Overall Energy Balance for the Corn Stover to Ethanol Process

Brianna G. Atherton, Mark F. Ruth,

John L. Jechura, Kelly N. Ibsen

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Methodology

Aspen Plus® energy balance basis converted to heat of combustion basis

- Ethanol energy ultimately released via combustion
- All energy flows put on a common basis for comparison
  - » Higher heating value (HHV) used for combustion heat
  - » Liquid water has negligible contribution to HHV

Results

- Energy available in inlet & outlet streams
  - » Ethanol energy yield

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Enthalpy Calculation Scheme

$$n\tilde{H}(T) = \sum n_i \left[\tilde{H}_{F,i}^*(T_{ref}) + \int_{T_{ref}}^{T} \tilde{C}_{p,i}^* dT \right] + n\Delta\tilde{H}^{residual}(T)$$

$$= \sum n_i \left[\tilde{H}_{F,i}^*(T_{ref}) + n_i \tilde{H}_i^*(T) \right] + n\Delta\tilde{H}^{residual}(T)$$
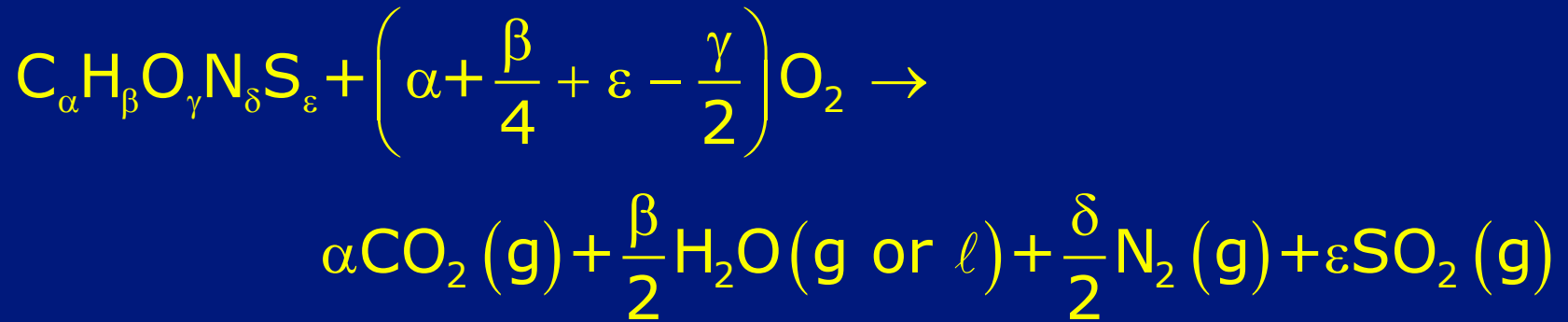
Ideal State Enthalpy

- Constant of integration at reference temperature
  - » Typically set to match enthalpy of formation

Residual Correction

- Convert "ideal" state to real state
- Phase change latent heat effects
- Non-ideal mixture effects

Heat of Combustion

$$C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon + \left(\alpha + \frac{\beta}{4} + \varepsilon - \frac{\gamma}{2} \right) O_2 \rightarrow$$

$$\alpha CO_2 (g) + \frac{\beta}{2} H_2O (g \text{ or } \ell) + \frac{\delta}{2} N_2 (g) + \varepsilon SO_2 (g)$$
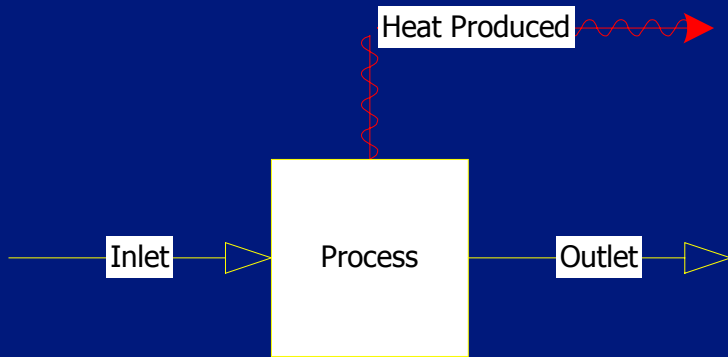
- Lower heating value (LHV) — water in gas state

$$\tilde{H}^*_{LHV, C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon} = -\tilde{H}^*_{F, C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon}$$

$$-\alpha \tilde{H}^*_{F, CO_2} - \frac{\beta}{2} \tilde{H}^*_{F, H_2O} - \varepsilon \tilde{H}^*_{F, SO_2}$$

- Higher heating value (HHV) — water in liquid state

$$\tilde{H}^*_{HHV, C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon} = \tilde{H}^*_{LHV, C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon} + \frac{\beta}{2} \Delta \tilde{H}^{vap}_{H_2O} (T_{ref})$$

Energy Balance Equations

Heat Produced

Inlet → Process → Outlet

$$0 = \text{Energy In } - \text{ Energy Out}$$

$$0 = n_{in}\tilde{H}\left(T_{in}\right) - n_{out}\tilde{H}\left(T_{out}\right) - Q$$

$$Q = \sum_i \left(n_{i,in} - n_{i,out}\right)\tilde{H}^*_{F,i}\left(T_{ref}\right)$$

$$+ \sum_i \left[n_{i,in}\tilde{H}^*_i\left(T_{in}\right) - n_{i,out}\tilde{H}^*_i\left(T_{out}\right)\right]$$

$$+ \left[n_{in}\Delta\tilde{H}^{residual}\left(T_{in}\right) - n_{out}\Delta\tilde{H}^{residual}\left(T_{out}\right)\right]$$

- No chemical reaction, constant of integration term disappears
  » $n_{i,in} - n_{i,out} = 0$

Heat of Combustion
Related to Heat of Formation

$$\sum_i \left(n_{i,in} - n_{i,out} \right) \tilde{H}^*_{F,i} = \sum_i \left(n_{i,in} - n_{i,out} \right) \tilde{H}^*_{c,i}$$

$$+ \underbrace{\left[\sum_i \left(n_{C,in} - n_{C,out} \right) \right]}_{0} \tilde{H}^*_{F,CO_2} + \underbrace{\left[\sum_i \left(n_{H,in} - n_{H,out} \right) \right]}_{0} \tilde{H}^*_{F,H_2O}$$

$$+ \underbrace{\left[\sum_i \left(n_{S,in} - n_{S,out} \right) \right]}_{0} \tilde{H}^*_{F,SO_2}$$

$$\therefore \quad \sum_i \left(n_{i,in} - n_{i,out} \right) \tilde{H}^*_{F,i} = \sum_i \left(n_{i,in} - n_{i,out} \right) \tilde{H}^*_{c,i}$$

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Alternate Ways to Convert Results to Heat of Combustion Basis

1. Calculate the pieces
   - Heat of combustion at reference temperature (25°C)
   - Sensible heat effect for temperatures other than 25°C
     » Use Aspen Plus calculated overall heat capacity for each stream
   - Latent heat effect for liquid components in gas phase
     » Use heat of vaporization for each component at 25°C
2. Directly adjust the Aspen Plus calculated enthalpy
   - Avoids potential problems of appropriateness of overall heat capacity
   - Does not split out the different effects

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Feedstock Potential

Component	% Feed Flow (Mass)	% Feed Flow (Energy)
Ethanol Producing Reactants		
Cellulose	37%	36%
Xylan	20%	21%
Arabinan	2.5%	3.0%
Galactan	1.6%	1.9%
Mannan	1.3%	1.5%
Total	62%	63%
Non-Ethanol Producing Reactants		
Lignin	18%	26%
Soluble Solids	5.2%	1.0%
Protein	4.0%	3.0%
Extractives	2.6%	5.0%
Acetate	2.4%	2.5%
Miscellaneous	5.2%	2.5%
Total	38%	37%

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Process Energy Balance
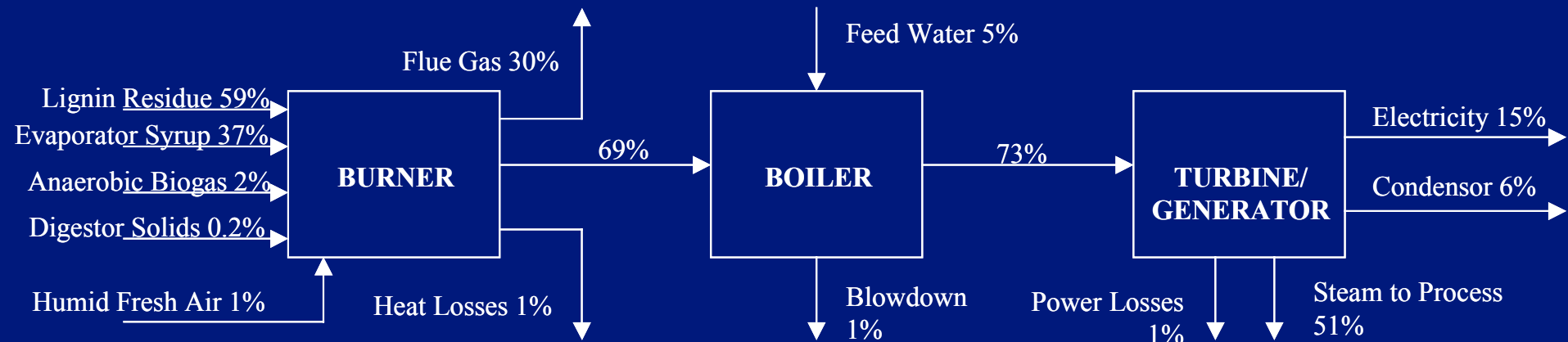## [2,000 tonne/day (dry) Feed]
[69 MM gal/yr Ethanol]

	% Biomass Feedstock
Energy Inlets	
Feedstock	100%
Enzymes	0.9%
Air	0.5%
Energy Outlets	
Ethanol	49%
Cooling Tower	22%
Combustion Exhaust	15%
Ambient Heat & Work Losses	5.8%
Byproduct Electricity	4.8%
Loss to Atmosphere	0.4%
Ash	0.3%
Aerobic Vent	0.1%

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Process Energy Balance
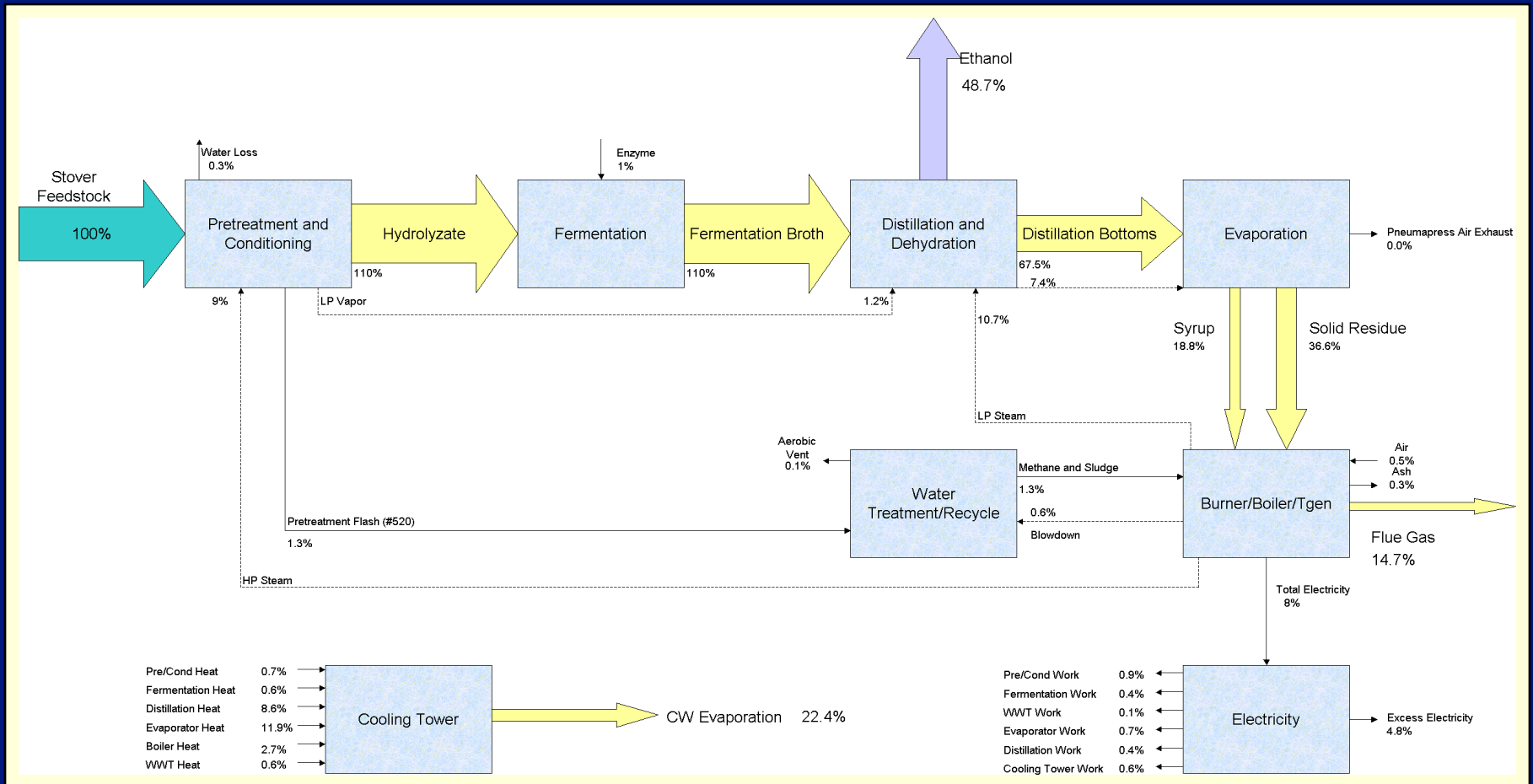
Not all streams shown in diagram. Individual sections may not appear to balance.

Section Energy Balance

Flue Gas 30%

Feed Water 5%

Lignin Residue 59%
Evaporator Syrup 37%
Anaerobic Biogas 2%
Digestor Solids 0.2%

BURNER

69%

BOILER

73%

TURBINE/ GENERATOR

Electricity 15%

Condensor 6%

Humid Fresh Air 1%

Heat Losses 1%

Blowdown 1%

Power Losses 1%

Steam to Process 51%

- Lignin residue provides majority of the energy
- Steam to process gives an overall high energy recovery
- Flue gas energy content primarily due to condensables in gas phase

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Energy Balance Observations

Over 50% of the available energy exits process as ethanol product or exported electricity

Flue gas energy due to latent heat effects
- Must remain hot enough to keep any acidic liquids from condensing

More heat integration could potentially reduce cooling tower losses

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Other Process: Integrated Gasification Combined-Cycle Power System

		Net Efficiency (%) (HHV Basis)
High Pressure Gasifier	Aero-derivative gas turbine	36%
	Advanced Utility Turbine	40%
Low Pressure Gasifier	Indirectly Heated Utility Gas Turbine	35%
	Air-Blown Advance Utility Gas Turbine	37%

Comparison With Other Processes
[Basis: 100 kcal Biomass Feed]

	Biomass to Ethanol		Corn Dry Mill	Biomass Power	
	Power Generation	Import Power & Steam		Direct Fired Boiler	Gasifier
Biomass Feed	100	100	100	100	100
Ethanol Product	49	49	57	N/A	N/A
Electricity	5	-3	-2	28	40
Steam & Natural Gas	N/A	-32	-26	N/A	N/A
Co-Product	N/A	48	35	N/A	N/A
Total	54	62	64	28	40
Net Efficiency	54%	72%	72%	28%	40%

"Comparison of USDA and Pimentel Energy Balances," Michael S. Grabowski, National Corn Growers Association Position Paper, August 22, 2001.

"Determining the Cost of Producing Ethanol From Corn Starch and Lignocellulosic Feedstocks," Kelly Ibsen, Andy McAloon, Frank Taylor, Robert Wooley, Winnie Yee, NREL/TP-580-28893, October 5, 2000.

"Renewable Energy Technology Characterizations," TR-109496, Topical Report, prepared by the Office of Utility Technologies, U.S. Department of Energy, & EPRI, December 1997.

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Acknowledgments

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