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Thermodynamic Investigation on Biomass Derived Syngas Fueled Combined Cycle Power Plant

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Abstract : This article reports the results of syngas fueled combined power cycle which was analyzed from both energy and exergy point of views. A parametric investigation was carried out to ascertain the effects of change in biomass material, gas turbine inlet temperature, and steam turbine inlet pressure on performance of the biomass gasifier integrated combined cycle plant. The results obtained clearly reveal that first law efficiency and second law efficiency of the combined cycle significantly vary with the change in gas turbine inlet temperature and steam turbine inlet pressure but the change in biomass material shows small variation in these parameters.
Keywords: Combined Cycle, Thermo-Chemical Equilibrium, Gasification, Syngas, Power Generation

1.Introduction

The energy and environment norms regarding the ozone layer depletion and the global warming are becoming more and more stringent in almost all over the world. In this challenging scenario, biomass gasification energy for producing electricity gaining popularity, because they use zero global warming and ozone depletion. However, these systems have lower efficiency than the conventional power plants and need optimization from thermodynamic point of view. Direct combustion of biomass is worsened by heterogeneous composition of waste biomass leading to unacceptable consequences because it has low efficiency and a high environmental impact, due tothe unburned hydrocarbons and the release of particulates matter. Gasification of biomass is an attractive technology for power generation. The use of biomass gasification process is a key element in an advanced gas turbine combined cycle system.

Various investigations based on conventional first – law of thermodynamic method have been carried out in the past on biomass integrated gasification combined cycle. These investigations laid a foundation for the proper utilization of biomass using gasification technology effectively. Marcio[1] proposed a thermodynamic methodology for the viability of a power generating system based on atmospheric gasification of sugarcane bagasse using fluidized- bed gasifier. In this study various configurations of the power unit were tried until the most efficient was found. Ciferno and Marano [2] reported benchmarking biomass gasification technology for fuels, chemicals and hydrogen production. Larson et al. [3] carried out the cost benefit assessment of biomass gasification power generation in the pulp and paper industry. De Souza Santos [4] described a theory of solid fuels combustion and gasification. The material reported has been found of much use for the analysis of solid fueled power generation system simultaneously involved in the processes of gasification and combustion.

Most of the studies reported in the literature as discussed above are based on first law analysis or energy balance approach. First – law of thermodynamics simply deals with the conversion of energy from one form to another. It fails to identify and quantify the sources of thermodynamic losses which are responsible to deteriorate the performance of thermal energy systems and cannot answer why the actual operational performance of energy system differ from the design one. In order to overcome with these limitations of the first law, second law of thermodynamics has been adopted by many investigators for the last decade and it is observed that combined application of first and second laws of thermodynamics results to provide credible information about the real performance of thermal power generation systems [5].Wu et al. [6] carried out first law simulation for 450 kW gas engine using fluidized bed gasifier and reported that its overall efficiency can be achieved 26-28%. For rice husk and agricultural waste plant they found gasifier as the major source of exergy losses.

Brown et al. [7] addresses the issues of thermo economic assessment of wood gasification for electricity generation. They identified the operating conditions for maximum exergy efficiency of the plant with minimal investment cost.Bhattacharya et al. [8] conducted a thermodynamic analysis of biomass integrated gasification combined cycle considering the combustion of supplementary biomass fuel using the oxygen available in gas turbine exhaust. There results show the plant efficiencies increase with the increase in both pressure and temperature ratios: however, the latter has a stronger influence than the former.Srinivas et al. [9] predicted the thermal performance of a biomass based IGCC plant and examined the effects of gasifier conditions on the efficiency and power generation capacity of the plant as well as their effect on NO_X and CO_2 emissions.Most recently theoretical investigations on different biomass material gasification at ambient conditions for gas turbine power generation have also been presented for various operating conditions [10-12].

In this context the current study has been carried out to evaluate the thermodynamic performance of various biomass fueled combined gas - steam cycle for power generation. The effect of change in biomass material and some influenced thermodynamic parameters have been observed on the first law and second law performance of the proposed cycle.

2. Problem formulation

Figure 1 shows athermo – chemical modelof biomass gasification combinedpower cycle power plant.The biomassfed to the gasifier. The compressed air at state 2 and saturatedsteam at state 4 enter the gasifer where syngas is produced and goes to the combustion chamberafter passing through a gas cleanup unit where tar and char removed.Incombustion chamber the chemical reaction are taking place. The products of combustion go to the gas turbine where they expandandproduce power. The exhaustgassesofgas turbine enter the heat recovery steam generator (HRSG)where superheated steam is produced. This superheated steam is used to runthe steam turbine and produceelectric power and exhaust steam from steam turbinerouted tothe condenser where its phase changes from vapor to liquid and then pumpedback to theHRSG. The wastegasesavailable at the exit of HRSGdischarge to the atmosphere at ambient pressure.The analysis was carried out as per the assumptions taken by Wu et al. (2008) [6]

3. Firstandsecond lawanalyses of a combined power cycle

The gasification reactions in the gasifier are explain as

$$\mathrm{C_{a0}H_{a1}O_{a2}N_{a3}} + \mathrm{wH_2O} + \mathrm{a_4(O_2 + 3.76N_2)} + \mathrm{a_5H_2O} = \mathrm{b_1CH_4 + b_2CO + b_3CO_2 + b_4H_2 + b_5H_2O + b_6N_2} \ldots\ldots(1)$$

The syngas obtained after gasification was used in combustion chamber as a fuel reported as

$$b_1CH_4 + b_2CO + b_3CO_2 + b_4H_2 + b_5H_2O + b_6N_2 + a_7(O_2 + 3.76N_2) = b_7CO_2 + b_8H_2O + b_9N_2 \ldots\ldots(2)$$

The composition of syngas formed after gasification of biomass was computed after following the model developed by Bhattacharya et al. [8].

The thermodynamic performance parameters for the first and second law efficiency of the proposed combined cycle were calculated after using

$$\eta_I = \frac{\dot{W}_{GT} + \dot{W}_{ST} - \dot{W}_{AC} - \dot{W}_{FP}}{\dot{m}_f LHV} \ldots\ldots(3)$$

$$\eta_{II} = \frac{\dot{W}_{GT} + \dot{W}_{ST} - \dot{W}_{AC} - \dot{W}_{FP}}{\dot{E}_{fuel,in}} \ldots\ldots(4)$$

4. Results and discussion

The present study is carried out toidentify the effect of various influenced parameters on the performance of the integrated gasification combustion chamber in the range of operation, gas turbine inlet temperature (1273 –1473K), turbine inlet pressure (30 bar to 70 bar) and approach temperature (288 K). The proposed model developed in this paper for solid waste, rice husk and sugarcane bagasseare tested by comparing the result with the published papers of relevant researchers [12].

Figs. 2-3 shows the variation of first and second law efficiencies of biomass gasification of combined power cyclewith the change in gas turbine inlet temperature. In general, second law efficiencies of combined are slightly lower than their first law efficiencies. This is due to the fact that the chemical exergy of biomass fuel which is considered as the input in second law analysis is higher than the calorific value of the fuel which is considered as the input in the first law analysis. Figs. 2-3 reveal that both first law and second law efficiencies increase linearly as gas turbine inlet temperature for all three cases of biomass considered. It is further noticed that both first and second law efficiencies ofcombined power cycle are higher for solid waste and lower for sugar cane bagasse. This is due to the fact that gasifier temperature and lower heating value of syngas is higher in case of solid waste and lower in case of sugarcanebagasse.

Figs. 4-5 shows the variation of first and second law efficiencies of combined power cycle with the change in steam turbine inlet pressure. It is found that both first and second law efficiencies decrease with the increase in steam turbine inlet pressure. The reason for this kind of trend is that increase in steam turbine inlet pressure results in lower mass flow rate of steam produced in theHRSG which in turn reduces the steam output and hence decreases the overall efficiency of the cycle. Since the contribution of gas turbine towards the overall power generation is much higher and is three times larger than the contribution of the steam turbine, and change in steam turbine pressure only effects the steam turbine output not the gas turbine output, therefore, first law efficiency of combined power cycle slightly drops with the increase in steam turbine inlet pressure. For the similar reasons, second law efficiency also drops slightly with the same.

5. Conclusions

The proposed biomass derived syngas fueledcombined power cycle was analyzed by using first and second law of thermodynamics. The performance of the system was examined under the variation of gas turbineand steam turbine. The main conclusionsdrawn from this study can be summarized as follows:

- Both first and second law efficiencies increases considerably with the rise of gas turbine inlet temperature. First law efficiency has been foundmaximum for solid waste and minimum for sugarcane bagasse.
- Second law efficiency also increases significantly with the increase in gas turbine inlet temperature and it was maximum for solid waste and minimum for sugarcane bagasse fueled cycle.
- Both first and second law efficiencies decrease significantly with the increase in steam turbine inlet pressure.

Nomenclature

$\dot{W}$	power (KW)
η_I	first law efficiency
η_{II}	second law efficiency
φ	exergy ratio
1-8	state points of Brayton cycle
a-e	state points of the steam cycle

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Figure 1 Schematic diagram of biomass fueled combined power cycle plant

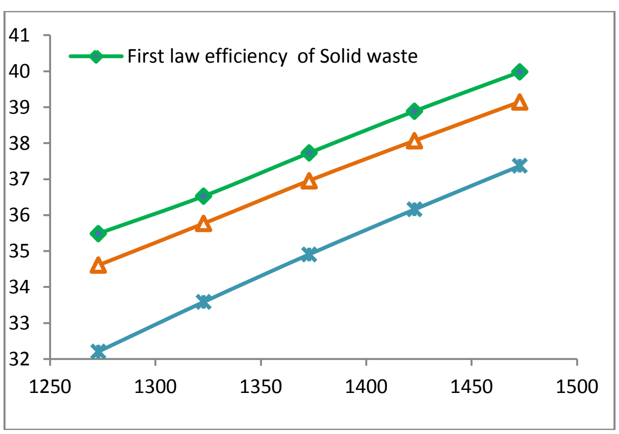

Figure 2 Variation of first law efficiency with turbine inlet temperature of combined power cycle

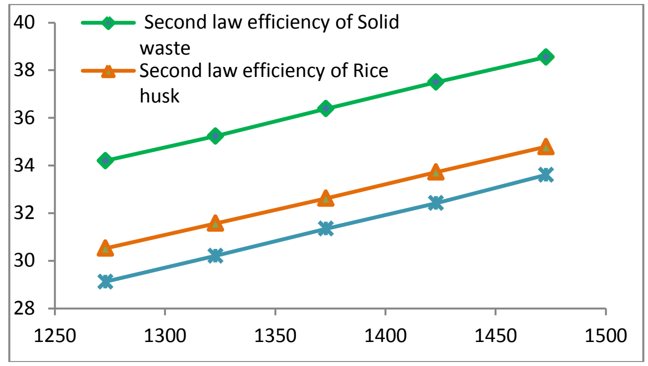

Figure 3 Variation of second law efficiency with turbine inlet temperature of combined power cycle

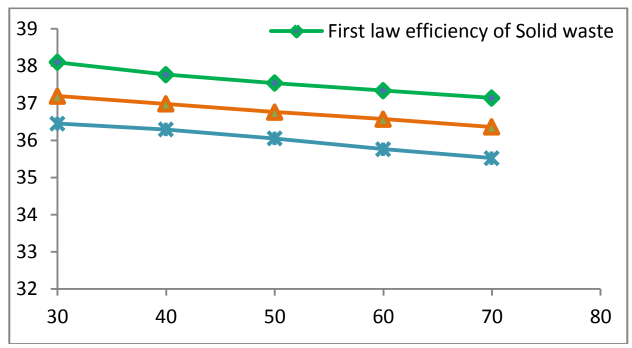

Figure 4 Variation of first law efficiency with pressure ratio of combined cycle power cycle

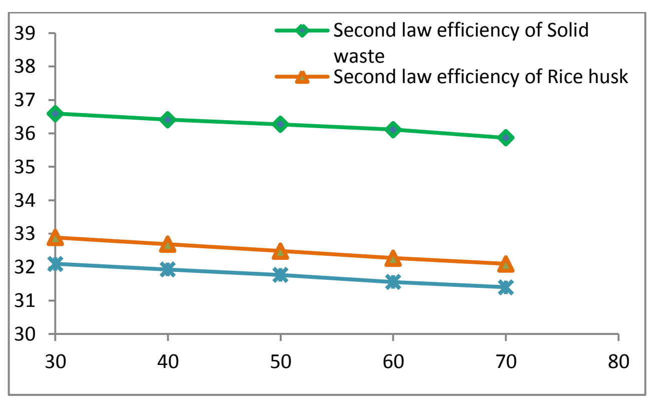

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Figure 5 Variation of second law efficiency with pressure ratio of combined cycle power cycle