UNIVERSITY OF FLORIDA

Combined Cooling, Heat, Power, and Biofuel from Biomass and Solid Waste

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Description: The goal of this project is to provide the underlying research and demonstration of a novel technology which would enable the economic utilization of dispersed biomass and solid waste resources to produce electric power, cooling, heat, and transportation fuels. This integrated gasification and power generation system combines University of Florida advances in high-temperature gasification, hydrogen generation and separation, and advanced gas turbine systems. Their integration is expected to result in significant improvements in the cost, emissions, feedstock flexibility, and water requirements, all in a relatively compact, modular plant system. This in turn will enable much greater utilization of renewable energy supplies, helping the development of a sustainable energy supply infrastructure.
Budget: $576,000
Universities: UF

External Collaborators: Siemens Power Generation, Florida Turbine Technologies, Energy Concepts Co., PlanetGreenSolutions Inc., LPP Combustion, LLC.

Progress Summary

The current project focus is in three areas: development of a system architecture and thermodynamic model, development of models and system-level experiments for the PoWER gas turbine unit, and exploration of the underlying science and demonstration of the high temperature steam gasification (HiTS) subsystem. These activities are structured in such a way as to allow stepwise research and development of the overall plant in outlying years.

The system architecture includes the full integration of waste heat and water produced in the gas turbine module with the gasification subsystem. This in turn allows efficiency gains, reducing the proportion of hydrogen utilized internally, and allows zero net usage of external water resources. A thermodynamic system model has been refined during the current year, and the architecture is suitable for inclusion of more complete subsystem models as their development continues. The PoWER and HiTS subsystem models have been further developed to include more detailed physics and, for the PoWER model, transient effects.

The PoWER system has been implemented as an experimental system in previous programs, and a demonstration-level plant is nearing completion. Early stage integration of the HiTS and PoWER subsystems includes operation of a Capstone C-60 gas turbine engine on syngas from the developmental gasifier. Installation of the Capstone unit, including gas handling subsystem and load bank, has been accomplished during this reporting period.

On the gasification side, first we have developed a physics-based thermal-chemical high-temperature steam gasification model that is based on a completely self-sustained gasification process with no external heat source require nor water supply needed. The only input materials are the biomass feedstock and pure oxygen for the hydrogen combustor. Through the combustion of the hydrogen taken from the produced syngas with the externally supplied oxygen, the hydrogen combustor produces the high-temperature steam that is used as the gasifying agent. The water vapor in the syngas is retrieved through a condenser and re-heated by the syngas in a heat exchanger to supplement the gasifying stean stream and to conserve water. After performing a heat and mass balance analysis using the model, the results suggest that with a steam temperature of 2000C, the fraction of hydrogen taken from the syngas for the hydrogen combustor is around 60% for a steam to biomass ratio of 3. For the syngas composition, 40% in mole fraction is hydrogen and 20% is carbon monoxide at a steam to biomass ratio of 3. The rest are methane, carbon dioxide and water vapor.

We have also re-designed and made improvements on the trailer-scale biomass-to-energy system. It now generates high quality syngas with negligible amounts of tar. This system has been used as an experimental apparatus and also for demonstration to the public. The system is composed of a gasifier, cleaning system and an engine-generator set with a load bank. The gasifier is the main part of the system and is a basic down-draft system with the capacity of handling about 7 kg of biomass per hour in a batch process. We have performed several experiments with four different feedstocks using the modified system and obtained results. We have measured the gasifier temperature profiles at various locations and evaluated the syngas contents. The electrical power generated for each feedstock was also measured using a loadbank. Among the four feedstocks, red oak was found to be the best in the conversion of biomass to energy by thermal-chemical gasification.

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I. Experimental Facility Development – A Trailer Scale Biomass-to-Energy System

We have re-designed and incorporated new improvements to the system reported last year. The new system is shown in Fig. 1 below, the system is composed of a gasifier, cleaning system and an engine-generator set with a load bank. The gasifier has been re-designed and modified with a throat region which enhances the combustion in generating higher temperatures for effective cracking of the tar vapor. The old syngas cleaning system was totally replaced by a much more efficient cooling tower and a two-stage filter component. The cleaning system effectively removes most dust and tar. This is to ensure the quality of syngas that is fed to the engine. Now the syngas going into the engine is virtually tar-free. The gasifier is the main part of the system and is a basic down-draft system with the capacity of handling about 10 kg of biomass per batch.

Figure 1. Trailer scale biomass to energy system

The final component of the system is a conversion unit that turns the enthalpy available in the syngas (heat energy) to electrical energy. We use a Ford DSG-423 four cylinder IC engine with a generator set for this purpose. The electrical power produced could be used directly to run any loads or could be stored in battery packs. The rpm of the engine has been turned down to 1800 to ensure complete combustion of the gas that is being fed in to the combustion chambers and to prevent deposition of soot particles on the engine compartments. The engine generator set is connected to a load bank to obtain the load and power generated data.

II. Biomass Gasification Experiment and Results

We have used four different feedstocks, pine wood, horse manure, red oak and cardboard respectively for our experiment and analysis. All four feedstocks were evaluated in separate experiments and the corresponding data sets were collected. After a detailed analysis it was found that the red oak is the most powerful feedstock that generates a peak electrical output of 13 KW. Horse manure produced a lot of tar and pine was confirmed to be the second best feedstock. The temperature profiles at various locations in the gasifier for red oak feedstock are provided in Fig. 2. The combustion zone is the hottest and its temperature averages around 1000 ^{o}C.

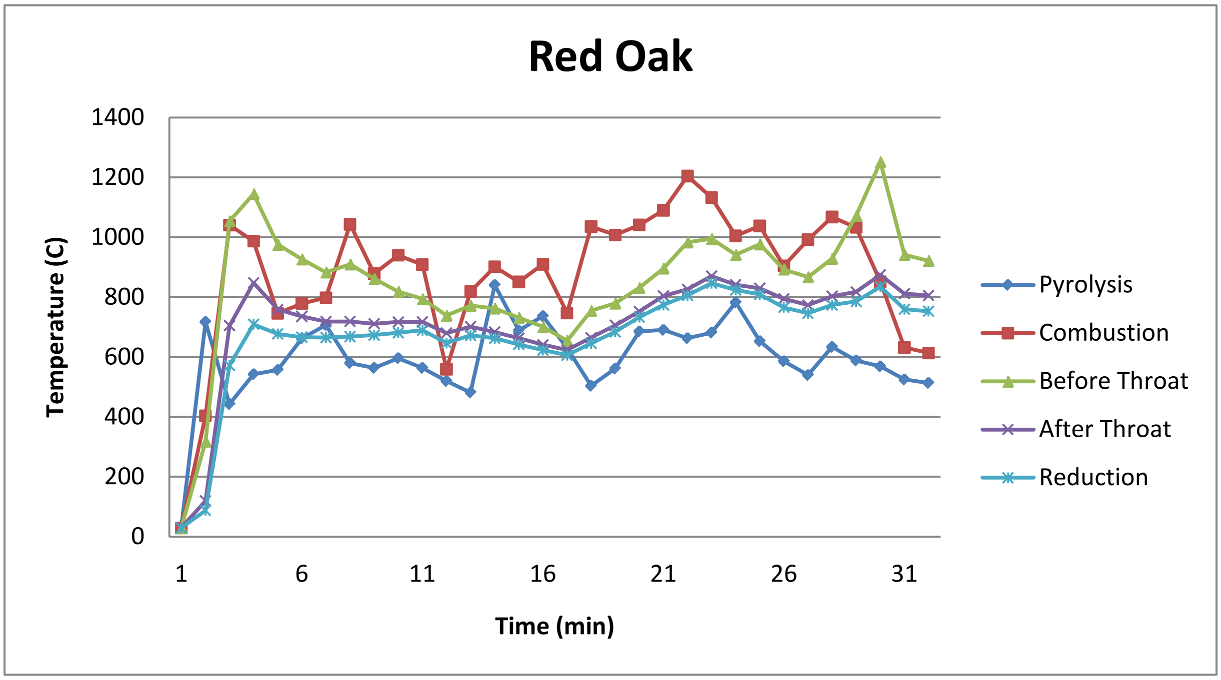


Figure 2. Temperature Profile History in the Gasifier

The Table below gives the volume fractions of sysgas components, peak power level and electrical power generated per pound of biomass for each feedstock. Fig. 3 demonstartes the peak power versus the hydrogen volume fraction for each feedstock. It can be concluded that the red oak was found to be the best among the four feedstocks in the coversion of biomass to energy by gasification.

Datasets Measured	**Pinewood**	**Red Oak**	**Horse Manure**	**MSW**
Syngas Gas Composition (Vol %)				
H2	15	22	20	11
CH4	5	2	3	2
Peak Ele. Output (KW)	11.76	13.1	10.54	9.6
Electrical Energy Generated/lb Biomass (KW Hr/lb)	0.75	1.01	0.56	0.73

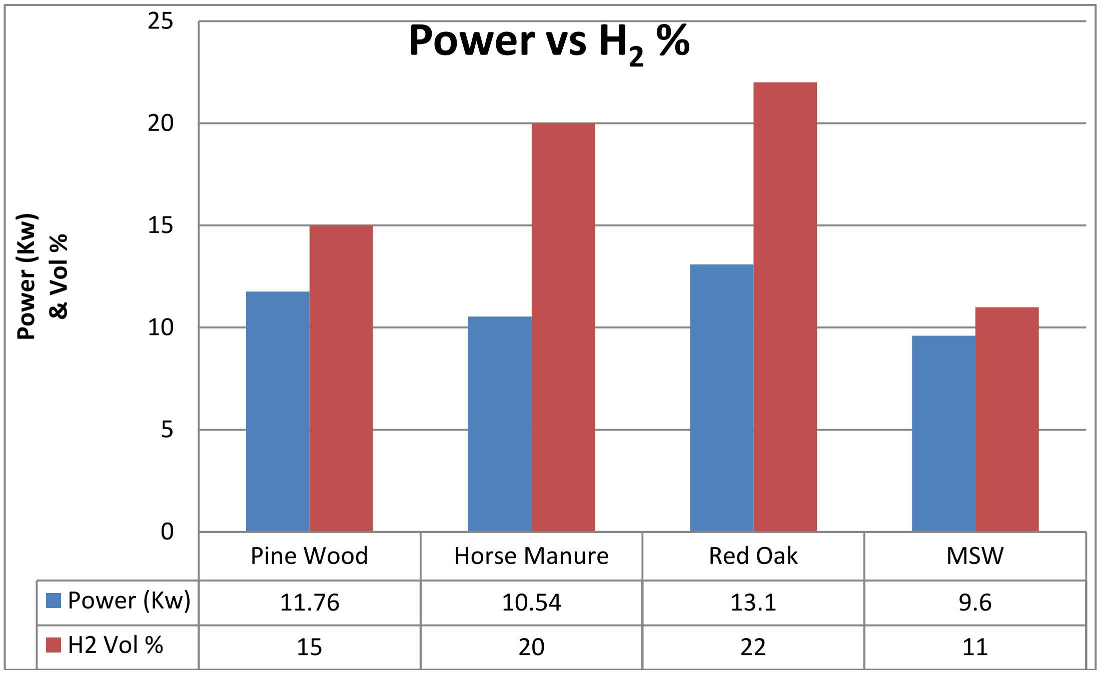


Figure 3. Peak Power versus the Hydrogen Volume Fraction for All Feedstocks.

II. Flameless Combustion Experiments and Modeling

The Power, Water Extraction, and Refrigeration (PoWER) system is the energy conversion subsystem to be eventually integrated with the steam gasification plant described above. One important feature of the PoWER system is that the combustion environment features high diluent concentrations, resulting in significantly reduced flame temperature. This in turn produces a flame characterized by very low soot production, highly-uniform temperature field, and low flame luminosity, so that the regime is termed flameless combustion. The low flame temperature reduces NOx without complex dry low-NOx technology; the low soot formation helps to reduce CO emissions. Overall, the primary regulated pollutants – NOx, particulates, unburned hydrocarbons, and CO – are simultaneously reduced to levels well below the current state of the art. At the same time, fuel flexibility is enhanced, making this system ideal for coupling to a biomass/MSW gasifier with a wide range of syngas compositions. This in turn makes the economics more attractive, as a single system is expected to be applicable in multiple applications with minimal or no modification.

Current activities have focused on coupling the output fuel stream of the gasifyer to a modified, conventional microturbine in order to characterize the suitability of the various syngas variants for gas turbine operation. The gas turbine system is based on a Capstone C60™ microturbine (60KW) and multiple fuel sources, including methane, syngas, and a LPP Combustion, LLC gasified fuel skid, shown in Figure 7. The controls allow automatic, rapid switching between two gasified fuel paths, gasified liquid fuel (LPP) and biomass fuel. For test runs using stored syngas or other low-pressure fuel, we integrated a Copeland™ gas booster into the system. A Merlin Simplex portable load bank with 200 KW capacity is used to dissipate the electrical power as well as to control the engine output.

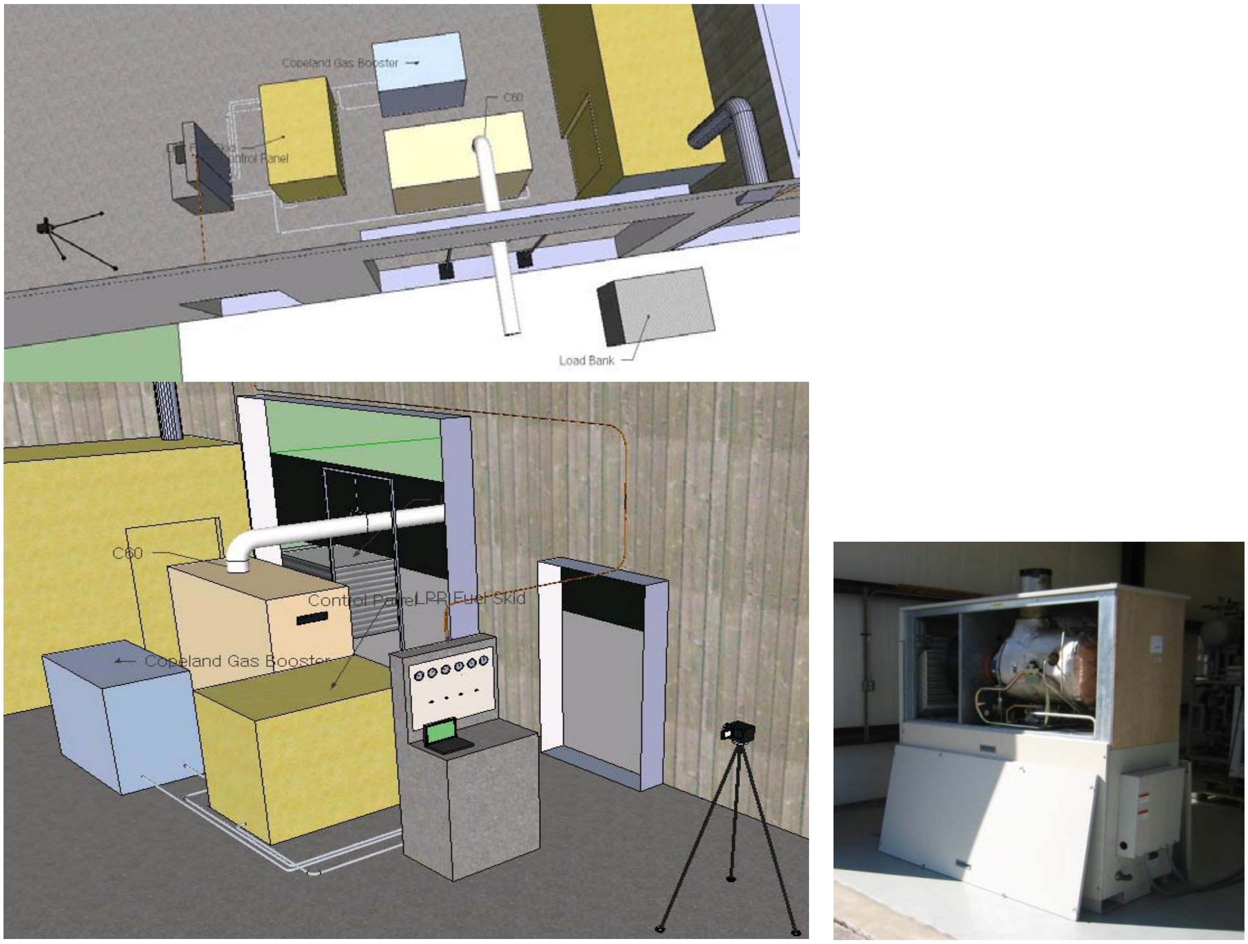


Figure 7. Micro-turbine test system schematic diagram and photograph.

Integrated system modeling, gasification and PoWER system parts, is being simulated by using MATLAB® and C++. The system modeling architecture is shown in Figure 8. Three subsystem simulation programs are coupled to form the integrated plant model: turbocharger and microturbine system, vapor absorption refrigeration rystem (VARS), and HiTS.

In the Gasifier simulation part, from biomass content, biomass flow rate, reactor design temperatures, component efficiencies and PoWER system water extraction are input data. Predicted temperatures, pressures and flowrates, energy flows, and syngas flow, temperature and compositions will be obtained as output data. Model chemical kinetics of the reactions in the gasifier have so far been made using an equilibrium assumption; the highly non-linear set of equations is solved solved using MAPLE as indicated in Figure 9.

The modeling developments are steps along the path towards an integrated overall system simulation code. Such a code will allow determination of optimal flowpath configuration to enable capture of waste heat and minimization of exergy destruction, as well a parametric optimization for design purposes. The model is to be validated via interrim experiments described above, so that the full plant design can be accomplished with confidence.

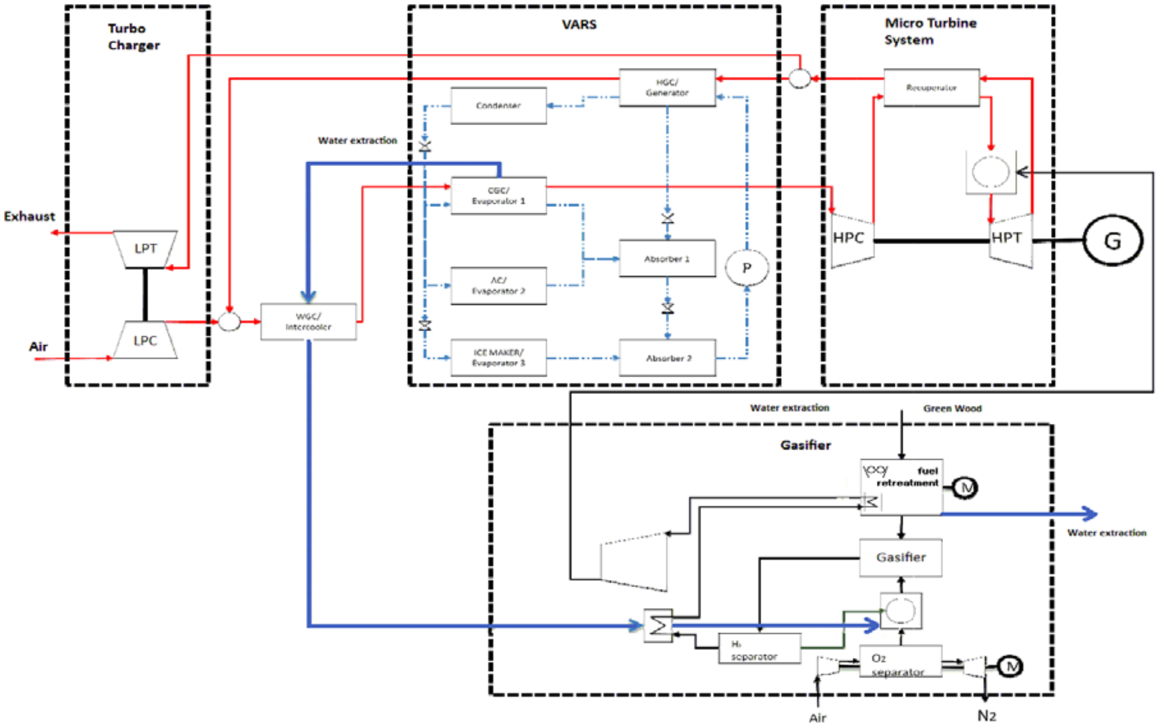
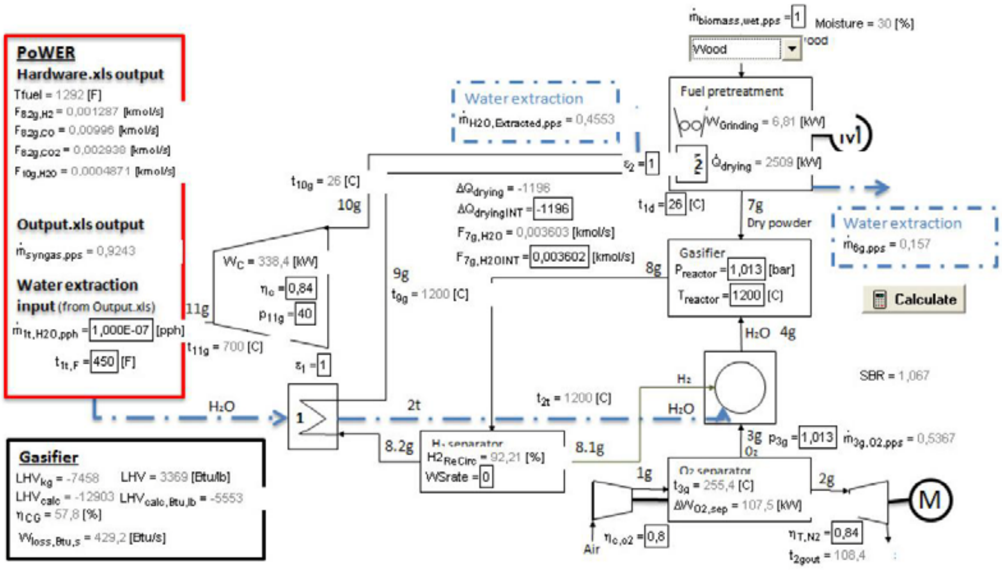


Figure 8. Integrated system modeling



PoWER

Hardware.xls output

Tfuel = 1292 [F]

$F_{8.2g,H2}$ = 0,001287 [kmol/s]

$F_{8.2g,CO}$ = 0,00996 [kmol/s]

$F_{8.2g,CO2}$ = 0,002938 [kmol/s]

$F_{10g,H20}$ = 0,0004871 [kmol/s]

Output.xls output

$\dot{m}_{syngas,pps}$ = 0,9243

Water extraction input (from Output.xls)

$\dot{m}_{1t,H2O,pph}$ = 1,000E-07 [pph]

$t_{1t,F}$ = 450 [F]

Gasifier

LHV_{kg} = -7458

LHV = 3369 [Btu/lb]

LHV_{calc} = -12903

$LHV_{calc,Btu,lb}$ = -5553

η_{CG} = 57,8 [%]

$W_{loss,Btu,s}$ = 429,2 [Btu/s]

$\dot{m}_{biomass,wet,pps}$ = 1

Moisture = 30 [%]

Wood

Water extraction

$\dot{m}_{H2O,Extracted,pps}$ = 0,4553

Fuel pretreatment

$W_{Grinding}$ = 6,81 [kW]

$\dot{Q}_{drying}$ = 2509 [kW]

ε_2 = 1

t_{10g} = 26 [C]

ΔQ_{drying} = -1196

$\Delta Q_{dryingINT}$ = -1196

$F_{7g,H2O}$ = 0,003603 [kmol/s]

$F_{7g,H2OINT}$ = 0,003602 [kmol/s]

t_{1d} = 26 [C]

7g Dry powder

Water extraction

$\dot{m}_{6g,pps}$ = 0,157

W_C = 338,4 [kW]

η_c = 0,84

p_{11g} = 40

t_{11g} = 700 [C]

ε_1 = 1

t_{9g} = 1200 [C]

Gasifier

$P_{reactor}$ = 1,013 [bar]

$T_{reactor}$ = 1200 [C]

SBR = 1,067

t_{2t} = 1200 [C]

H₂ separator

$H2_{ReCirc}$ = 92,21 [%]

WSrate = 0

p_{3g} = 1,013

$\dot{m}_{3g,O2,pps}$ = 0,5367

O₂ separator

t_{3g} = 255,4 [C]

$\Delta W_{O2,sep}$ = 107,5 [kW]

$\eta_{c,o2}$ = 0,8

$\eta_{T,N2}$ = 0,84

t_{2gout} = 108,4

Figure 9. Sample view of simulation program