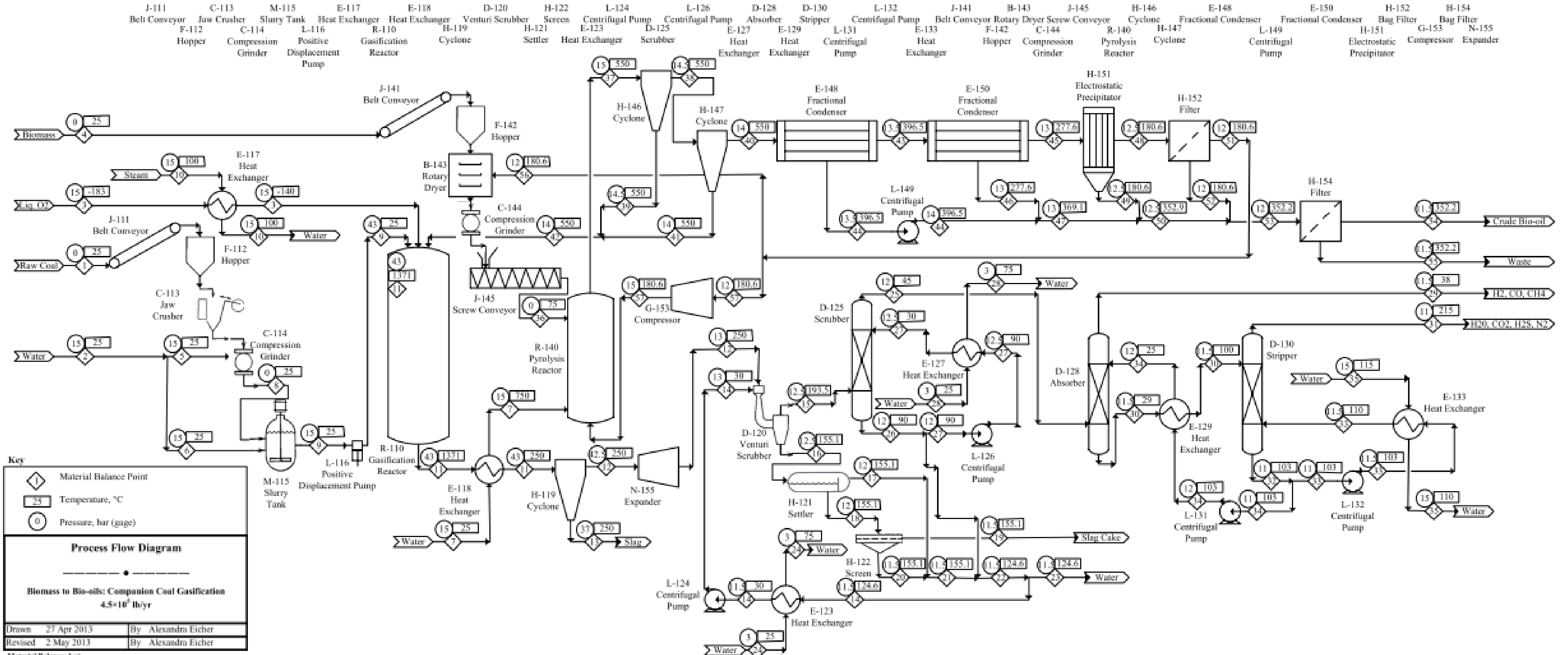
7. **Processing Limitations**
    a. The mass flow rate of the biomass rate is tied to the steam mass flow rate from the heat exchanger in the coal gasifier. This limitation is designed to take full advantage

of all of the waste heat from the coal gasifier. Due to this, the mass flow rate of the resulting bio-oil is also limited.

b. The mass flow rate of the feed water is limited to 40% of the slurry mass flow rate to ensure that the temperature in the coal gasifier does not exceed optimal operating temperatures.

PROCESS FLOW DIAGRAM (PFD)

The PFD is attached on the next page. It includes all process equipment items, process streams, and utility streams. Each process equipment item is named and numbered. Each process and utility stream is numbered and labeled with its operating temperature and pressure. The Steam Attributes table is included on the PFD. This table lists each stream number and name, the mass flow rate of each component in each stream, and the total mass flow rate of each stream.



Process Flow Diagram

Biomass to Bio-oils: Companion Coal Gasification
4.5×10^5 lb/yr

Drawn 27 Apr 2013	By Alexandra Eicher
Revised 2 May 2013	By Alexandra Eicher

Material Balance: kg/s

Component	MW	Stream 1	Stream 2	Stream 3	Stream 4	Stream 5	Stream 6	Stream 7	Stream 8	Stream 9	Stream 10	Stream 11	Stream 12
		Raw Coal Feed	Water Feed	Liquid Oxygen Feed	Raw Biomass Feed	Water to C114	Water to M115	Water to E118	Wet Coal to M115	Coal Slurry to R110	Vaporizer Steam	R110 Products	Gas from H119
C	12	36.68							36.68	36.68			
H	1	2.524							2.524	2.524			
N	14	0.7287							0.7287	0.7287			
N_2	28											1.784	1.784
S	32	1.895							1.895	1.895			
O	16	4.075							4.075	4.075			
O_2	32			50.49								1.427	1.427
H_2O	18		35.23		9.479	24.661	10.569	15.65	24.661	35.23	6.571	19.96	19.96
H_2	2											3.645	3.645
CO	28											68.51	68.51
CO_2	44											35.32	35.32
CH_4	16											0.1529	0.1529
MEA	61.1												
H_2S	34											2.08	2.08
Ash		6.142							6.142	6.142			
Slag												6.289	0.6289
Biomass					9.479								
Total		52.04	35.23	50.49	18.96	24.66	10.57	15.65	76.71	87.27	6.571	139.2	133.5

Component	MW	Stream 13	Stream 14	Stream 15	Stream 16	Stream 17	Stream 18	Stream 19	Stream 20	Stream 21	Stream 22	Stream 23	Stream 24
		Slag from H119	Recycle Water to D120	Gas to D125	Slag to H121	Water from H121	Slag to H122	Slag Cake from H122	Water from H122	Water from H121 and H122	Water from H121, H122, and D125	Waste Water	Cooling Water for D120
C	12												
H	1												
N	14												
N_2	28			1.784									
S	32												
O	16												
O_2	32			1.427									
H_2O	18		22.19	19.96	22.19	21.56	0.6277	0.06277	0.5649	22.13	41.93	19.74	42.28
H_2	2			3.645									
CO	28			68.51									
CO_2	44			35.32									
CH_4	16			0.1529									
MEA	61.1												
H_2S	34			2.08									
Ash													
Slag		5.66		tr	0.6283	tr	0.6277	0.6271	tr				
Biomass													
Total		5.66	22.19	132.9	22.82	21.56	1.255	0.6899	0.5649	22.13	41.93	19.74	42.28

Component	MW	Stream 25	Stream 26	Stream 27	Stream 28	Stream 29	Stream 30	Stream 31	Stream 32	Stream 33	Stream 34	Stream 35	Stream 36
		Gas from D125	Water from D125	Recycle Water to D125	Cooling Water for D125	Syngas	Sat. MEA from D128	Waste Gases to Stack	Recycle MEA from D130	Recycle MEA to D130	Recycle MEA to D128	Water to E133	Dried Biomass to R140
C	12												
H	1												
N	14												
N_2	28	1.784					1.782	1.782					
S	32												
O	16												
O_2	32	1.427											
H_2O	18	0.1583	115.9	96.07	115.7		78.62	78.62	86.31	7.847	78.47	0.03857	2.13
H_2	2	3.645				3.645							
CO	28	68.51				68.51							
CO_2	44	35.32					35.29	35.29					
CH_4	16	0.1529				0.1529							
MEA	61.1						19.61		21.58	1.961	19.61		
H_2S	34	2.08					2.078	2.078					
Ash													
Slag		tr											
Biomass													9.479
Total		113.1	115.9	96.07	115.7	72.31	137.4	117.8	107.9	9.808	98.08	0.03857	11.61

Component	MW	Stream 37	Stream 38	Stream 39	Stream 40	Stream 41	Stream 42	Stream 43	Stream 44	Stream 45	Stream 46	Stream 47
		Biogas to H146	Biogas to H147	Char from H146	Biogas to E148	Char from H147	Recycle Char to R140	Biogas to E150	Bio-oil from E148	Biogas to H151	Bio-oil from E150	Bio-oil from E148 and E150
Bio-oil		7.899	7.899		7.899			2.37	5.53	0.7109	1.659	7.188
Biogas		1.369	1.369		1.369			1.369		1.369		
Biochar		1.264	0.1264	1.138	tr	0.1138	1.251		tr			tr
Total		10.53	9.394	1.138	9.268	0.1138	1.251	3.739	5.53	2.080	1.659	7.188

Component	MW	Stream 48	Stream 49	Stream 50	Stream 51	Stream 52	Stream 53	Stream 54	Stream 55	Stream 56	Stream 57
		Biogas to H152	Bio-oil from H151	Bio-oil from E148, E150, and	Biogas from H152	Bio-oil from H152	Bio-oil from E148, E150,	Bio-oil Product	Waste	Recycle Biogas to S143	Recycle Biogas to R140
Bio-oil		0.03555	0.6754	7.864	tr	0.03377	7.898	7.898			
Biogas		1.369			1.369					1.095	0.2745
Biochar				tr			tr		tr		
Total		1.405	0.6754	7.864	1.369	0.03377	7.898	7.898	0	1.095	0.2745

PROCESS DESCRIPTION

Raw coal enters the plant and travels through a series of solids handling equipment to prepare the coal for the gasification reactor. The coal is conveyed via a belt conveyor to a hopper where it is stored until it is released into a jaw crusher. After the jaw crusher, the coal is fed into a rolling compression grinder where it is wet-milled to 100 µm. Once the desired particle size is reached, the coal is mixed with water to form a slurry with a coal concentration of 60%. About 70% of the feed water is used to wet-mill the coal and the rest of the water is added to the slurry tank to mix the coal. From there, the slurry is charged to the reactor using a positive displacement pump. The slurry, oxygen, and recycled bio-char are introduced into the gasifier through the feed-injector at the top of the reactor (Higman, 2008). The reactor is a top-fired, coal-water slurry feed, slagging, entrained-flow gasifier (Higman, 2008). The AFT of the reactor is 1371ºC (Zheng, 2005). The gas from the gasification reactor is immediately cooled to 250ºC using a heat exchanger that converts cooling water to steam. This steam is then used to heat the biomass in the biomass pyrolysis reactor.

The gas from the gasification reactor then goes through a series of separation processes to isolate methane, carbon monoxide, and hydrogen. First, the gasification products travel through a cyclone to remove 90% of the slag. Then, the product steam is sent through an expander to reduce its pressure from 43.5 bara to 14 bara. From theer, the product stream goes through a Venturi scrubber. The Venturi scrubber removes 99.9% of the remaining slag by cycling water through the gas. After the venture scrubber, only a negligible amount of slag is left in the product stream. The water and slag from the Venturi scrubber flows through a settler and filter to remove the slag from the waste water. The slag is pressed into an slag cake and some of the waste water is recycled back through the process. The product stream with trace slag is sent through a scrubber to further cool the stream to 45ºC. Most of the water from the scrubber is recycled; some of it is purged and added to the Venturi scrubber waste water recycle stream. The product stream then goes through an absorber to remove hydrogen sulfide, carbon dioxide, and nitrogen. The absorber uses an aqueous solution of monoethanolamine (MEA) to absorb these waste gases. The amount of MEA required to remove the waste gasses is determined by equations 1 through 5.

$$2C_2H_7NO + H_2S \rightleftharpoons (C_2H_7NO)_2S \tag{1}$$

$$(C_2H_7NO)_2S + H_2S \rightleftharpoons (2C_2H_8NO)HS \tag{2}$$

$$2C_2H_7NO + CO_2 + H_2O \rightleftharpoons (C_2H_7NO)_2CO_2 \tag{3}$$

$$(C_2H_7NO)_2CO_2 + CO_2 + H_2O \rightleftharpoons (2C_2H_8NO)HCO_2 \tag{4}$$

$$2C_2H_7NO + CO_2 \rightleftharpoons C_2H_7NO_3C_2H_8NO \tag{5}$$

The product stream leaves the absorber, ready to be sent to Fisher Tropsch processing. The waste gas and MEA solution is sent through a stripper to separate the waste gases from the aqueous MEA. The MEA is then recycled back through the absorber. After the stripper, the waste gases do not need to be process further and are sent through flue-gas stack.

Raw biomass enters the plant in a similar fashion as the raw coal. It is conveyed via a belt conveyor to a hopper where it is stored until it is released into a rotary dryer. Recycled bio-gas is used to heat the raw biomass and dry it until the biomass has a moisture content of 10 wt%. From there, the dried biomass is fed into a rolling compression grinder where it is ground to a particle size of 100 µm. Then, a screw conveyor conveys the biomass to the biomass pyrolysis reactor where the steam from the coal gasifier's heat exchanger rapidly heats the biomass. Recycled bio-gas blows the biomass up through the fluidized bed.

After fast pyrolysis, bio-char is removed from the bio-gas and bio-vapors via two cyclones in series. Each cyclone is 90% efficient. The bio-char that is removed by the cyclones is sent back to the coal gasifier. The bio-gas and bio-vapors are then sent through a series of shell-and-tube condensers to condenser the bio-vapors into bio-oils. Each condenser is 70% efficient. The rest of the bio-gas is sent through an electrostatic precipitator to remove any bio-vapor aerosols and a filter to remove any final bio-oil particulates. Both the electrostatic precipitator and the filter are 95% efficient. The bio-gas is recycled to dry the raw biomass to a moisture content of 10% and blow the dried biomass through the fluidized bed reactor. Finally, the bio-oils are sent through one final filter to remove any bio-char particulates. The bio-oils are ready to be hydrotreated.

MAJOR EQUIPMENT

Mixers: The slurry tank (M-115) is an axial turbine agitator made of carbon steel. Its purpose is to mix the wet, ground coal with additional water to form a coal-water slurry that has a coal concentration of about 60 wt%. The turbine impeller is mounted on a shaft that is powered by a motor. Axial turbine impellers are characterized by blades that are pitched at about 45° (Ulrich, 2004). This angle forces the liquid to flow downward, parallel to the shaft, across the bottom of the vessel, and then upward along the wall of the tank (Ulrich, 2004). Given a residence time of 2 hours, the slurry tank has a volume of 766.9 m^3 and a corresponding power consumption of 203.1 kW. At these conditions, the slurry tank mixers the slurry with vigorous agitation of 0.2649 kW/m^3. The slurry tank mixes 52.04 kg/s of coal and 35.23 kg/s of water into a 60 wt% coal slurry.

Pumps: There are five radial centrifugal pumps (L-124, L-126, L-131, L-132, and L-149), all made of cast iron, in this process design. The purpose of these pumps is to overcome pressure drops over the length of long, narrow pipes and to pump fluids, such as water and MEA, through recycle streams. The shaft power of each pump, respectfully, is 3.196 kW, 5.561 kW, 11.51 kW, 0.5767 kW, and 0.2706 kW. The volumetric flow rates though each pump, respectfully, is 2219 cm^3/s, 96070 cm^3/s, 97850 cm^3/s, 9785 cm^3/s, and 4601 cm^3/s. There is one reciprocating, positive displacement pump (L-116) in this process. It is also made of cast iron. The purpose of this pump is to pump the viscous coal slurry to the coal gasifier. This is accomplished via a piston system that physically pushes the slurry through the pipe to the coal gasifier. This pump has a shaft power of 350.9 kW and a volumetric flow rate of 0.1065 m^3/s flows through this pump.

Heat Exchangers: There are eight shell and tube heat exchangers (E-117, E-118, E-123, E-127, E-129, E-133, E-148, and E-150), all made of carbon steel, in this process. They are used to either cool down or heat up the various process streams. This is accomplished by flow either cooling water (to cool down the stream) or steam (to heat up the stream). E-118 was designed as a fixed tube sheet and U- tube heat exchanger with a total heat transfer area of 1079 m^2. E-118 cools down the 139.2 kg/s of gas from the coal gasifier from 1371°C to 250°C using 14.65 kg/s of cooling water at 25°C. The rest of the heat exchangers were designed as double pipe heat exchangers. E-117 has a total heat transfer area of 23.88 m^2 and heats up 50.49 kg/s of liquid oxygen from -183°C to -140°C using 6.571 kg/s of steam at 100°C. E-123 has a total heat transfer area of 477.7 m^2 and cools down 22.19 kg/s of water from 124.6°C to 30°C using 42.28 kg/s of cooling water at 25°C. E-127 has a total heat transfer area of 2791 m^2 and cools down 96.07 kg/s of water from 90°C to 30°C using 115.7 kg/s of cooling water at 25°C. E-129 has a total heat transfer area of 6542 m^2 and heats up 137.4 kg/s of saturated MEA from 29°C to 100°C by cooling down 98.08 of recycled MEA from 103°C to 25°C. E-133 has a total heat transfer area of 46.82 m^2 and heats up 9.808 kg/s of recycled MEA from 103°C to 110°C using 38.58 g/s of water at 115°C. E-148 has a total heat transfer area of 12.15 m^2 and condenses 5.53 kg/s of bio-oil from 550°C to 396.5°C. E-150 has a total heat transfer area of 6.386 m^2 and condenses 1.659 kg/s of bio-oil from 396.5°C to 277.6°C. Both condensers are 70% efficient.

Gas Movers and Compressors: The axial compressor (G-153) is designed to compress the recycled bio-gas to the coal gasifier from 13 bara to 16 bara and is made of carbon steel. This is accomplished through a series of rotating blades that increase the velocity of the bio-gas and, therefore, its pressure. This compressor has a fluid power of 13.27 W and compresses 274.5 g/s of bio-gas.

Gas-Solid Contacting Equipment: The rotary dryer (B-143) is a direct contact dryer, made of carbon steel, that is designed to dry the raw biomass to a moisture content of 10%. This is accomplished by feeding the biomass into the elevated side of the rotary dryer and allowing it to slowly migrate to the discharge end while hot bio-gas flows, counter-currently, up through the dryer (Ulrich, 2004). This dryer has an internal volume of 4.731 m^3 and heats 18.96 kg/s of raw biomass from 25°C to 75°C using 1.095 kg/s of bio-gas at 180.6°C.

Drivers and Power Recovery Machines: The radial gas expander (N-155) is designed to expand the gas from the coal gasifier from 43.5 bara to 14 bara and is made of carbon steel. This is accomplished by decreasing the velocity of the gas in a manner opposite of the axial compressor. This expander has a shaft power of 14,000 kW and expands 133.5 kg/s of gas.

Separators: There are three cyclones (H-119, H-146, and H-147), all made of carbon steel, that are used in this process. These cyclones use centrifugal forces to remove particulates (slag for H-119 and bio-char for H-146 and H-147) from gaseous streams (gas for H-119 and bio-gas for H-146 and H-147) and are 90% efficient. The volumetric flow rates through each cyclone, respectfully, are 6.244 m^3/s, 0.3285 m^3/s, and 0.3389 m^3/s. The settler (H-121) is a single-compartment drum made of carbon steel. It is designed to remove slag from water. It has a filter area of 13.17 m^2 and 22.82 kg/s of water and slag flow through it. The vibratory screen (H-122) is also made of carbon steel and it designed to remove slag from water. Its power consumption is 23.85 kW and 1.255 kg/s of water and slag flows through it. There are two gas bag filters (H-152 and H-154), both made of carbon steel, that are designed to remove either bio-oils from bio-gas (H-152) or bio-char from bio-oil (H-154). The volumetric flow rate of bio-oils and bio-gas through H-152 is 0.3821 m^3/s the volumetric flow rate of bio-char and bio-oil through H-154 is 6571 cm^3/s. They are both 95% efficient. The electrostatic precipitator (H-151) uses an electric field to apply a charge to the aerosol bio-vapors so that they can be collected and removed from the bio-gas (Ulrich, 2004). The volumetric flow rate of bio-vapors and bio-gas through the electrostatic precipitator is 0.3689 m^3/s. It is made of carbon steel. It is 95% efficient.

Crushers, Mills, and Grinders: The jaw crusher (C-113) is designed to crush the raw coal into a particle size of about 1 cm. It is ideal for hard solids and abrasive materials (Ulrich, 2004). The power consumption of the jaw crusher is 131.7 kW and the mass flow rate of raw coal through it is 52.04 kg/s. There are two rolling compression grinders (C-114 and C-144) that are designed to crush either coal (C-114) or biomass (C-144) to a particle size of about 100 µm. Rolling compression grinders are ideal for soft materials and wet grinding (Ulrich, 2004). The power consumption of C-114 is 238.7 kW and the mass flow rate of coal through it is 52.04 kg/s. The power consumption of C-144 is 52.34 kW and the mass flow rate of biomass is 11.61 kg/s.

Conveyors: There are two belt conveyors (J-111 and J-141) that are designed to convey raw coal (J-111) or raw biomass (J-141) to a storage hopper. Both conveyors have a height of 25 meters, a width of one meter, a conveying distance of 50 meters, and an incline angle of 45°. J-111 conveys 52.04 kg/s of coal and J-141 conveys 18.96 kg/s of raw biomass. The screw conveyor (J-145) is designed to convey dried biomass to the biomass pyrolysis reactor. It has a conveying distance of 25 meters and a width of 0.325 meters. It conveys 11.61 kg/s of dried biomass.

Storage Vessels: There are two atmospheric bins (F-112 and F-142) that are designed to store coal (F-112) or biomass (F-142). Both are made of carbon steel. Given a residence time of eight hours, F-112 has a volume of 2053 m^3 and F-142 has a volume of 1021 m^3.

Reactors: The gasification reactor (R-110) is a top-fired, coal-water slurry feed, slagging, entrained-flow gasifier. Essentially, it acts as a pyrolysis furnace with a large operating temperature to allow for the conversion of coal into syngas. This process needs five gasification reactors to accommodate the extraordinary heating duty needed to cool the syngas from 1371°C to 250°C. Each unit has a heating duty of 55,000 kJ/s and the cooling pipes are made of stainless steel. They all operate at a pressure of 44 bara and 1371°C. The biomass pyrolysis reactor (R-140) is a fluidized bed reactor. It also acts as a pyrolysis furnace. Steam from R-110 is used to heat the dried biomass within the pyrolysis reactor. It has a heating duty of 7026 kJ/s and is made of stainless steel. It operates at a pressure of 16 bara and 550°C.

Process Vessels: The Venturi scrubber (D-120) is used to remove solid particles from large-volume gas streams via water. The advantage of Venturi scrubbers is that there is a minimal pressure drop across the unit. For this process, the Venturi scrubber is designed to remove slag from the product gas stream. It is made of carbon steel and the volumetric flow rate of the gas through it is 22.21 m^3/s. The general scrubber (D-125) is designed to further cool down the gas stream through direct contact with water. Given a residence time of ten seconds, the column has a diameter of 3.589 meters and a height of 17.95 meters. The scrubber is made of carbon steel and the mass flow rate of gas through it is 132.9 kg/s. It is assumed to be 99.9% efficient. The absorber (D-128) is designed to remove unwanted components from a gas stream. This is accomplished by flowing a solvent, such as MEA, across the gas stream and allowing certain components of the gas stream to diffusive into the liquid stream. Using solubility properties, it is possible to determine the composition of the liquid and vapor phases as well as the number of theoretical trays needed to achieve a certain separation. The absorber in this process has a diameter of 3.001 meters and a height of 15.01 meters. It is made of carbon steel and the total mass flow rate through it is 211.2 kg/s. The stripper (D-130) is designed to strip away waste gases from a solvent, such as MEA, so that the solvent can be re-used. Stripping is a physical separation process where one or more components are removed from liquid streams by vapor streams. In this process, the stripper has a diameter of 3.086 meters and a height of 15.43 meters. It is made of carbon steel and the total mass flow rate through it is 147.2 kg/s. It is assumed that the stripper is 99% efficient.

PROCESS CONTROL STRATEGY

A control system has been added to the gasification reactor to monitor the pressure and temperature within the reactor. If the temperature is too high, the coal slurry stream can be adjusted to prevent further reaction and, therefore, higher temperatures. The system can also be designed to supply cooling water to the reactor jackets if the reaction temperature exceeds the recommended operating temperature. If the pressure is too high, the liquid oxygen feed can be adjusted to lower the pressure. Temperature and pressure gauges have been installed on the reactor so operators can monitor them and take appropriate action if the temperature or pressure of the reactor exceeds the bounds of the design parameters.

The reactor has been fitted with the following controls, as shown in Figure 1:

1.) Pneumatic valves (K-156, and K-157) have been installed to control the flow rate of the liquid oxygen feed and the coal slurry stream to the gasification reactor (G-110). The flow rate of the liquid oxygen feed adjusts the pressure within the reactor and the flow rate of the coal slurry stream controls the temperature of the reactor.

2.) PID controllers (K-158, K-159, K-160, and K-161) have been installed to monitor the reactor's temperature and pressure as well as to control the pneumatic valves. Temperature and pressure readings from sensors located within the reactor are converted into an electrical signal that travels to the respective PID controller. Each controller then manipulates the air pressure to the pneumatic valve, thus opening or closing the pneumatic valve. This affects the flow rate of each stream and, thereby, adjusts either the temperature or the pressure within the reactor.

3.) A similar process can be applied to other parts of the process. For example, to lower the temperature of the reactor by adjusting the flow rate of cooling water entering the reactor jacket.

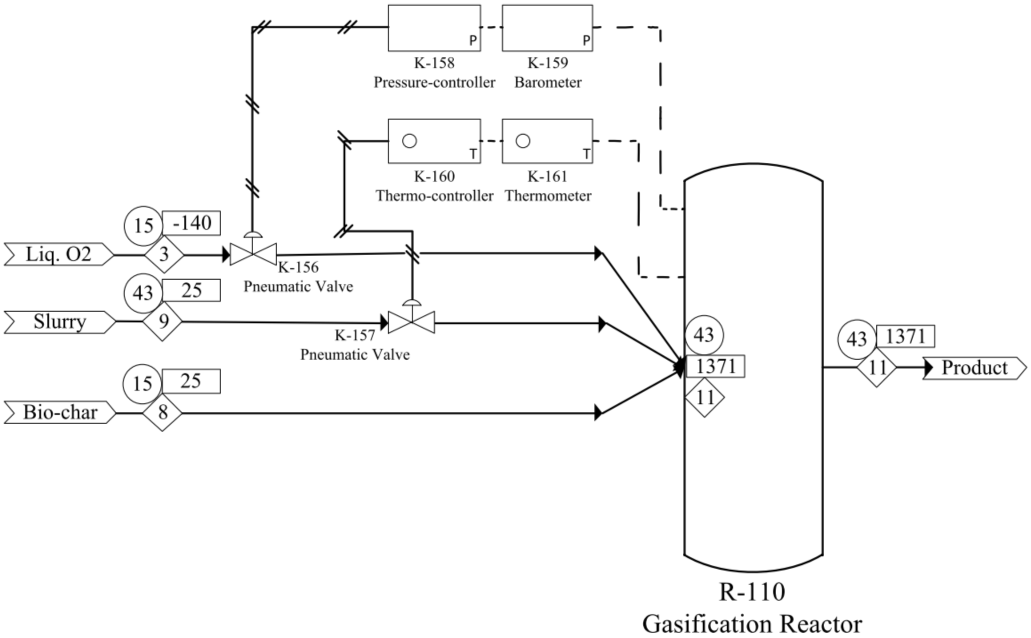


Figure 1: A diagram of possible controls surrounding the Gasification Reactor (R-110).

SAFETY

This safety review consists of two sections: 1.) Chemical Hazards & Safety Measures and 2.) Process Hazards & Safety Measures. The first section discusses the dangers of the chemicals used in this process and the safety measures that have been taken to prevent accidents from occurring. For specific and detailed safety precautions and health hazards of each chemical please referrer to the referenced MSDS sheets. The second section discusses the dangers inherent in this process and the associated safety measures that have been taken to prevent accidents from occurring.

1.) Chemical Hazards and Safety Measures

a.) Hazards

1.) Liquid Oxygen:
   - i. Oxidizer.
   - ii. Contact with combustible material may cause fire.
   - iii. Extremely cold liquid and gas under pressure.
   - iv. May cause severe frostbite.
   - v. Refer to Reference No. 9.

2.) Hydrogen Sulfide:
   - i. Flammable gas.
   - ii. May cause flash fire.
   - iii. May be fatal if inhaled.

        iv. May cause eye and skin irritation.
        v. Keep away from heat, sparks, and flame.
        vi. Do not breathe gas and avoid contact with eyes, skin, and clothing.
        vii. Use only with adequate ventilation.
        viii. Refer to Reference No. 6.

    3.) Methane:
        i. Extremely flammable.
        ii. May cause flash fire.
        iii. Can cause rapid suffocation.
        iv. May cause severe frostbite.
        v. Refer to Reference No. 7.

    4.) Monoethanolamine (MEA):
        i. Causes eye and skin burns.
        ii. Harmful if inhaled or absorbed through skin.
        iii. Harmful if swallowed.
        iv. If exposure occurs, evacuate area and keep upwind of spill.
        v. Refer to Reference No. 8.

    5.) Carbon Monoxide:
        i. Flammable gas.
        ii. May cause flash fire.
        iii. May be fatal if inhaled.
        iv. Keep away from heat, sparks, and flame.
        v. Avoid breathing gas.
        vi. Use only with adequate ventilation.
        vii. Refer to Reference No. 5.

b.) Safety Measures

To address the previously mentioned hazards the following safety measures should be followed:

1.) All Material Data and Safety Sheets should be printed out and kept within easy access.
2.) Safety glasses should be worn at all times.
3.) All operators should know the location of all eye-wash stations, emergency showers, and fire extinguishers.

2.) Process Hazards and Safety Measures

a.) Hazards

1.) Exothermic chemical reaction.

2.) Consequences of deviation from designed operation:
    i. Loss of water to heat exchanger. May result in a runaway reaction.
    ii. Reduction in reactor temperature. May result in a runaway reaction.
    iii. Piping leaks. May results in contamination, fire, or explosion.

iv. Spring loaded or pressure relief valves leak. May result in safety features not operating under specification.

v. Power failure to cooling pumps. May result in a runaway reaction.

b.) Safety Measures

To address the previously mentioned hazards the following safety measures have been added to this design:

1.) A spring loaded relief valve and a bursting disc have been installed on both reactors to allow for a release of excess pressure in the event of a runaway reaction. Figure 2 shows a spring loaded relief valve and a bursting disc fitted to the gasification reactor (R-110).

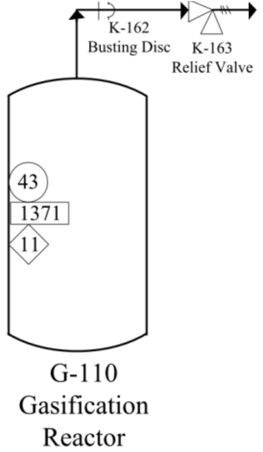


Figure 2: A spring loaded relief valve (K-163) and a bursting disc (K-162) for the Gasification Reactor (G-110).

2.) Cooling water is supplied to the reactor jackets to prevent the reactors from operating above the recommended temperature.

3.) All storage vessels have been fitted with pressure relief valves to protect against back flow. For example, the stream line from the liquid oxygen storage vessel must have a pressure relief valve in order to prevent any back flow from the Gasification Reactor (G-110). A representation of this system is shown in Fig. 3.

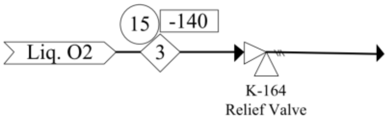


Figure 3: A pressure relief valve (K-164) after the liquid oxygen storage vessel.

4.) Pressure relief valves have also been installed on the discharge side of all pumps, compressors, and expanders. Figure 4 shows an example of a compressor with a pressure relief valve on its discharge side.

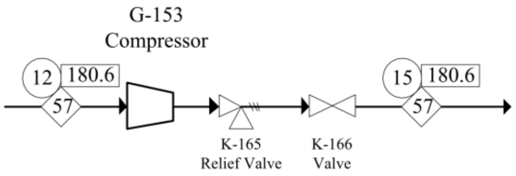


Figure 4: A pressure relief valve (K-165) on the discharge side of a compressor (G-112).

5.) Double block and bleeds have been installed to blocked in sections of cool liquid-liquid lines that are exposed to heat as well as feed lines. Figure 5 shows an example of a double block and bleed that consists of two valves and a relief valve.

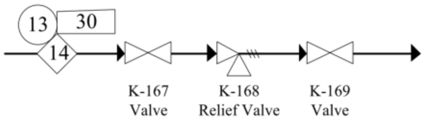


Figure 5: An example of a double-block-and-bleed system.

6.) Line and equipment checks should be performed by the operators periodically.

7.) Generators should be installed to ensure that necessary processes, like cooling water, still operate during a power failure.

8.) Sensors should be installed on the reactors to alert the operators if the temperature or pressure of the reactors exceeds design specifications.

ENVIRONMENTAL

The main environmental advantage of this plant is the reduction of carbon dioxide emissions. By burning bio-oils derived from biomass, instead of burning crude-oil or even coal, less carbon dioxide gas will accumulate in the atmosphere. However, this is only true if the biomass source is replenished. As biomass grows, it absorbs as much carbon dioxide from the atmosphere as it emits when it is burned. If the biomass source is not replenished, then burning bio-oils could have an even greater effect on the accumulation of carbon dioxide in the atmosphere then burning either crude-oil or coal. As such, it is imperative that, if industrial bio-oil plants become a more economically attractive option than industrial syngas plants, a concerted effort for reforestation is established and maintained.

UTILITY SUMMARY

Table 1 itemizes each utility by user. The table gives (1) the user, (2) the specific utility, (3) mass flow rate in kg/s, (4) mass flow rate in kg/yr, (5) price of utility in \$/kg, (6) volumetric flow rate in m^3/s, (7) volumetric flow rate in m^3/yr, (8) price of utility in \$/m^3, (9) electricity usage in kW, (10) electricity usage in kWh, (11) price of electricity usage in \$/kWh, and (12) price of utility in \$/yr.

Table 1: Utility Table Itemizing All Major Sources of Utility Usage

User	Utility	kg/s	kg/yr	$/kg	m^3/s	m^3/yr	$/$m^3$	kW	kWh	$/kWh	$/yr
E-117	Steam	6.571	1.87E+08	$0.0161							$3,010,036
E-118	Cooling Water	15.65	4.44E+08	$0.0001	0.01565	4.44E+05	$0.1378				$61,218
E-123	Cooling Water	42.28	1.20E+09	$0.0001	0.04228	1.20E+06	$0.1378				$165,386
E-127	Cooling Water	115.7	3.28E+09	$0.0001	0.1157	3.28E+06	$0.1378				$452,582
Waste Disposal	Waste Water	19.74	5.60E+08	$0.0013	0.01974	5.60E+05	$1.2746				$714,096
	Slag Cake	0.6899	1.96E+07	$0.1785							$3,495,212
C-113	Electricity							131.7	1038323	$0.104	$107,934
C-114	Electricity							238.7	1881911	$0.104	$195,625
C-144	Electricity							52.34	412649	$0.104	$42,895
G-153	Electricity							0.01327	104.621	$0.104	$11
H-122	Electricity							23.85	188033	$0.104	$19,546
J-111	Electricity							6.306	49716.5	$0.104	$5,168
J-141	Electricity							2.713	21389.3	$0.104	$2,223
J-145	Electricity							14.09	111086	$0.104	$11,547
L-116	Electricity							350.9	2766496	$0.104	$287,577
L-124	Electricity							3.916	30873.7	$0.104	$3,209
L-126	Electricity							5.651	44552.5	$0.104	$4,631
L-131	Electricity							11.51	90744.8	$0.104	$9,433
L-132	Electricity							0.5756	4538.03	$0.104	$472
L-149	Electricity							0.2706	2133.41	$0.104	$222
M-115	Electricity							203.1	1601240	$0.104	$166,449
N-155	Electricity							13961	1.1E+08	$0.104	$11,441,623
										TOTAL	**$20,197,093**

OPERATING COST SUMMARY

Table 2 itemizes the cost of each operating cost. The tables gives each category's annual cost along with, when applicable, its cost per kg, m^3, or kWh. The table breaks down the utilities into mass and volumetric flow rates of material usage along with kWh of electricity usage.

EQUIPMENT INFORMATION SUMMARY

Table 3 itemizes the cost of each process equipment item. The table gives the (1) name and type, (2) number, (3) capacity or size specification as well as the material of construction, (4) purchase cost of the base material, (5) base bare module factor, (6) material factor, (7) pressure factor, and (8) actual bare module cost for each equipment.

CAPITAL ESTIMATE

Table 4 presents the total capital investment for this plant. The Total Bare Module Cost is the sum of process equipment costs from Table 3. Contingency and Fee is 18% of the Total Bare Module Cost. Total Module Cost is the sum of Total Bare Module Cost and Contingency and Fee. Auxiliary Facilities is 30% of the Total Module Cost. Grass Roots Capital is the sum of Total Bare Module Cost and Auxiliary Facilities. Working Capital is 20% of the Grass Roots Capital. Total Capital Investment is the sum of Grass Roots Capital and Working Capital.

Table 4: Total Capital Investment

Total Bare Module Cost	$93,700,00
Contingency and Fee	$16,900,00
Total Module Cost	$111,000,000
Auxiliary Facilities	$33,100,000
Grass Roots Capital	$144,000,000
Working Capital	$28,800,000
Total Capital Investment	$173,000,000

ECONOMIC ANALYSIS

Figure 6 shows the Yearly Discounted Cash Flow ($) over Time (years). It displays the cash flow for an interest rate of 0%, 10%, and 13%. The Net Present Value of the plant is $194 Million with a 0% interest rate, $21 Million with a 10% interest rate, and $0 with a 13% interest rate. Figure 6 also shows the Net Payout Time (8.25 years), the Payback Period (4.5 years), and the Discounted Break-even Point (11.5 years).

Table 5 summaries the economic parameters derived from Graph 1 along with the Net Rate of Return (20%), the Discounted Cash Flow Rate of Return (12.59%), and the Selling Price of Bio-oils ($0.79/kg).

TABLE 2: OPERATING COST SUMMARY **Job Title: Biomass to Bio-oils: Companion Coal Gasification** Capacity: 2.24×10^8 kg/yr of bio-oils	Date to Which Estimate Applies: 18 May 2014 Cost Index Type: CE Plant Cost Index Value: 595	Page: 20 of 51 By: Alexandra Eicher Date: 08 May 2013

Capital					
Fixed capital, C_{FC}				$143,757,255	
Working capital (10-20% of fixed capital), C_{WC}				$28,751,451	
Total capital investment, C_{TC}				$172,508,705	
Manufacturing Expenses					
Direct				**\$/yr**	**\$/kg**
Raw materials				$696,735,641	$0.63
By-product credits				($841,455,851)	$0.41
Catalysts and solvents				$49,399	$1.91
Operating labor				$1,257,906	
Supervisory and clerical labor (10-20% of operating labor)				$251,581	
Utilities					
Steam	186,500,750 kg/yr	15 barg @	$0.0161 \$/kg	$3,010,036	$0.0161
Electricity	118,312,314 kWh @	$0.104 \$/kWh		$12,298,565	
Cooling water	4,928,036 m^3/yr @	$0.14 \$/m^3		$679,088	$0.0001
Waste disposal	19,581,018 kg/yr @	$0.18 \$/kg	$3,495,212 \$/yr	$4,209,307	$0.1798
	560,269 m^3/yr @	$1.27 \$/m^3	$714,096 \$/yr		
Maintenance and repairs (2-10% of fixed capital)				$14,375,725	
Operating supplies (10-20% of maint & repairs)				$2,875,145	
Laboratory charges (10-20% of operating labor)				$251,581	
Patents and royalties (0-6% of total expense)				$8,442,000	
Total, A_{DME}				($97,019,876)	
Indirect					
Overhead (payroll and plant), packaging, storage (50-70% of op. Labor+supervision+ maint.)				$11,119,649	
Local taxes (1-3% of fixed capital)				$4,312,718	
Insurance (1-2% of fixed capital)				$2,875,145	
Total, A_{IME}				$18,307,512	
Total manufacturing expense, $A_{ME}=A_{DME}+A_{IME}$				($78,712,365)	
General Expenses					
Administrative costs (25% of overhead)				$2,779,912	
Distribution and selling (10% of total expense)				$14,070,000	
Research and development (5% of total expense)				$7,035,000	
Total general expense, A_{GE}				$23,884,912	
Depreciation (approximately 10% of fixed capital), A_{BD}				$14,375,725	
Total Expenses, A_{TE}				$140,700,000	
Revenue from Sales	(224,000,000 kg/yr @	$0.79 \$/kg), A_s		$176,086,401	$0.79
Net annual profit, A_{NP}				$35,386,401	
Income taxes (net annual profit times the tax rate), A_{IT}				$12,385,240	
Net annual profit after taxes (A_{NP}-A_{IT}), A_{NNP}				$23,001,161	
				Aftertax rate of return, i = (1.5 A_{NNP}/C_{TC}) x 100 =	20 %

TABLE 3: EQUIPMENT INFORMATION SUMMARY
Job Title: Biomass to Bio-oils: Companion Coal Gasification
Capacity: 2.24×10^{8} kg/yr of bio-oils

Date to which estimate applies: 18 May 2014
Cost Index Type: CE Plant
Cost Index Value: 595

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By: Alexandra Eicher
Date: 08 May 2013

Equipment Identification	Number	Capacity or Size Specifications (Material of Construction)	Purchased Equipment Cost (base material) Year 2013	Base Bare Module Factor, F_{BM}	Material Factor, F_M	Pressure or other Factors, F_P	Actual Bare Module Cost, C_{BM}
Mixers							
Slurry Tank: Agitator (Axial Turbine)	M-115	Power Consumption (kW): 101.55 (2 units) (Carbon Steel)	$231,868	2.0			$463,737
Total Mixers	1						$463,737
Pumps							
Centrifugal (Radial)	L-124	Shaft Power (kW): 3.196 (Cast Iron)	$8,337		1.00	1.09	$29,968
Centrifugal (Radial)	L-126	Shaft Power (kW): 5.651 (Cast Iron)	$10,320		1.00	1.11	$37,488
Centrifugal (Radial)	L-131	Shaft Power (kW): 11.51 (Cast Iron)	$13,671		1.00	1.06	$48,607
Centrifugal (Radial)	L-132	Shaft Power (kW): 0.5756 (Cast Iron)	$4,733		1.00	1.06	$16,829
Centrifugal (Radial)	L-149	Shaft Power (kW): 0.2706 (Cast Iron)	$3,846		1.00	1.18	$14,385
Reciprocating (Positive Displacement)	L-116	Shaft Power (kW): 175.45 (2 units) (Cast Iron)	$678,063		1.00	1.15	$2,504,289
Total Pumps	6						$2,651,566
Heat Exchangers							
Shell and Tube (Double Pipe)	E-117	Surface Area (m^2): 23.88 (Carbon Steel/Carbon Steel)	$15,323		1.00	1.00	$48,730
Shell and Tube (Double Pipe)	E-123	Surface Area (m^2): 477.7 (Carbon Steel/Carbon Steel)	$241,627		1.00	1.00	$768,396
Shell and Tube (Double Pipe)	E-127	Surface Area (m^2): 558.2 (5 units) (Carbon Steel/Carbon Steel)	$1,407,529		1.00	1.00	$4,476,083
Shell and Tube (Double Pipe)	E-129	Surface Area (m^2): 594.818 (11 units) (Carbon Steel/Carbon Steel)	$3,295,698		1.00	1.00	$10,480,648
Shell and Tube (Double Pipe)	E-133	Surface Area (m^2): 46.82 (Carbon Steel/Carbon Steel)	$25,102		1.00	1.00	$79,827
Condenser: Shell and Tube (Double Pipe)	E-148	Surface Area (m^2): 12.15 (Carbon Steel/Carbon Steel)	$9,945		1.00	1.00	$31,625
Condenser: Shell and Tube (Double Pipe)	E-150	Surface Area (m^2): 6.386 (Carbon Steel/Carbon Steel)	$6,838		1.00	1.00	$21,745
Shell and Tube (Fixed Tube Sheet and U-tube)	E-118	Surface Area (m^2): 539.5 (2 units) (Carbon Steel/Carbon Steel)	$112,505		1.00	1.05	$365,028
Total Heat Exchangers	8						$16,272,082
Gas Movers and Compressors							
Compressor (Axial)	G-153	Fluid Power (kW): 0.01327 (Carbon Steel)	$23,364	3.5			$81,775
Total Gas Movers and Compressors	1						$81,775
Gas-Solid Contacting Equipment							
Rotary Dryer (Direct)	B-143	Internal Volume (m^3): 4.731 (Carbon Steel)	$90,770	2.3			$208,771
Total Gas-Solid Contacting Equipment	1						$208,771
Drivers and Power Recovery Machines							
Radial Gas Expander	N-155	Shaft Power (kW): 1269.182 (11 units) (Carbon Steel)	$2,575,076	3.0			$7,725,229
Total Drivers and Power Recovery Machines	1						$7,725,229
Separators							
Cyclone	H-119	Volumetric Flow Rate (m^3/s): 6.244(Carbon Steel)	$13,448	3.0			$40,343
Cyclone	H-146	Volumetric Flow Rate (m^3/s): 0.3285 (Carbon Steel)	$3,138	3.0			$9,415
Cyclone	H-147	Volumetric Flow Rate (m^3/s): 0.3389 (Carbon Steel)	$3,167	3.0			$9,502
Settler (Single-compartment Drum)	H-121	Filter Area (m^2): 13.17 (Carbon Steel)	$293,802	2.4			$705,125
Vibratory Screen	H-122	Power Consumption (kW): 23.85 (Carbon Steel)	$4,958	2.8			$13,882
Gas Bag Filter	H-152	Volumetric Flow Rate (m^3/s): 0.3821 (Carbon Steel)	$44,282	2.2			$97,421
Gas Bag Filter	H-154	Volumetric Flow Rate (m^3/s): 0.006571 (Carbon Steel)	$44,282	2.2			$97,421
Electrostatic Precipitator	H-151	Volumetric Flow Rate (m^3/s): 0.3689 (Carbon Steel)	$455,900	2.3			$1,046,271
Total Separators	8						$2,019,380
Crushers, Mills, and Grinders							
Jaw Crusher	C-113	Capacity (kg/s): 52.04	$269,188	2.1			$565,294
Rolling Compression Grinder	C-114	Capacity (kg/s): 17.347 (3 units)	$1,411,644	2.8			$3,952,603
Rolling Compression Grinder	C-144	Capacity (kg/s): 11.61	$363,767	2.8			$1,018,549
Total Crushers, Mills, and Grinders	3						$5,536,446
Conveyors							
Belt	J-111	Conveying Distance: 50 m (Height: 25m, Width: 1m)	$73,572	2.4			$176,574
Belt	J-141	Conveying Distance: 50 m (Height: 25m, Width: 1m)	$73,572	2.4			$176,574
Screw: Auger	J-145	Conveying Distance: 25m, (Width: 0.325 m)	$13,814	2.2			$30,391
Total Conveyors	3						$383,539
Storage Vessels							
Hopper (Atmospheric Bin)	F-112	Volume (m^3): 2053 (Carbon Steel)	$9,375	2.1			$19,688
Hopper (Atmospheric Bin)	F-142	Volume (m^3): 1021 (Carbon Steel)	$5,826	2.1			$12,235
Total Storage Vessels	2						$31,923
Process Vessels							
Gasification Reactor	R-110	Heating Duty (kJ/s): 54695.4 (5 units) (Stainless Steel)	$19,309,589	2.7		1.03	$53,905,852
Pyrolysis Reactor	R-140	Heating Duty (kJ/s): 7026 (Stainless Steel)	$720,158	2.7		0.99	$1,921,394
Venturi Scrubber	D-120	Volumetric Flow Rate (m^3/s): 22.21 (Carbon Steel)	$170,011	2.5			$425,027
Scrubber	D-125	Column Diameter (m): 3.589; Height (m): 17.95 (Carbon Steel)	$151,290		1.00	1.70	$830,690
Absorber	D-128	Column Diameter (m): 3.001; Height (m): 15.01 (Carbon Steel)	$113,818		1.00	1.67	$617,895
Stripper	D-130	Column Diameter (m): 3.086; Height (m): 15.43 (Carbon Steel)	$119,038		1.00	1.63	$638,680
Total Process Vessels	6						$58,339,538
						Total Bare Module Cost	**$93,713,986**

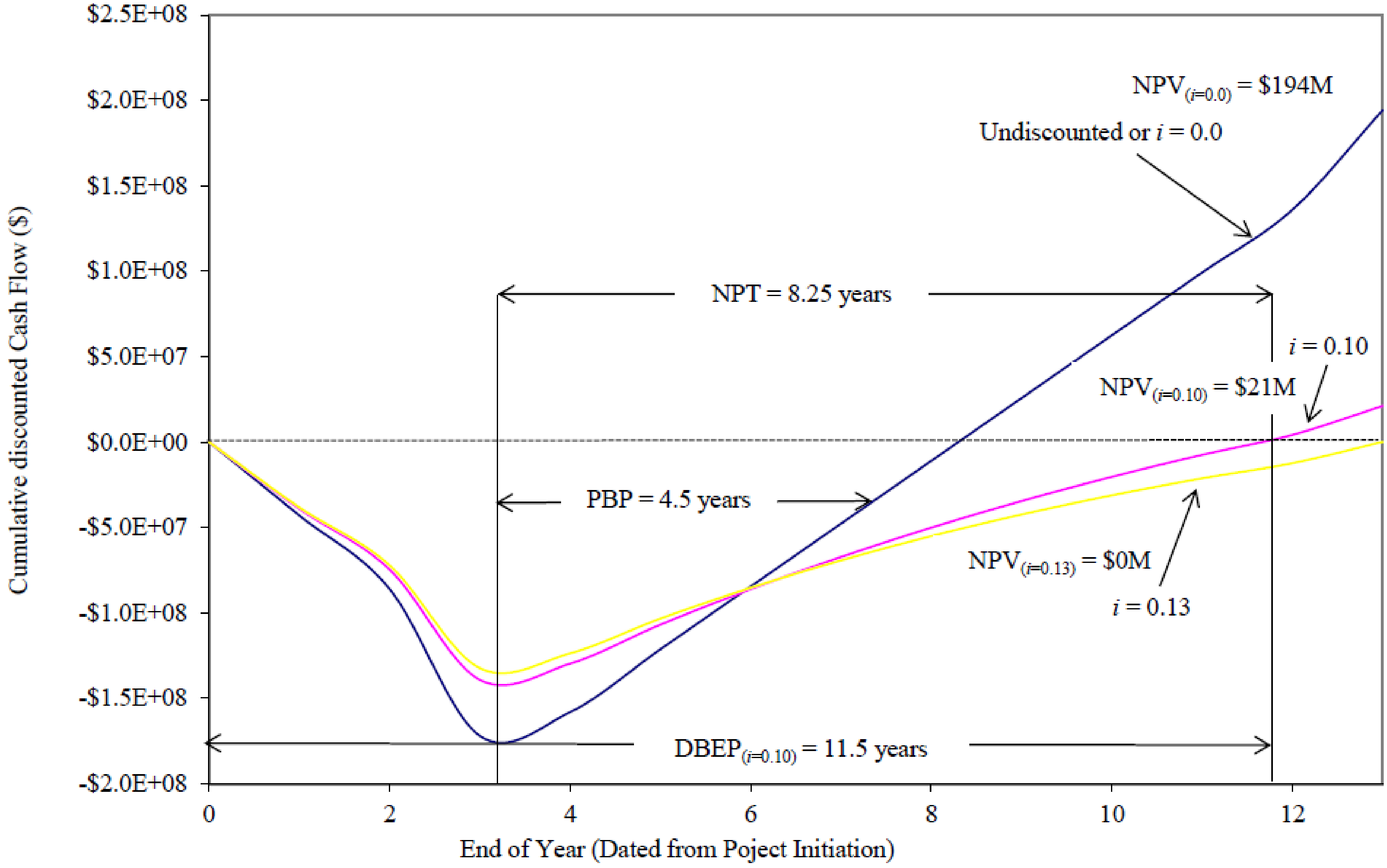

Figure 6: Yearly Discounted Cash Flow ($) per Year

Table 5: Summarization of Economic Parameters

Selling Price of Bio-oils	$0.79/kg
NPV (*i* = 0.13)	$0
NPV (*i* = 0.10)	$21,000,000
NPV (*i* = 0.10)	$21,000,000
DCFRR	12.59%
DBEP	11.5 years
NRR	20%
NPT	8.25 years
PBP	4.5 years

INNOVATION AND OPTIMIZATION

This plant design features a few key, innovative systems. First, steam from the gasifier is used to heat the biomass. This takes advantage of excess heat, in the form of steam, from the coal gasifier. Not only does this increase the thermal efficiency of the gasifier but it also provides a convenient and inexpensive method to heat the biomass. Second, bio-char from the pyrolysis of biomass is recycled to the gasifier. This decreases the amount of raw coal needed to be fed to the coal gasifier, thus, decreasing the cost of raw materials. Third, the bio-gas from the pyrolysis of biomass is used to dry the raw biomass to a moisture content of 10% as well as to blow the biomass up through the fluidized bed. This decreases waste streams, and the cost associated with processing waste streams, leaving the plant.

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COMPUTER PROGRAMS

MATERIAL AND ENERGY BALANCES - EES

Input:

```
"This unit system is set to temperature in K, pressure in Bara, energy in kJ, and specific properties to a molar basis"

"Ultimate Compostion of Coal A in wt% (Zheng, 2005)"
wt%_C_1=0.7048
wt%_H_1=0.0485
wt%_N_1=0.014
wt%_S_1=0.0364
wt%_O_1=0.0783
wt%_Ash_1=0.118

"Given a Coal Feed to Gasifier Flow Rate of 53.3 kg/s (Zheng, 2005)"
Coal_1=53.3-Biochar_42
C_1=wt%_C_1*Coal_1
H_1=wt%_H_1*Coal_1
N_1=wt%_N_1*Coal_1
S_1=wt%_S_1*Coal_1
O_1=wt%_O_1*Coal_1
Ash_1=wt%_Ash_1*Coal_1

"Other Feed Rates in kg/s (Zheng, 2005)"
O2_3=0.97*Coal_1

"Composition of Raw Gases from Texaco Process in mol% (Zheng, 2005)"
mol%_O2_11=0.007
mol%_N2_11=0.01
mol%_H2_11=0.286
mol%_CO_11=0.384
mol%_CO2_11=0.126
mol%_H2O_11=0.174
mol%_CH4_11=0.0015
mol%_H2S_11=0.0096

"Molecular Weights of Raw Gases from Texaco Process in kg/kmol"
MW_O2=32
MW_N2=28
MW_H2=2
MW_CO=28
MW_CO2=44
MW_H2O=18
MW_CH4=16
MW_H2S=34

"Other Molecular Weights in kg/kmol"
MW_C=12
MW_H=1
MW_N=14
MW_S=32
MW_O=16
```

```
"Composition of Raw Gases from Texaco Process in kg using a 1 kmol basis"
mass_O2_11=mol%_O2_11*MW_O2
mass_N2_11=mol%_N2_11*MW_N2
mass_H2_11=mol%_H2_11*MW_H2
mass_CO_11=mol%_CO_11*MW_CO
mass_CO2_11=mol%_CO2_11*MW_CO2
mass_H2O_11=mol%_H2O_11*MW_H2O
mass_CH4_11=mol%_CH4_11*MW_CH4
mass_H2S_11=mol%_H2S_11*MW_H2S
mass_Total_11=mass_O2_11+mass_N2_11+mass_H2_11+mass_CO_11+mass_CO2_11+mass_H2O_11+mass_CH4_11+mass_H2S_11

"Composition of Raw Syngas from Texaco Process in wt%"
wt%_O2_11=mass_O2_11/mass_Total_11
wt%_N2_11=mass_N2_11/mass_Total_11
wt%_H2_11=mass_H2_11/mass_Total_11
wt%_CO_11=mass_CO_11/mass_Total_11
wt%_CO2_11=mass_CO2_11/mass_Total_11
wt%_H2O_11=mass_H2O_11/mass_Total_11
wt%_CH4_11=mass_CH4_11/mass_Total_11
wt%_H2S_11=mass_H2S_11/mass_Total_11

Product_11=Coal_1+Biochar_42+H2O_2+O2_3-Ash_1
O2_11=wt%_O2_11*Product_11
N2_11=wt%_N2_11*Product_11
H2_11=wt%_H2_11*Product_11
CO_11=wt%_CO_11*Product_11
CO2_11=wt%_CO2_11*Product_11
H2O_11=wt%_H2O_11*Product_11
CH4_11=wt%_CH4_11*Product_11
H2S_11=wt%_H2S_11*Product_11
Slag_11=Ash_1+Ash_42

"---------------------------------H-119---------------------------------"
Slag_13=Slag_11*0.9
Slag_12=Slag_11*0.1

"---------------------------------E-117---------------------------------"
"Assume the liquid oxygen feed is at 90 K."
"At 90 K, the enthalpy of vaporization of O2 212.98 kJ/kg."
"The heat capacity of oxygen gas is 29 kJ/kmol*K."
H_E117=(O2_3*212.98)+((O2_3/MW_O2)*29*(133-90))
Q_E117=O2_3*212.98
"cooling steam"
H_E117=(mol_H2O_10)*(enthalpy(Steam,x=1,P=16)-enthalpy(Steam,x=0,P=16))
H2O_10=mol_H2O_10*MW_H2O

"---------------------------------R-110---------------------------------"
T_ref=298.15 "reference temperature"
T_3=133
T_9=298.15
T_11_1=1644 "(Ackerson, 2012)"

P_ref=1 "reference temperature"
P_3=16
P_9=44
```

```
call JANAF('H2O(l)',T_ref:cph,hh,sh)

"Reactants"
C_9=C_1
H_9=H_1
N_9=N_1
S_9=S_1
O_9=O_1
Ash_9=Ash_1
H2O_9=H2O_2

mol_C_9=C_9/MW_C
mol_H_9=H_9/MW_H
mol_N_9=N_9/MW_N
mol_S_9=S_9/MW_S
mol_O_9=O_9/MW_O
mol_H2O_9=H2O_9/MW_H2O
mol_O2_3=O2_3/MW_O2

C_42=wt%_C_1*Biochar_42
H_42=wt%_H_1*Biochar_42
N_42=wt%_N_1*Biochar_42
S_42=wt%_S_1*Biochar_42
O_42=wt%_O_1*Biochar_42
Ash_42=wt%_Ash_1*Biochar_42

mol_C_42=C_42/MW_C
mol_H_42=H_42/MW_H
mol_N_42=N_42/MW_N
mol_S_42=S_42/MW_S
mol_O_42=O_42/MW_O

h_C_42=mol_C_42*(enthalpy(C,T=T_37)-enthalpy(C,T=T_ref))
h_H_42=mol_H_42*(enthalpy(H,T=T_37)-enthalpy(H,T=T_ref))
h_N_42=mol_N_42*(enthalpy(N,T=T_37)-enthalpy(N,T=T_ref))
h_S_42=mol_S_42*(enthalpy(S,T=T_37)-enthalpy(S,T=T_ref))
h_O_42=mol_O_42*(enthalpy(O,T=T_37)-enthalpy(O,T=T_ref))

h_H2O_9_ref=enthalpy(Water,T=T_ref,P=P_ref)
h_H2O_9_at=enthalpy(Water,T=T_9,P=P_9)
h_H2O_9=mol_H2O_9*(h_H2O_9_at-h_H2O_9_ref)

h_O2_3_ref=enthalpy(O2,T=T_ref)
h_O2_3_at=enthalpy(O2,T=T_3)
h_O2_3=mol_O2_3*(h_O2_3_at-h_O2_3_ref)

h_reactants=h_H2O_9+h_O2_3+h_C_42+h_H_42+h_N_42+h_S_42+h_O_42

"Products"
mol_N2_11=N2_11/MW_N2
mol_H2_11=H2_11/MW_H2
mol_CO_11=CO_11/MW_CO
mol_CO2_11=CO2_11/MW_CO2
mol_H2O_11=H2O_11/MW_H2O
mol_CH4_11=CH4_11/MW_CH4
```

```
mol_H2S_11=H2S_11/MW_H2S

h_N2_11=mol_N2_11*enthalpy(N2,T=T_ref)
h_H2_11=mol_H2_11*enthalpy(N2,T=T_ref)
h_CO_11=mol_CO_11*enthalpy(CO,T=T_ref)
h_CO2_11=mol_CO2_11*enthalpy(CO2,T=T_ref)
h_H2O_11=mol_H2O_11*enthalpy(H2O,T=T_ref)
h_CH4_11=mol_CH4_11*enthalpy(CH4,T=T_ref)
h_H2S_11=mol_H2S_11*enthalpy(H2S,T=T_ref)

"Heat of Combustion"
"Heat Capacity of Coal is 31400 kJ/kg"
h_combustion=(mol_C_9+mol_C_42)*enthalpy(CO2,T=T_ref)+(mol_H_9+mol_H_42)*0.5*hh+(
mol_S_9+mol_S_42)*enthalpy(SO2,T=T_ref)+31400*(Coal_1+Biochar_42)

"Heat of Reaction"
h_reaction=h_N2_11+h_H2_11+h_CO_11+h_CO2_11+h_H2O_11+h_CH4_11+h_H2S_11-
h_combustion-mol_H2O_9*hh

"Heating products from 298 to 1644"
"Heat Capacity of Slag is 2 kJ/kg"
lh_H2O_11=(mol_H2O_11)*(enthalpy(steam,x=1,P=44)-enthalpy(steam,x=0,P=44))
h_products=mol_N2_11*(enthalpy(N2,T=T_11_1)-
enthalpy(N2,T=T_ref))+mol_H2_11*(enthalpy(H2,T=T_11_1)-
enthalpy(H2,T=T_ref))+mol_CO_11*(enthalpy(CO,T=T_11_1)-
enthalpy(CO,T=T_ref))+mol_CO2_11*(enthalpy(CO2,T=T_11_1)-
enthalpy(CO2,T=T_ref))+mol_H2O_11*(enthalpy(H2O,T=T_11_1)-
enthalpy(H2O,T=T_ref))+mol_CH4_11*(enthalpy(CH4,T=T_11_1)-enthalpy(CH4,
T=T_ref))+mol_H2S_11*(enthalpy(H2S,T=T_11_1)-
enthalpy(H2S,T=T_ref))+Slag_11*2*(T_11_1-T_ref)
0=h_products+h_reactants+h_reaction+lh_H2O_11

"----------------------------------E-118----------------------------------"
T_11_2=523
T_7_2=1023 "This is the maximum temperature that you can create steam at from water
through a heat exchanger."
T_7_1=298
H_E118=+mol_H2_11*(enthalpy(H2,T=T_11_2)-
enthalpy(H2,T=T_11_1))+mol_CO_11*(enthalpy(CO,T=T_11_2)-
enthalpy(CO,T=T_11_1))+mol_CO2_11*(enthalpy(CO2,T=T_11_2)-
enthalpy(CO2,T=T_11_1))+mol_H2O_11*(enthalpy(H2O,T=T_11_2)-
enthalpy(H2O,T=T_11_1))+mol_CH4_11*(enthalpy(CH4,T=T_11_2)-enthalpy(CH4,
T=T_11_1))+mol_H2S_11*(enthalpy(H2S,T=T_11_2)-
enthalpy(H2S,T=T_11_1))+Slag_11*2*(T_11_2-T_11_1)
H_E118=mol_H2O_7*(enthalpy(H2O,T=T_7_1)-enthalpy(Steam,T=T_7_2,P=16))
H2O_7=mol_H2O_7*MW_H2O

"----------------------------------D-120----------------------------------"
"Material"
T_12=523
P_12=14
H2S_rho=Density(H2S,T=T_12,P=P_12)
N2_rho=Density(N2,T=T_12,P=P_12)
CO_rho=Density(CO,T=T_12,P=P_12)
CO2_rho=Density(CO2,T=T_12,P=P_12)
CH4_rho=Density(CH4,T=T_12,P=P_12)
```

```
H2O_rho=Density(H2O,T=T_12,P=P_12)
H2_rho=Density(H2,T=T_12,P=P_12)
Slag_16=Slag_12*0.999
Slag_15=Slag_12*0.001
H2_12=H2_11
CO_12=CO_11
CH4_12=CH4_11
CO2_12=CO2_11
H2S_12=H2S_11
N2_12=N2_11
H2O_12=H2O_11
Gas_12=H2S_12+N2_12+CO_12+CO2_12+CH4_12+H2O_12+H2_12
Vol_Gas_12=(H2S_12/MW_H2S/H2S_rho)+(N2_12/MW_H2/N2_rho)+(CO_12/MW_CO/CO_rh
o)+(CO2_12/MW_CO2/CO2_rho)+(CH4_12/MW_CH4/CH4_rho)+(H2O_12/MW_H2O/H2O_rh
o)+(H2_12/MW_H2/H2_rho)+Slag_12/2114
H2O_14=Vol_Gas_12
Vol_H2O_14=H2O_14/1000
Vol_D120=Vol_Gas_12+Vol_H2O_14
H2O_15=H2O_12
mol_H2O_15=H2O_15/MW_H2O
H2O_16=H2O_14
mol_H2O_16=H2O_16/MW_H2O
H2_15=H2_12
CO_15=CO_12
CH4_15=CH4_12
CO2_15=CO2_12
H2S_15=H2S_12
N2_15=N2_12

"Energy"
T_15=T_sat(Water,P=13.5)
mol_N2_15=N2_15/MW_N2
mol_H2_15=H2_15/MW_H2
mol_CO_15=CO_15/MW_CO
mol_CO2_15=CO2_15/MW_CO2
mol_CH4_15=CH4_15/MW_CH4
mol_H2S_15=H2S_15/MW_H2S
H_D120=mol_N2_15*(enthalpy(N2,T=T_15)-
enthalpy(N2,T=T_12))+mol_H2_15*(enthalpy(H2,T=T_15)-
enthalpy(H2,T=T_12))+mol_CO_15*(enthalpy(CO,T=T_15)-
enthalpy(CO,T=T_12))+mol_CO2_15*(enthalpy(CO2,T=T_15)-
enthalpy(CO2,T=T_12))+mol_H2O_15*(enthalpy(H2O,T=T_15)-
enthalpy(H2O,T=T_12))+mol_CH4_15*(enthalpy(CH4,T=T_15)-enthalpy(CH4,
T=T_12))+mol_H2S_15*(enthalpy(H2S,T=T_15)-enthalpy(H2S,T=T_12))+Slag_15*2*(T_15-
T_12)
H_D120=mol_H2O_16*(Enthalpy(Water,T=303,P=14)-
Enthalpy(Water,T=T_16,P=13.5))+Slag_16*2*(T_12-T_16)

"---------------------------------H-121---------------------------------"
Slag_18=Slag_16*0.999
Slag_17=Slag_16*0.001
H2O_18=Slag_18
H2O_17=H2O_16-H2O_18

"---------------------------------H-122---------------------------------"
Slag_19=Slag_18*0.999
```

```
Slag_20=Slag_18*0.001
H2O_19=H2O_18*.1
H2O_20=H2O_18*.9
H2O_21=H2O_20+H2O_17
mol_H2O_21=H2O_21/MW_H2O
H2O_22=H2O_21+(H2O_26-H2O_27)
mol_H2O_22=H2O_22/MW_H2O
mol_H2O_2627=(H2O_26-H2O_27)/MW_H2O
H2O_23=H2O_22-H2O_14

"----------------------------------E-123----------------------------------"
H_22=(mol_H2O_21*Enthalpy(Water,T=T_16,P=12.5))+(mol_H2O_2627*Enthalpy(Water,T=T_
26,P=13))
H_22=mol_H2O_22*Enthalpy(Water,T=T_22,P=12.5)
T_14=T_22
T_24=348
H_E123=mol_H2O_14*(Enthalpy(Water,T=T_14,P=12.5)-Enthalpy(Water,T=303,P=12.5))
H_E123=mol_H2O_24*(Enthalpy(Water,T=T_24,P=4)-Enthalpy(Water,T=T_ref,P=4))
mol_H2O_14=H2O_14/MW_H2O
mol_H2O_24=H2O_24/MW_H2O

"----------------------------------D-125----------------------------------"
"Material"
P_H2O_sat=P_sat(Steam,T=T_25)
H2O_factor=P_H2O_sat/12
H2O_25=H2O_15*H2O_factor
H2O_26=(H2O_15*(1-H2O_factor))+H2O_27
mol_H2O_25=H2O_25/MW_H2O
mol_H2O_26=H2O_26/MW_H2O
H2_25=H2_15
CO_25=CO_15
CH4_25=CH4_15
CO2_25=CO2_15
H2S_25=H2S_15
N2_25=N2_15
Slag_25=Slag_15
mol_N2_25=N2_25/MW_N2
mol_H2_25=H2_25/MW_H2
mol_CO_25=CO_25/MW_CO
mol_CO2_25=CO2_25/MW_CO2
mol_CH4_25=CH4_25/MW_CH4
mol_H2S_25=H2S_25/MW_H2S

"Energy"
T_25=318
T_26=363
H_D125=mol_N2_25*(enthalpy(N2,T=T_25)-
enthalpy(N2,T=T_15))+mol_H2_25*(enthalpy(H2,T=T_25)-
enthalpy(H2,T=T_15))+mol_CO_25*(enthalpy(CO,T=T_25)-
enthalpy(CO,T=T_15))+mol_CO2_25*(enthalpy(CO2,T=T_25)-
enthalpy(CO2,T=T_15))+mol_H2O_25*(enthalpy(H2O,T=T_25)-
enthalpy(H2O,T=T_15))+mol_CH4_25*(enthalpy(CH4,T=T_25)-enthalpy(CH4,
T=T_15))+mol_H2S_25*(enthalpy(H2S,T=T_25)-enthalpy(H2S,T=T_15))+Slag_25*2*(T_25-
T_15)
H_D125=mol_H2O_27*(Enthalpy(Water,T=303,P=13.5)-Enthalpy(Water,T=T_26,P=13.5))
H2O_27=mol_H2O_27*MW_H2O
```

```
"---------------------------------E-127---------------------------------"
T_27=T_26
T_28=348
H_E127=mol_H2O_27*(Enthalpy(Water,T=T_27,P=13.5)-Enthalpy(Water,T=303,P=13.5))
H_E127=mol_H2O_28*(Enthalpy(Water,T=T_28,P=4)-Enthalpy(Water,T=T_ref,P=4))
mol_H2O_28=H2O_28/MW_H2O

"---------------------------------D-128---------------------------------"
"Material"
absorb_eff=.999
H2_29=H2_25
CO_29=CO_25
CH4_29=CH4_25
mol_MEA_34=.4*mol_CO2_25
MEA_34=mol_MEA_34*61.08
MEA_30=MEA_34
mol_MEA_30=mol_MEA_34
MEAaqu_34=MEA_34/0.2 "Assume 20wt% MEA aqueous feed."
aquFORmea_34=MEAaqu_34-MEA_34
H2O_34=aquFORmea_34
mol_H2O_34=H2O_34/MW_H2O
mol_CO2_30=absorb_eff*mol_CO2_25
CO2_30=mol_CO2_30*MW_CO2
mol_H2S_30=absorb_eff*mol_H2S_25
H2S_30=mol_H2S_30*MW_H2S
H2O_30=H2O_34+H2O_25
mol_H2O_30=H2O_30/MW_H2O
mol_N2_30=absorb_eff*mol_N2_25
N2_30=mol_N2_30*MW_N2

"Energy"
T_29=311
T_34=298.15 "Entering Absorber, After Heat Exchanger"
0=mol_CO_25*(enthalpy(CO,T=T_29)-
enthalpy(CO,T=T_25))+mol_H2_25*(enthalpy(H2,T=T_29)-
enthalpy(H2,T=T_25))+mol_CH4_25*(enthalpy(CH4,T=T_25)-enthalpy(CH4,
T=T_ref))+mol_CO2_30*(enthalpy(CO2,T=T_30)-
enthalpy(CO2,T=T_25))+mol_N2_30*(enthalpy(N2,T=T_30)-
enthalpy(N2,T=T_25))+mol_H2S_30*(enthalpy(H2S,T=T_30)-
enthalpy(H2S,T=T_25))+mol_MEA_30*140.508*(T_30-
T_34)+mol_H2O_25*(Enthalpy(Water,T=T_30,P=12.5)-
Enthalpy(Water,T=T_25,P=13))+mol_H2O_34*(Enthalpy(Water,T=T_30,P=12.5)-
Enthalpy(Water,T=T_34,P=13))

"---------------------------------E-129---------------------------------"
T_30_1=373 "Entering Stipper, After Heat Exchanger"
H_E129=mol_CO2_30*(enthalpy(CO2,T=T_30_1)-
enthalpy(CO2,T=T_30))+mol_N2_30*(enthalpy(N2,T=T_30_1)-
enthalpy(N2,T=T_30))+mol_H2S_30*(enthalpy(H2S,T=T_30_1)-
enthalpy(H2S,T=T_30))+mol_MEA_30*140.508*(T_30_1-
T_30)+mol_H2O_30*(Enthalpy(Water,T=T_30_1,P=12.5)-Enthalpy(Water,T=T_30,P=12.5))
H_E129=mol_MEA_34*140.508*(T_34_1-
T_34)+mol_H2O_34*(Enthalpy(Water,T=T_34_1,P=13)-Enthalpy(Water,T=T_34,P=13))

"---------------------------------D-130---------------------------------"
```

```
"Material"
H2S_31=H2S_30
mol_H2S_31=H2S_31/MW_H2S
CO2_31=CO2_30
mol_CO2_31=CO2_31/MW_CO2
N2_31=N2_30
mol_N2_31=N2_31/MW_N2
H2O_31=H2O_30
mol_H2O_31=H2O_31/MW_H2O

mol_MEA_33=mol_MEA_34*0.1
MEA_33=mol_MEA_33*61.08
MEAaqu_33=MEA_33/0.2"this is an assumption"
aquFORmea_33=MEAaqu_33-MEA_33
H2O_33=aquFORmea_33
mol_H2O_33=H2O_33/MW_H2O

mol_MEA_32=mol_MEA_34+mol_MEA_33
MEA_32=mol_MEA_32*61.08
H2O_32=H2O_34+H2O_33
mol_H2O_32=H2O_32/MW_H2O

"Energy"
T_32=T_34_1
T_33=T_34_1
T_33_2=383
H_D130=mol_MEA_30*140.508*(T_30_1-T_ref)+mol_MEA_33*140.508*(T_33_2-
T_ref)+mol_H2O_30*(Enthalpy(Water,T=T_30_1,P=1)-
Enthalpy(Water,T=T_ref,P=112.5))+mol_H2O_33*(Enthalpy(Steam,T=T_33_2,P=1)-
Enthalpy(steam,T=T_ref,P=12.5))+mol_CO2_30*(enthalpy(CO2,T=T_30_1)-
enthalpy(CO2,T=T_ref))+mol_N2_30*(enthalpy(N2,T=T_30)-
enthalpy(N2,T=T_ref))+mol_H2S_30*(enthalpy(H2S,T=T_30)-enthalpy(H2S,T=T_ref))
h_MEA_32=mol_MEA_32*140.508*(T_32-T_ref)
h_H2O_32=mol_H2O_32*(Enthalpy(Water,T=T_32,P=12)-Enthalpy(Water,T=T_ref,P=1))
h_CO2_31=mol_CO2_31*(enthalpy(CO2,T=T_31)-enthalpy(CO2,T=T_30_1))
h_N2_31=mol_N2_31*(enthalpy(N2,T=T_31)-enthalpy(N2,T=T_30_1))
h_H2S_31=mol_H2S_31*(enthalpy(H2S,T=T_31)-enthalpy(H2S,T=T_30_1))
h_H2O_31=mol_H2O_31*(Enthalpy(Water,T=T_31,P=12)-Enthalpy(Water,T=T_30_1,P=12.5))
H_D130=h_CO2_31+h_N2_31+h_H2S_31+h_H2O_31+h_MEA_32+h_H2O_32

"----------------------------------E-133----------------------------------"
T_35_1=388
T_35_2=383
H_E133=mol_MEA_33*140.508*(T_33_2-
T_33)+mol_H2O_33*(Enthalpy(Water,T=T_33_2,P=12.5)-Enthalpy(Water,T=T_33,P=12.5))
H_E133=mol_H2O_35*(Enthalpy(Water,T=T_35_1,P=16)-Enthalpy(Water,T=T_35_2,P=16))
H2O_35=mol_H2O_35/MW_H2O

"----------------------------------R-140----------------------------------"
T_36=348
T_37=823
H2O_Biomass_4=Biomass_4
Biomass_36=Biomass_4
H2O_Biomass_36=Biomass_36/9 "assuming that the biomass has a moisture content of 10%"
H2O_36=H2O_Biomass_36+Biogas_56
```

```
"Heat Capacity of Biomass is 531 kJ/kg"
0=Biomass_36*531+H2O_36/MW_H2O*(enthalpy(H2O,T=T_37)-
enthalpy(H2O,T=T_36))+mol_H2O_7*(enthalpy(H2O,T=T_37)-enthalpy(H2O,T=T_7_2))
H_R140=Biomass_36*531+H2O_36/MW_H2O*(enthalpy(H2O,T=T_37)-
enthalpy(H2O,T=T_36))

"Given a yield of 75% bio-oil, 12% biochar, and 13% biogas (Ringer, 2006)"
Biototal_36=Biomass_36+H2O_Biomass_36
Biooil_37=Biototal_36*0.75
Biochar_37=Biototal_36*0.12
Biogas_37=Biototal_36*0.13

"---------------------------------H-146---------------------------------"
Biochar_39=Biochar_37*0.9
Biochar_38=Biochar_37*0.1
Biochar_41=Biochar_38*0.9
Biochar_40=Biochar_38*0.1
Biochar_42=Biochar_39+Biochar_41

"---------------------------------E-148---------------------------------"
Biooil_44=Biooil_37*0.7
Biooil_43=Biooil_37*0.3
T_40=T_37
Biogas_43=Biogas_37
"Heat capacity of the biogas is assumed to be the heat capacity of steam which is 2 kJ/kg/K."
"Heat capacity of bio-oil is 2.435 kJ/kg/K (Goteti, 2010)."
"Heat of vaporization for bio-oil is 609.9 kJ/kg (Goteti, 2010)."
T_44=T_43
0=Biogas_43*2*(T_43-T_40)+Biooil_44*(609.9+(2.435*(T_44-T_40)))+Biooil_43*2.435*(T_43-
T_40)
H_E148=Biooil_44*(609.9+(2.435*(T_44-T_40)))

"---------------------------------E-150---------------------------------"
Biooil_46=Biooil_43*0.7
Biooil_45=Biooil_43*0.3
Biogas_45=Biogas_43
T_46=T_45
0=Biogas_45*2*(T_45-T_43)+Biooil_46*(609.9+(2.435*(T_46-T_43)))+Biooil_45*2.435*(T_45-
T_43)
H_E150=Biooil_46*(609.9+(2.435*(T_46-T_43)))
Biooil_47=Biooil_44+Biooil_46
H_47=(Biooil_44*2.435*T_44)+(Biooil_46*2.435*T_46)
H_47=Biooil_47*2.435*T_47

"---------------------------------H-151---------------------------------"
Biooil_49=Biooil_45*0.95
Biooil_48=Biooil_45*0.05
Biogas_48=Biogas_45
T_49=T_48
0=Biogas_48*2*(T_48-T_45)+Biooil_49*(609.9+(2.435*(T_49-
T_45)))+Biooil_48*(609.9+(2.435*(T_49-T_45)))
Biooil_50=Biooil_47+Biooil_49
H_50=(Biooil_49*2.435*T_49)+(Biooil_47*2.435*T_47)
H_50=Biooil_50*2.435*T_50

"---------------------------------H-152---------------------------------"
```

```
Biooil_52=Biooil_48*0.95
Biogas_51=Biogas_48
T_52=T_51
0=Biogas_51*2*(T_51-T_48)+Biooil_52*2.435*(T_52-T_48)
Biooil_53=Biooil_50+Biooil_52
H_53=(Biooil_52*2.435*T_52)+(Biooil_50*2.435*T_50)
H_53=Biooil_53*2.435*T_53

"----------------------------------B-143----------------------------------"
"Heat  capacity  of  biomass  is  1.2 KJ/kg/K  (Goteti, 2010)"
"Heat capacity of water is 4.181 kJ/kg/K (Goteti, 2010)"
"Heat of vaporization of the biogas is assumed to be the heat of vaporization of water at 75C is
2322.87 kJ/kg (Goteti, 2010)"
0=Biomass_4*1.2*(T_36-T_ref)+H2O_Biomass_4*4.181*(T_36-T_ref)-Biogas_56*2322.8
Biogas_57=Biogas_51-Biogas_56
H_B143=Biomass_4*1.2*(T_36-T_ref)+H2O_Biomass_4*4.181*(T_36-T_ref)
T_57=T_51

"----------------------------------G-153----------------------------------"
mol_Biogas_57=Biogas_57/MW_H2O
H_G153=mol_Biogas_57*(enthalpy(Steam,T=T_57,P=16)-enthalpy(Steam,T=T_57,P=13))

"----------------------------------H-119----------------------------------"
H2S_rho_H119=Density(H2S,T=T_12,P=44)*MW_H2S
N2_rho_H119=Density(N2,T=T_12,P=44)*MW_N2
CO_rho_H119=Density(CO,T=T_12,P=44)*MW_CO
CO2_rho_H119=Density(CO2,T=T_12,P=44)*MW_CO2
CH4_rho_H119=Density(CH4,T=T_12,P=44)*MW_CH4
H2O_rho_H119=Density(H2O,T=T_12,P=44)*MW_H2O
H2_rho_H119=Density(H2,T=T_12,P=44)*MW_H2
V_H119=H2S_11/H2S_rho_H119+N2_11/N2_rho_H119+CO_11/CO_rho_H119+CO2_11/CO2
_rho_H119+CH4_11/CH4_rho_H119+H2O_11/H2O_rho_H119+H2_11/H2_rho_H119+Slag_1
1/2114

"----------------------------------N-155----------------------------------"
H2S_rho_N155=Density(H2S,T=T_12,P=42.5)*MW_H2S
N2_rho_N155=Density(N2,T=T_12,P=42.5)*MW_N2
CO_rho_N155=Density(CO,T=T_12,P=42.5)*MW_CO
CO2_rho_N155=Density(CO2,T=T_12,P=42.5)*MW_CO2
CH4_rho_N155=Density(CH4,T=T_12,P=42.5)*MW_CH4
H2O_rho_N155=Density(H2O,T=T_12,P=42.5)*MW_H2O
H2_rho_N155=Density(H2,T=T_12,P=42.5)*MW_H2
V_N155=H2S_11/H2S_rho_N155+N2_11/N2_rho_N155+CO_11/CO_rho_N155+CO2_11/CO2
_rho_N155+CH4_11/CH4_rho_N155+H2O_11/H2O_rho_N155+H2_11/H2_rho_N155+Slag_1
2/2114
M_N155=H2S_11+N2_11+CO_11+CO2_11+CH4_11+H2O_11+H2_11+Slag_12
rho_N155=M_N155/V_N155

"----------------------------------D-125----------------------------------"
H2S_rho_D125=Density(H2S,T=T_15,P=13.5)*MW_H2S
N2_rho_D125=Density(N2,T=T_15,P=13.5)*MW_N2
CO_rho_D125=Density(CO,T=T_15,P=13.5)*MW_CO
CO2_rho_D125=Density(CO2,T=T_15,P=13.5)*MW_CO2
CH4_rho_D125=Density(CH4,T=T_15,P=13.5)*MW_CH4
H2O_rho_D125=Density(H2O,T=T_15,P=13.5)*MW_H2O
H2_rho_D125=Density(H2,T=T_15,P=13.5)*MW_H2
```

```
V_D125=H2S_11/H2S_rho_D125+N2_11/N2_rho_D125+CO_11/CO_rho_D125+CO2_11/CO2
_rho_D125+CH4_11/CH4_rho_D125+H2O_11/H2O_rho_D125+H2_11/H2_rho_D125

"----------------------------------D-128----------------------------------"
H2S_rho_D128=Density(H2S,T=T_25,P=13)*MW_H2S
N2_rho_D128=Density(N2,T=T_25,P=13)*MW_N2
CO_rho_D128=Density(CO,T=T_25,P=13)*MW_CO
CO2_rho_D128=Density(CO2,T=T_25,P=13)*MW_CO2
CH4_rho_D128=Density(CH4,T=T_25,P=13)*MW_CH4
H2O_rho_D128=Density(H2O,T=T_25,P=13)*MW_H2O
H2_rho_D128=Density(H2,T=T_25,P=13)*MW_H2
V_D128=H2S_25/H2S_rho_D128+N2_25/N2_rho_D128+CO_25/CO_rho_D128+CO2_25/CO2
_rho_D128+CH4_25/CH4_rho_D128+H2O_25/H2O_rho_D128+H2_25/H2_rho_D128

"----------------------------------D-128----------------------------------"
H2S_rho_D130=Density(H2S,T=T_30,P=12.5)*MW_H2S
N2_rho_D130=Density(N2,T=T_30,P=12.5)*MW_N2
CO2_rho_D130=Density(CO2,T=T_30,P=12.5)*MW_CO2
H2O_rho_D130=Density(H2O,T=T_30,P=12.5)*MW_H2O
V_D130=H2S_30/H2S_rho_D130+N2_30/N2_rho_D130+CO2_30/CO2_rho_D130+H2O_30/H
2O_rho_D130+MEA_30/1010+H2O_33/H2O_rho_D130+MEA_33/1010
```

Output:

```
absorb_eff=0.999                     Biooil_48=0.03525
aquFORmea_33=7.847                   Biooil_49=0.6697
aquFORmea_34=78.47                   Biooil_50=7.798
Ash_1=6.143                          Biooil_52=0.03349
Ash_42=0.1464                        Biooil_53=7.831
Ash_9=6.143                          Biototal_36=10.44
Biochar_37=1.253                     CH4_11=0.1529
Biochar_38=0.1253                    CH4_12=0.1529
Biochar_39=1.128                     CH4_15=0.1529
Biochar_40=0.01253                   CH4_25=0.1529
Biochar_41=0.1128                    CH4_29=0.1529
Biochar_42=1.241                     CH4_rho=0.322
Biogas_37=1.358                      CH4_rho_D125=5.569
Biogas_43=1.358                      CH4_rho_D128=7.867
Biogas_45=1.358                      CH4_rho_H119=16.19
Biogas_48=1.358                      CH4_rho_N155=15.64
Biogas_51=1.358                      CO2_11=35.33
Biogas_56=1.085                      CO2_12=35.33
Biogas_57=0.2722                     CO2_15=35.33
Biomass_36=9.399                     CO2_25=35.33
Biomass_4=9.399                      CO2_30=35.29
Biooil_37=7.833                      CO2_31=35.29
Biooil_43=2.35                       CO2_rho=0.322
Biooil_44=5.483                      CO2_rho_D125=15.31
Biooil_45=0.705                      CO2_rho_D128=21.63
Biooil_46=1.645                      CO2_rho_D130=21.91
Biooil_47=7.128                      CO2_rho_H119=44.52
```

CO2_rho_N155=43
Coal_1=52.06
CO_11=68.51
CO_12=68.51
CO_15=68.51
CO_25=68.51
CO_29=68.51
CO_rho=0.322
CO_rho_D125=9.745
CO_rho_D128=13.77
CO_rho_H119=28.33
CO_rho_N155=27.37
cph=75.3
C_1=36.69
C_42=0.8745
C_9=36.69
Gas_12=131.5
H2O_10=6.571
H2O_11=19.96
H2O_12=19.96
H2O_14=22.19
H2O_15=19.96
H2O_16=22.19
H2O_17=21.56
H2O_18=0.6277
H2O_19=0.06277
H2O_2=35.23
H2O_20=0.5649
H2O_21=22.13
H2O_22=41.93
H2O_23=19.74
H2O_24=42.28
H2O_25=0.1583
H2O_26=115.9
H2O_27=96.07
H2O_28=115.7
H2O_30=78.62
H2O_31=78.62
H2O_32=86.31
H2O_33=7.847
H2O_34=78.47
H2O_35=0.03857
H2O_36=2.13
H2O_7=15.65
H2O_9=35.23
H2O_Biomass_36=1.044
H2O_Biomass_4=9.399
H2O_factor=0.00793
H2O_rho=0.322
H2O_rho_D125=6.265
H2O_rho_D128=8.85
H2O_rho_D130=8.962
H2O_rho_H119=18.21
H2O_rho_N155=17.59
H2S_11=2.08
H2S_12=2.08
H2S_15=2.08
H2S_25=2.08
H2S_30=2.078
H2S_31=2.078
H2S_rho=0.322
H2S_rho_D125=11.83
H2S_rho_D128=16.72
H2S_rho_D130=16.93
H2S_rho_H119=34.4
H2S_rho_N155=33.23
H2_11=3.645
H2_12=3.645
H2_15=3.645
H2_25=3.645
H2_29=3.645
H2_rho=0.322
H2_rho_D125=0.6961
H2_rho_D128=0.9834
H2_rho_H119=2.024
H2_rho_N155=1.955
hh=-285830
H_1=2.525
H_22=21963
H_42=0.06018
H_47=11144
H_50=11884
H_53=11921
H_9=2.525
H_B143=2521
h_CH4_11=-713
h_CO2_11=-315930
h_CO2_31=3915
h_combustion=54381
h_CO_11=-270456
h_C_42=795.7
H_D120=-11606

H_D125=-24137
H_D130=227926
H_E117=12723
H_E118=-273477
H_E123=8822
H_E127=24137
H_E129=29108
H_E133=264.7
H_E148=1295
H_E150=527
H_G153=0.04109
h_H2O_11=-268112
h_H2O_31=191434
h_H2O_32=28245
h_H2O_9=140.1
h_H2O_9_at=1960
h_H2O_9_ref=1889
h_H2S_11=-1260
h_H2S_31=254
h_H2_11=0
h_H_42=656.5
h_MEA_32=3863
h_N2_11=0
h_N2_31=214.9
h_N_42=13.54
h_O2_3=-7827
h_O2_3_at=-4960
h_O2_3_ref=0
h_O_42=67.72
h_products=323866
H_R140=7026
h_reactants=-6137
h_reaction=-351349
h_S_42=16.73
lh_H2O_11=33620
mass_CH4_11=0.024
mass_CO2_11=5.544
mass_CO_11=10.75
mass_H2O_11=3.132
mass_H2S_11=0.3264
mass_H2_11=0.572
mass_N2_11=0.28
mass_O2_11=0.224
mass_Total_11=20.85
MEAaqu_33=9.808
MEAaqu_34=98.08
MEA_30=19.62
MEA_32=21.58
MEA_33=1.962
MEA_34=19.62
mol%_CH4_11=0.0015
mol%_CO2_11=0.126
mol%_CO_11=0.384
mol%_H2O_11=0.174
mol%_H2S_11=0.0096
mol%_H2_11=0.286
mol%_N2_11=0.01
mol%_O2_11=0.007
mol_Biogas_57=0.01512
mol_CH4_11=0.009558
mol_CH4_15=0.009558
mol_CH4_25=0.009558
mol_CO2_11=0.8029
mol_CO2_15=0.8029
mol_CO2_25=0.8029
mol_CO2_30=0.8021
mol_CO2_31=0.8021
mol_CO_11=2.447
mol_CO_15=2.447
mol_CO_25=2.447
mol_C_42=0.07287
mol_C_9=3.058
mol_H2O_10=0.365
mol_H2O_11=1.109
mol_H2O_14=1.233
mol_H2O_15=1.109
mol_H2O_16=1.233
mol_H2O_21=1.229
mol_H2O_22=2.329
mol_H2O_24=2.349
mol_H2O_25=0.008793
mol_H2O_26=6.437
mol_H2O_2627=1.1
mol_H2O_27=5.337
mol_H2O_28=6.426
mol_H2O_30=4.368
mol_H2O_31=4.368
mol_H2O_32=4.795
mol_H2O_33=0.4359
mol_H2O_34=4.359
mol_H2O_35=0.6942
mol_H2O_7=0.8695

mol_H2O_9=1.957
mol_H2S_11=0.06117
mol_H2S_15=0.06117
mol_H2S_25=0.06117
mol_H2S_30=0.06111
mol_H2S_31=0.06111
mol_H2_11=1.822
mol_H2_15=1.822
mol_H2_25=1.822
mol_H_42=0.06018
mol_H_9=2.525
mol_MEA_30=0.3212
mol_MEA_32=0.3533
mol_MEA_33=0.03212
mol_MEA_34=0.3212
mol_N2_11=0.06372
mol_N2_15=0.06372
mol_N2_25=0.06372
mol_N2_30=0.06366
mol_N2_31=0.06366
mol_N_42=0.001241
mol_N_9=0.05206
mol_O2_3=1.578
mol_O_42=0.006072
mol_O_9=0.2548
mol_S_42=0.001411
mol_S_9=0.05922
MW_C=12
MW_CH4=16
MW_CO=28
MW_CO2=44
MW_H=1
MW_H2=2
MW_H2O=18
MW_H2S=34
MW_N=14
MW_N2=28
MW_O=16
MW_O2=32
MW_S=32
M_N155=132.1
N2_11=1.784
N2_12=1.784
N2_15=1.784
N2_25=1.784
N2_30=1.782
N2_31=1.782
N2_rho=0.322
N2_rho_D125=9.745
N2_rho_D128=13.77
N2_rho_D130=13.94
N2_rho_H119=28.33
N2_rho_N155=27.37
N_1=0.7288
N_42=0.01737
N_9=0.7288
O2_11=1.427
O2_3=50.5
O_1=4.076
O_42=0.09715
O_9=4.076
Product_11=132.9
P_12=14
P_3=16
P_9=44
P_H2O_sat=0.09516
P_ref=1
Q_E117=10755
rho_N155=20.44
sh=69.94
Slag_11=6.289
Slag_12=0.6289
Slag_13=5.66
Slag_15=0.0006289
Slag_16=0.6283
Slag_17=0.0006283
Slag_18=0.6277
Slag_19=0.6271
Slag_20=0.0006277
Slag_25=0.0006289
S_1=1.895
S_42=0.04516
S_9=1.895
T_11_1=1644
T_11_2=523
T_12=523
T_14=397.6
T_15=466.5
T_16=428.1
T_22=397.6
T_24=348
T_25=318

```
T_26=363
T_27=363
T_28=348
T_29=311
T_3=133
T_30=302
T_30_1=373
T_31=488
T_32=376
T_33=376
T_33_2=383
T_34=298.2
T_34_1=376
T_35_1=388
T_35_2=383
T_36=348
T_37=823
T_40=823
T_43=669.5
T_44=669.5
T_45=550.6
T_46=550.6
T_47=642.1
T_48=453.6
T_49=453.6
T_50=625.9
T_51=453.6
T_52=453.6
```

```
T_53=625.2
T_57=453.6
T_7_1=298
T_7_2=1023
T_9=298.2
T_ref=298.2
Vol_D120=22.21
Vol_Gas_12=22.19
Vol_H2O_14=0.02219
V_D125=18.15
V_D128=10.61
V_D130=11.53
V_H119=6.244
V_N155=6.462
wt%_Ash_1=0.118
wt%_CH4_11=0.001151
wt%_CO2_11=0.2658
wt%_CO_11=0.5156
wt%_C_1=0.7048
wt%_H2O_11=0.1502
wt%_H2S_11=0.01565
wt%_H2_11=0.02743
wt%_H_1=0.0485
wt%_N2_11=0.01343
wt%_N_1=0.014
wt%_O2_11=0.01074
wt%_O_1=0.0783
```

SIZING - EES

Input:

```
"----------------------------------M-115----------------------------------"
rho_coal=730 "kg/m3"
rho_water=1000 "kg/m3"
t_M115=2*3600
V_coal_M115=52.04*t_M115/rho_coal
V_water_M115=35.23*t_M115/rho_water
V_M115=V_coal_M115+V_water_M115
P_M115=V_M115^0.8
ratio=P_M115/V_M115

"---------------------------------L-124---------------------------------"
q_water_L124=22.19/rho_water
dP_L124=150 "kPa"
epsilon_i_L124=0.85
P_L124=(q_water_L124*dP_L124)/epsilon_i_L124

"---------------------------------L-126---------------------------------"
```

```
q_water_L126=96.07/rho_water
dP_L126=50 "kPa"
epsilon_i_L126=0.85
P_L126=(q_water_L126*dP_L126)/epsilon_i_L126

"------------------------------L-131------------------------------"
rho_MEA=1012 "kg/m3"
q_L131=(78.47/rho_water)+(19.61/rho_MEA)
dP_L131=100 "kPa"
epsilon_i_L131=0.85
P_L131=(q_L131*dP_L131)/epsilon_i_L131

"------------------------------L-132------------------------------"
q_L132=(7.847/rho_water)+(1.961/rho_MEA)
dP_L132=50 "kPa"
epsilon_i_L132=0.85
P_L132=(q_L132*dP_L132)/epsilon_i_L132

"------------------------------L-149------------------------------"
rho_biooil=4.55/0.00378541 "kg/m3"
q_L149=5.53/rho_biooil
dP_L149=50 "kPa"
epsilon_i_L149=0.85
P_L149=(q_L149*dP_L149)/epsilon_i_L149

"------------------------------L-116------------------------------"
q_L116=(52.04/rho_coal)+(35.23/rho_water)
dP_L116=2800 "kPa"
epsilon_i_L116=0.85
P_L116=(q_L116*dP_L116)/epsilon_i_L116

"------------------------------E-117------------------------------"
Q_E117=10753*1000 "J/s"
U_E117=1300  "J/m2-s-K"
T_O2_E117=T_sat(Oxygen,P=16)
T_H2O_E117=T_sat(Water,P=16)
A_E117=Q_E117/(U_E117*(T_H2O_E117-T_O2_E117))

"------------------------------E-123------------------------------"
Q_E123=8821*1000 "J/s"
U_E123=950  "J/m2-s-K"
T1_E123=397.6
T2_E123=348
T3_E123=303
T4_E123=298
dTh_E123=T1_E123-T2_E123
dTc_E123=T3_E123-T4_E123
MTD_E123=(dTh_E123-dTc_E123)/ln(dTh_E123/dTc_E123)
A_E123=Q_E123/(U_E123*MTD_E123)

"------------------------------E-127------------------------------"
Q_E127=24135*1000 "J/s"
U_E127=950  "J/m2-s-K"
T1_E127=363
T2_E127=348
T3_E127=303
```

```
T4_E127=298
dTh_E127=T1_E127-T2_E127
dTc_E127=T3_E127-T4_E127
MTD_E127=(dTh_E127-dTc_E127)/ln(dTh_E127/dTc_E127)
A_E127=Q_E127/(U_E127*MTD_E127)

"---------------------------------E-129---------------------------------"
Q_E129=29105*1000 "J/s"
U_E129=950  "J/m2-s-K"
T1_E129=376
T2_E129=373
T3_E129=304.9
T4_E129=298
dTh_E129=T1_E129-T2_E129
dTc_E129=T3_E129-T4_E129
MTD_E129=(dTh_E129-dTc_E129)/ln(dTh_E129/dTc_E129)
A_E129=Q_E129/(U_E129*MTD_E129)

"---------------------------------E-133---------------------------------"
Q_E133=264.4*1000 "J/s"
U_E133=950  "J/m2-s-K"
T1_E133=388
T2_E133=383
T3_E133=383
T4_E133=376
dTh_E133=T1_E133-T2_E133
dTc_E133=T3_E133-T4_E133
MTD_E133=(dTh_E133-dTc_E133)/ln(dTh_E133/dTc_E133)
A_E133=Q_E133/(U_E133*MTD_E133)

"---------------------------------E-148---------------------------------"
Q_E148=1306*1000 "J/s"
U_E148=700  "J/m2-s-K"
T1_E148=823
T2_E148=669.5
A_E148=Q_E148/(U_E148*(T1_E148-T2_E148))

"---------------------------------E-150---------------------------------"
Q_E150=531.5*1000 "J/s"
U_E150=700  "J/m2-s-K"
T1_E150=669.5
T2_E150=550.6
A_E150=Q_E150/(U_E150*(T1_E150-T2_E150))

"---------------------------------E-118---------------------------------"
Q_E118=273477*1000 "J/s"
U_E118=650  "J/m2-s-K"
T1_E118=1644
T2_E118=1023
T3_E118=523
T4_E118=298
dTh_E118=T1_E118-T2_E118
dTc_E118=T3_E118-T4_E118
MTD_E118=(dTh_E118-dTc_E118)/ln(dTh_E118/dTc_E118)
A_E118=Q_E118/(U_E118*MTD_E118)
```

```
"---------------------------------G-153----------------------------------"
Biogas_G153=0.2745 "kg/s"
H_G153=0.04109  "kJ/s"
epsilon_i_G153=0.85
P_G153=(Biogas_G153*H_G153)/epsilon_i_G153

"---------------------------------B-143---------------------------------"
Q_B143=2521 "kJ/s"
U_B143=60*(A_B143^0.67)
T1_B143=453.6
T2_B143=348
T3_B143=348
T4_B143=298
dTh_B143=T1_B143-T2_B143
dTc_B143=T3_B143-T4_B143
MTD_B143=(dTh_B143-dTc_B143)/ln(dTh_B143/dTc_B143)
A_B143=Q_B143/(U_B143*MTD_B143)
A_B143=(((D_B143/2)^2)*3.14)
L_B143=D_B143*7
V_B143=A_B143*L_B143

"---------------------------------N-155---------------------------------"
epsilon_N155=.75
M_N155=133.5 "kg/s"
P1_N155=4250 "kPa"
P2_N155=1400 "kPa"
rho_N155=20.44 "kg/m3"
P_N155=epsilon_N155*M_N155*(P1_N155-P2_N155)/rho_N155

"---------------------------------H-146---------------------------------"
rho_biogas_H146=density(steam,T=823,P=16)
q_H146=7.899/rho_biooil+1.369/rho_biogas_H146

"---------------------------------H-147---------------------------------"
rho_biogas_H147=density(steam,T=823,P=15.5)
q_H147=7.899/rho_biooil+1.369/rho_biogas_H147

"---------------------------------H-121---------------------------------"
rho_slag=2114 "kg/m3"
t_H121=2*3600
V_H121=((22.19*t_H121)/rho_water)+(0.6283*t_H121/rho_slag)
V_H121=A_H121*L_H121
L_H121=3*D_H121
A_H121=(((D_H121/2)^2)*3.14)

"---------------------------------H-122---------------------------------"
P_H122=(5*(10^(-6)))*(rho_slag^2)*4.25/(100^0.3)

"---------------------------------H-152---------------------------------"
rho_biogas_H152=density(steam,T=823,P=13.5)
q_H152=0.03555/rho_biooil+1.369/rho_biogas_H152

"---------------------------------H-154--------------------------------"
q_H154=7.898/rho_biooil

"---------------------------------H-151---------------------------------"
```

```
rho_biogas_H151=density(steam,T=823,P=14)
q_H151=0.7109/rho_biooil+1.369/rho_biogas_H151

"--------------------------------C-113--------------------------------"
P_C113=0.5*(53.04^(0.88))*8

"--------------------------------C-114--------------------------------"
P_C114=0.3*53.04*15

"--------------------------------C-144--------------------------------"
P_C144=0.3*11.63*15

"--------------------------------J-111--------------------------------"
P_J111=0.0027*(53.04^0.82)*90

"--------------------------------J-141--------------------------------"
P_J141=0.0027*(18.96^0.82)*90

"--------------------------------J-145--------------------------------"
P_J145=0.07*(11.63^0.85)*25

"--------------------------------F-112--------------------------------"
t_F112=8*3600
V_F112=(52.04*t_F112)/rho_coal

"--------------------------------F-142--------------------------------"
rho_biomass=365 "kg/m3"
t_F142=8*3600
V_F142=((9.479*t_F142)/rho_water)+((9.479*t_F142)/rho_biomass)

"--------------------------------D-125--------------------------------"
t_D125=10
V_D125=18.15*t_D125
V_D125=A_D125*L_D125
L_D125=5*D_D125
A_D125=(((D_D125/2)^2)*3.14)

"--------------------------------D-128--------------------------------"
t_D128=10
V_D128=10.61*t_D128
V_D128=A_D128*L_D128
L_D128=5*D_D128
A_D128=(((D_D128/2)^2)*3.14)

"--------------------------------D-130--------------------------------"
t_D130=10
V_D130=11.53*t_D130
V_D130=A_D130*L_D130
L_D130=5*D_D130
A_D130=(((D_D130/2)^2)*3.14)
```

Output:

```
A_B143=0.7104                              A_D130=7.474
A_D125=10.11                               A_E117=23.88
A_D128=7.071                               A_E118=1079
```

A_E123=477.7
A_E127=2791
A_E129=6543
A_E133=46.82
A_E148=12.15
A_E150=6.386
A_H121=13.17
Biogas_G153=0.2745
dP_L116=2800
dP_L124=150
dP_L126=50
dP_L131=100
dP_L132=50
dP_L149=50
dTc_B143=50
dTc_E118=225
dTc_E123=5
dTc_E127=5
dTc_E129=6.9
dTc_E133=7
dTh_B143=105.6
dTh_E118=621
dTh_E123=49.6
dTh_E127=15
dTh_E129=3
dTh_E133=5
D_B143=0.9513
D_D125=3.589
D_D128=3.001
D_D130=3.086
D_H121=4.097
epsilon_i_G153=0.85
epsilon_i_L116=0.85
epsilon_i_L124=0.85
epsilon_i_L126=0.85
epsilon_i_L131=0.85
epsilon_i_L132=0.85
epsilon_i_L149=0.85
epsilon_N155=0.75
H_G153=0.04109
L_B143=6.659
L_D125=17.95
L_D128=15.01
L_D130=15.43
L_H121=12.29
MTD_B143=74.37
MTD_E118=390.1
MTD_E123=19.44
MTD_E127=9.102
MTD_E129=4.682
MTD_E133=5.944
M_N155=133.5
P1_N155=4250
P2_N155=1400
P_C113=131.7
P_C114=238.7
P_C144=52.34
P_G153=0.01327
P_H122=23.85
P_J111=6.306
P_J141=2.713
P_J145=14.09
P_L116=350.9
P_L124=3.916
P_L126=5.651
P_L131=11.51
P_L132=0.5756
P_L149=0.2706
P_M115=203.1
P_N155=13961
Q_B143=2521
Q_E117=1.075E+07
Q_E118=2.735E+08
Q_E123=8.821E+06
Q_E127=2.414E+07
Q_E129=2.911E+07
Q_E133=264400
Q_E148=1.306E+06
Q_E150=531500
q_H146=0.3285
q_H147=0.3389
q_H151=0.3689
q_H152=0.3821
q_H154=0.006571
q_L116=0.1065
q_L131=0.09785
q_L132=0.009785
q_L149=0.004601
q_water_L124=0.02219
q_water_L126=0.09607
ratio=0.2649
rho_biogas_H146=4.253

rho_biogas_H147=4.119
rho_biogas_H151=3.717
rho_biogas_H152=3.583
rho_biomass=365
rho_biooil=1202
rho_coal=730
rho_MEA=1012
rho_N155=20.44
rho_slag=2114
rho_water=1000
T1_B143=453.6
T1_E118=1644
T1_E123=397.6
T1_E127=363
T1_E129=376
T1_E133=388
T1_E148=823
T1_E150=669.5
T2_B143=348
T2_E118=1023
T2_E123=348
T2_E127=348
T2_E129=373
T2_E133=383
T2_E148=669.5
T2_E150=550.6
T3_B143=348
T3_E118=523
T3_E123=303
T3_E127=303
T3_E129=304.9
T3_E133=383
T4_B143=298
T4_E118=298
T4_E123=298
T4_E127=298
T4_E129=298
T4_E133=376
t_D125=10
t_D128=10
t_D130=10
t_F112=28800
t_F142=28800
t_H121=7200
T_H2O_E117=474.6
t_M115=7200
T_O2_E117=128.2
U_B143=47.72
U_E117=1300
U_E118=650
U_E123=950
U_E127=950
U_E129=950
U_E133=950
U_E148=700
U_E150=700
V_B143=4.731
V_coal_M115=513.3
V_D125=181.5
V_D128=106.1
V_D130=115.3
V_F112=2053
V_F142=1021
V_H121=161.9
V_M115=766.9
V_water_M115=253.7

CAPITAL COST ESTIMATION - ECONEXPERT

An Expert System for Capital Cost Estimation
Developed by P.T. Vasudevan and T. Ulrich
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Cost Summary
The cost index is 595.0

Mixers : Agitators and Inline Mixers : Agitator open tank

Total purchased cost = $ 231868
The bare module cost is = $ 463737

Pumps : Centrifugal
Total purchased cost = $ 8337
Material factor = 1.00
Pressure factor = 1.09
The bare module cost (incl. electric motor drive) is = $ 29968

Pumps : Centrifugal
Total purchased cost = $ 10320
Material factor = 1.00
Pressure factor = 1.11
The bare module cost (incl. electric motor drive) is = $ 37488

Pumps : Centrifugal
Total purchased cost = $ 13671
Material factor = 1.00
Pressure factor = 1.06
The bare module cost (incl. electric motor drive) is = $ 48607

Pumps : Centrifugal
Total purchased cost = $ 4733
Material factor = 1.00
Pressure factor = 1.06
The bare module cost (incl. electric motor drive) is = $ 16829

Pumps : Centrifugal
Total purchased cost = $ 3846
Material factor = 1.00
Pressure factor = 1.18
The bare module cost (incl. electric motor drive) is = $ 14385

Pumps : Reciprocating
Purchased cost for one unit = $ 339031
Total purchased cost = $ 678063
Material factor = 1.00
Pressure factor = 1.15
The bare module cost (incl. electric motor drive) is = $ 2504289

Heat Exchangers : Shell and Tube : Double pipe (multiple pipe for areas > 50 sq.m.)
Total purchased cost = $ 15323
Material factor = 1.00
Pressure factor = 1.00
The bare module cost is = $ 48730

Heat Exchangers : Shell and Tube : Double pipe (multiple pipe for areas > 50 sq.m.)
Total purchased cost = $ 241627
Material factor = 1.00
Pressure factor = 1.00
The bare module cost is = $ 768396

Heat Exchangers : Shell and Tube : Double pipe (multiple pipe for areas > 50 sq.m.)
Purchased cost for one unit = $ 281506
Total purchased cost = $ 1407529
Material factor = 1.00
Pressure factor = 1.00
The bare module cost is = $ 4476083

Heat Exchangers : Shell and Tube : Double pipe (multiple pipe for areas > 50 sq.m.)
Purchased cost for one unit = $ 299609
Total purchased cost = $ 3295698
Material factor = 1.00
Pressure factor = 1.00
The bare module cost is = $ 10480648

Heat Exchangers : Shell and Tube : Double pipe (multiple pipe for areas > 50 sq.m.)
Total purchased cost = $ 25102
Material factor = 1.00
Pressure factor = 1.00
The bare module cost is = $ 79827

Heat Exchangers : Shell and Tube : Double pipe (multiple pipe for areas > 50 sq.m.)
Total purchased cost = $ 9945
Material factor = 1.00
Pressure factor = 1.00
The bare module cost is = $ 31625

Heat Exchangers : Shell and Tube : Double pipe (multiple pipe for areas > 50 sq.m.)
Total purchased cost = $ 6838
Material factor = 1.00
Pressure factor = 1.00
The bare module cost is = $ 21745

Heat Exchangers : Shell and Tube : Fixed tube sheet and U-tube
Purchased cost for one unit = $ 56252
Total purchased cost = $ 112505
Material factor = 1.00
Pressure factor = 1.05
The bare module cost is = $ 365028

Gas Movers and Compressors : Blowers and compressors (cost of drive excluded) : Axial

Total purchased cost = $ 23364
The bare module cost is = $ 81775

Gas-Solid Contacting Equipment : Rotary and vertical tower contactors (incl. drive) : Rotary dryer (direct)
Total purchased cost = $ 90770
The bare module cost is = $ 208771

Drives and Power Recovery Machines : Power recovery machines
Purchased cost for one unit = $ 234098
Total purchased cost = $ 2575076
The bare module cost is = $ 7725229

Separators : Dust collectors : Gas multi-cyclone
Total purchased cost = $ 13448
The bare module cost is = $ 40343

Separators : Dust collectors : Gas multi-cyclone
Total purchased cost = $ 3138
The bare module cost is = $ 9415

Separators : Dust collectors : Gas multi-cyclone
Total purchased cost = $ 3167
The bare module cost is = $ 9502

Separators : Liquid filters : Single-compartment drum (pressure)
Total purchased cost = $ 293802
The bare module cost is = $ 705125

Separators : Vibratory screens
Total purchased cost = $ 4958
The bare module cost is = $ 13882

Separators : Dust collectors : Gas bag filters
Total purchased cost = $ 44282
The bare module cost is = $ 97421

Separators : Dust collectors : Gas bag filters
Total purchased cost = $ 44282
The bare module cost is = $ 97421

Separators : Dust collectors : Electrostatic precipitators (wet)
Total purchased cost = $ 454900
The bare module cost is = $ 1046271

Crushers : Jaw

Total purchased cost = $ 269188
The bare module cost (incl. electric motor drive) is = $ 565294

Grinders : Rolling compression (bowl, pan, ring-roll)
Purchased cost for one unit = $ 470548
Total purchased cost = $ 1411644
The bare module cost (incl. electric motor drive) is = $ 3952603

Grinders : Rolling compression (bowl, pan, ring-roll)
Total purchased cost = $ 363767
The bare module cost (incl. electric motor drive) is = $ 1018549

Conveyors : Belt
Total purchased cost = $ 73572
The bare module cost is = $ 176574

Conveyors : Belt
Total purchased cost = $ 73572
The bare module cost is = $ 176574

Conveyors : Auger
Total purchased cost = $ 13814
The bare module cost is = $ 30391

Storage Vessels : Atmospheric pressure-Bins
Total purchased cost = $ 9375
The bare module cost is = $ 19688

Storage Vessels : Atmospheric pressure-Bins
Total purchased cost = $ 5826
The bare module cost is = $ 12235

Furnaces : Process heaters : Reactive - Pyrolysis furnace
Purchased cost for one unit = $ 3861918
Total purchased cost = $ 19309589
Pressure factor = 1.03
The bare module cost is = $ 53905852

Furnaces : Process heaters : Reactive - Pyrolysis furnace
Total purchased cost = $ 720158
Pressure factor = 0.99
The bare module cost is = $ 1921394

Separators : Dust collectors : Venturi scrubber
Total purchased cost = $ 170011
The bare module cost is = $ 425027

Process Vessels (including towers) : Vertically oriented : No packing or trays
Total purchased cost = $ 151290
Material factor = 1.00
Pressure factor = 1.70
The bare module cost is = $ 830690

Process Vessels (including towers) : Vertically oriented : No packing or trays
Total purchased cost = $ 113818
Material factor = 1.00
Pressure factor = 1.67
The bare module cost is = $ 617895

Process Vessels (including towers) : Vertically oriented : No packing or trays
Total purchased cost = $ 119038
Material factor = 1.00
Pressure factor = 1.63
The bare module cost is = $ 638680

Total Bare Module Cost = $ 93713986
Contingency and Fee = $ 16868517
Total Module Cost = $ 110582503
Auxiliary Facilities = $ 33174751
Grass Roots Capital = $ 143757255

CASH FLOW ANALYSIS - EXCEL

	Annual Capital	Sales	Expenses	Depreciation	Expenses excluding Depreciation Ame+Age	Cash Income	Allowance	ANP Profit BT	Income Tax	ANNP Profit after tax	Cash Income
1	($43,000,000)	$0	$0	$0	$0	$0	$0	$0	$0	$0	($43,000,000)
2	($43,000,000)	$0	$0	$0	$0	$0	$0	$0	$0	$0	($43,000,000)
3	($86,000,000)	$0	$0	$0	$0	$0	$0	$0	$0	$0	($86,000,000)
4	$0	$140,800,000	$141,000,000	$14,000,000	$127,000,000	$13,800,000	$0	($200,000)	($70,000)	($130,000)	$13,870,000
5	$0	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$36,750,000
6	$0	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$36,750,000
7	$0	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$36,750,000
8	$0	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$36,750,000
9	$0	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$36,750,000
10	$0	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$36,750,000
11	$0	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$36,750,000
12	$0	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$36,750,000
13	$21,500,000	$176,000,000	$141,000,000	$14,000,000	$127,000,000	$49,000,000	$0	$35,000,000	$12,250,000	$22,750,000	$58,250,000
											12.59%
											IRR

Net Present Value

	0% rate		10% rate			13%		
0	0	0	0	0	0	0%	0	0
1	($43,000,000)	(43,000,000)	1	(39,090,909)	(39,090,909)	1	(38,189,996)	(38,189,996)
2	($43,000,000)	(86,000,000)	1	(35,537,190)	(74,628,099)	1	(33,918,042)	(72,108,038)
3	($86,000,000)	(172,000,000)	1	(64,613,073)	(139,241,172)	1	(60,247,902)	(132,355,940)
4	13,870,000	(158,130,000)	1	9,473,397	(129,767,775)	1	8,629,807	(123,726,133)
5	36,750,000	(121,380,000)	1	22,818,859	(106,948,917)	1	20,307,812	(103,418,321)
6	36,750,000	(84,630,000)	1	20,744,417	(86,204,500)	0	18,036,169	(85,382,152)
7	36,750,000	(47,880,000)	1	18,858,561	(67,345,939)	0	16,018,633	(69,363,518)
8	36,750,000	(11,130,000)	0	17,144,146	(50,201,793)	0	14,226,780	(55,136,739)
9	36,750,000	25,620,000	0	15,585,587	(34,616,205)	0	12,635,364	(42,501,374)
10	36,750,000	62,370,000	0	14,168,716	(20,447,489)	0	11,221,966	(31,279,409)
11	36,750,000	99,120,000	0	12,880,651	(7,566,839)	0	9,966,670	(21,312,738)
12	36,750,000	135,870,000	0	11,709,683	4,142,844	0	8,851,793	(12,460,945)
13	58,250,000	194,120,000	0	16,872,950	21,015,794	0	12,460,945	(0)
	$194,120,000.00			**$21,015,794.03**			**($0.00)**	