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Thermodynamic Analysis of IGFC Systems Utilizing High-Ash Indian Coal and Rice Husk Blends

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Abstract - The Integrated Gasification Fuel Cell Combined Cycle (IGFC) has been thermodynamically analyzed. This study compares IGFC using coal and coal blended with rice husk (in various proportions) as fuel input. Rice husk is blended with Indian coal in three proportions (10, 20, and 40%). To model and simulate the proposed power plant, a computer program "Cycle-Tempo" is used. The thermodynamic analysis is based on variations in syngas compositions, H_2/CO ratios, and higher heating values of syngas with various steam-fuel ratios at a gasifier reaction temperature of 1000°C. According to the study, energy efficiency is highest and SO_2 emissions are lowest when 20% rice husk is blended with 80% coal; exergy efficiency is highest when 100% coal is used, and specific coal consumption is lowest when 40% rice husk is blended with 60% Indian coal.

Keywords: Solid Oxide Fuel cell, biomass, co-gasification, fluidized bed gasifier, combined cycle, Indian high ash coal

Introduction

With the rapid increase in urbanization, industrialization, and modernization, consumption of energy is increasing exponentially. Most of the demand is fulfilled using fossil fuels, namely coal, natural gas, and oil. The installed capacity in India is a total of 5,13,729.71 MW, out of which 2,40,321.62 MW is generated by mostly thermal power plants, where 42.74% of the total installed capacity of the power generation is carried out, by using coal as a fuel [1]. As India has a huge coal reserve, most of the power is generated by using it only. Indian coal has high ash content (35-55%) by mass. Using such coal results in high levels of fly ash emissions [2]. With the current consumption rate, coal is getting depleted day by day. Hence it is observed that over the last few years, there has been considerable growth in power generation by using renewable energy. Biomass energy is regarded as one of the promising renewable energy sources considering its benefits like high hydrogen content, negligible sulphur content, low ash content, non-polluting, carbon-neutral, readily available, and abundant resources [3]. India has the most rice cultivated land and produces approximately 127.93 million tonnes of rice in 2022-23, according to the report by the Ministry of Agriculture & Farmers Welfare. So, rice husk, a high energy content biomass, is abundant in India; however, because it has a relatively low density, utilizing it in gasifiers or combustion reactors creates issues regarding feeding and managing the reactions (heterogeneous and homogeneous) and volatile components. Despite using the recognized technologies for gasifying or burning rice husk, gasification of rice husk poses a number of challenges [2]. Simple biomass gasification, on the other hand, does not always appear to be a profitable alternative due to its low energy density and non-uniform availability throughout the year. Rather, for a variety of reasons, the combination of coal and biomass in varying amounts of biomass is gaining popularity. Because biomass has a lower density than coal, increasing the biomass loading in the feed increases the volume of the feed sample significantly. Because the capacity of the gasifier's feed line is set, the flow of coal-biomass-blended feed in the feed line was constrained. The biomass loading could not be increased above 40% due to operational difficulties [3]. The process of converting carbonaceous fuel (such as coal or biomass) into synthetic gas (syngas) using a gasifying medium (steam with air/oxygen) and heat is known as gasification. Fixed bed, fluidized bed, and entrained flow gasifiers are the three most common commercial gasifiers. The typical operating temperatures for fixed bed gasifiers are 800-1200°C, around 1000°C for fluidized bed gasifiers, and 1300-1800°C for entrained flow gasifiers [4]. Fluidized bed gasification reactors are the most versatile, as they typically use a wider range of fuel particle sizes[5]. So, they are suitable for co gasification of coal and rice husk. Solid oxide fuel cells (SOFCs) are one of the most efficient ways to convert syngas into electricity because they only require one phase of conversion, avoiding mechanical losses [6,7].

A lot of studies have been carried out on IGFC, but only a few research is done on IGFC Combined Cycle using biomass co-gasification. In this paper, a comparative thermodynamic analysis is made between Indian coal and coal blended with rice husk in 10%, 20%, and 40% proportions for a 100 MW combined cycle plant coupled with SOFCs.

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Methodology

Cycle tempo" a platform developed by Delft University of Technology (TU Delft), is used for simulation and analysis [8]. The program includes a vast number of models of apparatuses and pipes for building a system model such as a boiler, turbine, heat exchanger, compressor, pump, combustor, gasifier, and pipelines for various forms of media such as water, steam, gas mix, ash, flue gases, etc. The Mathematical model of this software is mainly governed by energy balance equations, exergy balance equations, chemical species balance equations, and enthalpy balance equations. Minimization of Gibbs free energy is used for thermodynamic calculations.

Plant Configurations

Figure 1 shows the schematic diagram of the IGFC Combined Cycle using a blending of coal and rick husk as a feedstock. Raw feedstock enters the gasifier and undergoes gasification in a fluidized bed gasifier at 1000°C using steam and air as a fluidizing agent. After that, syngas is extracted, which is composed of hydrogen, methane, carbon mono oxide, and carbon dioxide. Ash is collected at the bottom ash sink tank. Syngas is supplied at the anode, and at the cathode of the solid oxide fuel cell, preheated air is supplied. The exhaust gas from the cathode is then burned in a combustor and is passed through a gas turbine which generates power. The exhaust from the anode is then forwarded through a heat recovery steam generator (HRSG), where an exchange of heat takes place, and water converts into steam. The steam is channeled through a steam turbine, which generates additional electrical power from the recovered waste heat.

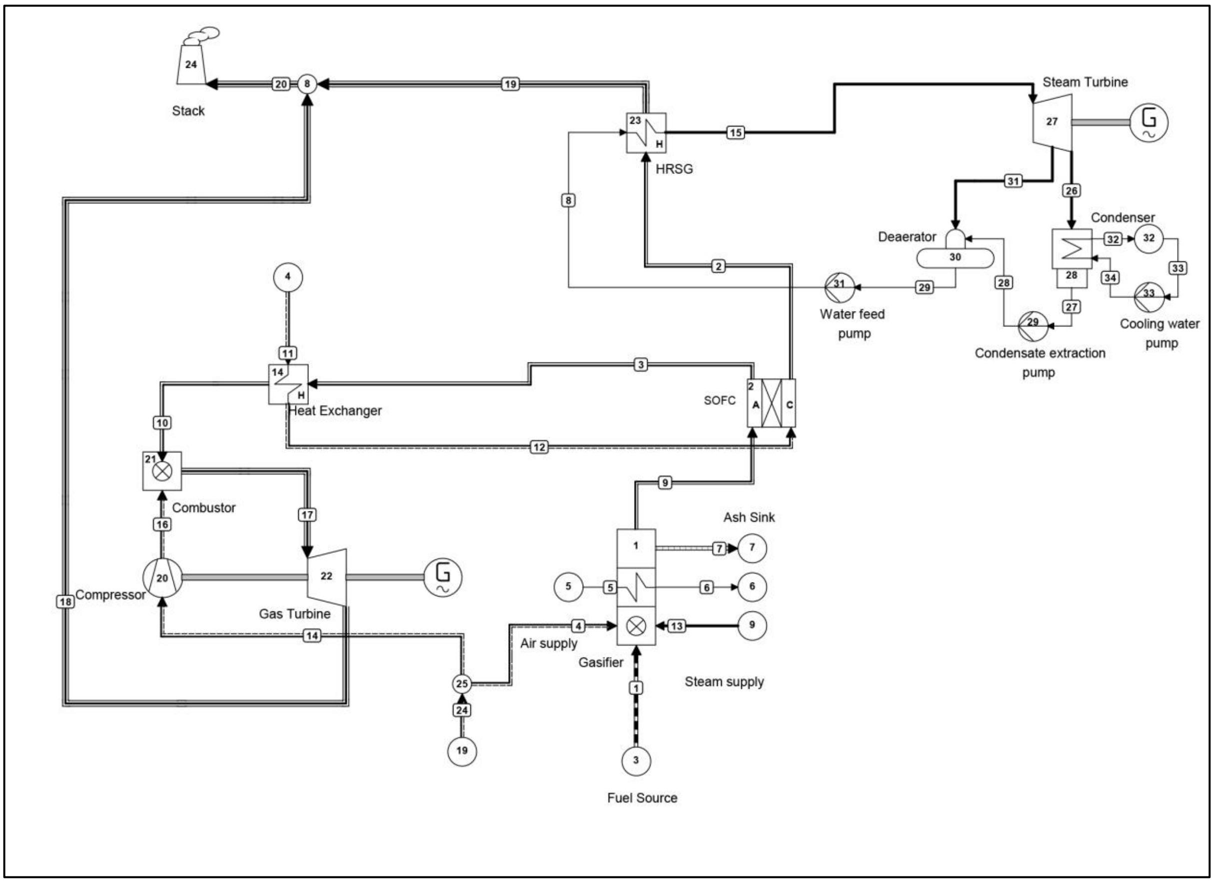

Fig.1. Schematic diagram of the IGFC

Assumptions

- The power plant output is 100MW (Excluding fuel cell).
- The isentropic efficiency of the compressor is 85% and the pump is 80%.
- The ambient pressure and temperature are 1.013 bar and 33°C.

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- The gasifier and fuel cell are both operated at atmospheric pressure.
- Direct internal reforming Solid Oxide Fuel cell with a reactiontemperature:850°C, cell voltage: 0.79 V, current density: 3000A/m2and cell utilization factor: 85%.
- In the Gas turbine cycle, the pressure ratio, combustion chamber reaction temperature, and turbine outlet pressure are 6, 1000 &1.01 bar, respectively.

Fuel Characteristics

The fuel considered for the proposed IGFC Combined Cycle plant is High ash-content India Coal and rice husk. Table 1 displays the heating values and composition of the Indian coal under consideration [6, 9].

Table 1. Composition of High ash Indian Coal and Rice husk (as dry basis)

Ultimate Analysis	Coal (wt%)	Rice husk (wt%)
C	39.16	38.43
H	2.76	2.97
O	7.92	36.36
N	0.78	0.49
S	0.51	0.07
Ash	48.87	21.68
HHV (MJ/kg)	15.83	11.86

Performance Parameters

The following are the parameters based on which the thermodynamic analysis has been done [9]:

$$W_{net} = W_{gross} - W_{auxiliary} \quad (1)$$

$$W_{gross} = W_{steam\ turbine} + W_{gas\ turbine} + W_{SOFC} \quad (2)$$

$$W_{auxiliary} = W_{compressor} + W_{pump} \quad (3)$$

$$\text{Energy Efficiency} = \frac{W_{net}}{\dot{m} \times HHV_{fuel}} \quad (4)$$

$$\text{Exergy Efficiency} = \frac{\sum Ex_{in} - \sum Ex_{loss}}{\sum Ex_{loss}} \quad (5)$$

$$\text{Specific fuel consumption} = \frac{\text{mass flow rate of fuel per hour}}{W_{gross}} \quad (6)$$

$$\text{Mass flow rate of } SO_2 \text{ through stack} = \frac{m_{gas}}{M_{gas}} \times (y_{SO_2} \times M_{SO_2}) \times 3600 \quad (7)$$

$$\text{Specific } SO_2 \text{ emission} = \frac{\dot{m}_{SO_2} \text{ in kg leaving through stack}}{W_{gross}} \quad (8)$$

Gasifier Model Validation

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To validate the gasifier model, the syngas composition is compared with the literature [10]. For this comparison, gasification of saw dust (with 10% moisture) has been done considering the same condition of gasification as the literature. Table 2 shows the comparison result. The comparison shows excellent agreement with a Root Mean Square Error (RMSE) of 2.816.

Table 2. Comparison of syngas composition between the proposed gasifier and literature.

Fuel gas composition on dry basis (vol%)	**Present study**	Literature [10]
H_2	**21.75**	21.40
CO	**23.75**	23.00
CH_4	**0.02**	0.01
CO_2	**7.98**	9.74
N_2	**39.32**	45.31

Results and Discussions

Efficiencies of plant

The net energy and exergy efficiency of the plant with different fuel inputs on a higher heating value (HHV) basis is shown in Table 3. It shows an increase in energy efficiency up to 20% because the carbon content of rice husk and coal is approx equal; after that, it decreases when the amount of rice husk present in the fuel mix is increased from 20% to 40% because HHV of rice husk is much less than that of coal, the effect of HHV of rice husk comes into picture when the percentage of it increases more than 20%.

Table 3. Efficiencies of the plant with respect to different fuel to biomass ratio.

Fuel type	Energy efficiency (%)	Exergy efficiency (%)
100% Coal	56.21	51.51
90% coal + 10% rice husk	56.22	51.42
80% coal + 20% rice husk	56.38	51.35
60% coal + 40% rice husk	56.22	51.08

Syngas composition for different fuel input

Syngas composition produced by coal and blending of coal and rice husk blended at a proportion of 10%, 20%, and 40%. From the graph (Fig.2) it is observed that the maximum amount of hydrogen, and carbon monoxide are produced from the gasification of coal, and the maximum amount of carbon dioxide is produced from the blending of coal and rice husk in the proportion of 60/40.

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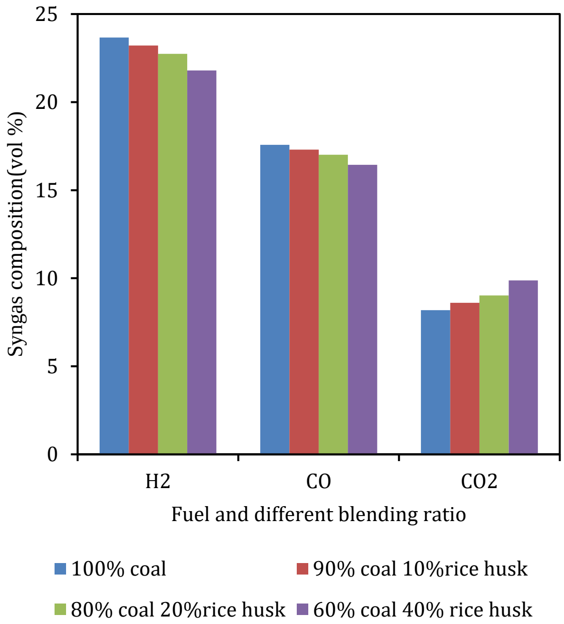

Fig.2. Syngas composition of coal and blending of coal and rice husk in different proportion.

Specific Fuel Consumption of proposed plant

Specific fuel consumption of coal is decreasing as the blending composition of rice husk in fuel is increasing; it is minimum when 60% coal is blended with 40% rice husk, shown in Table 4.

Table 4. Specific fuel consumption of plant with different blending ratio.

Specific fuel consumption (kg/KW)	100% Coal	90% coal + 10% rice husk	80% coal + 20% rice husk	60% coal + 40% rice husk
Coal	0.41	0.37	0.34	0.26
Rice Husk	-	0.04	0.08	0.18

SO_2 emission of the proposed plant

Figure 3 shows the SO_2 emission of the proposed plant. Specific SO_2 emission is minimum when 20% rice husk is blended with 80% coal because the sulphur content of rice husk is very much less than that of coal.

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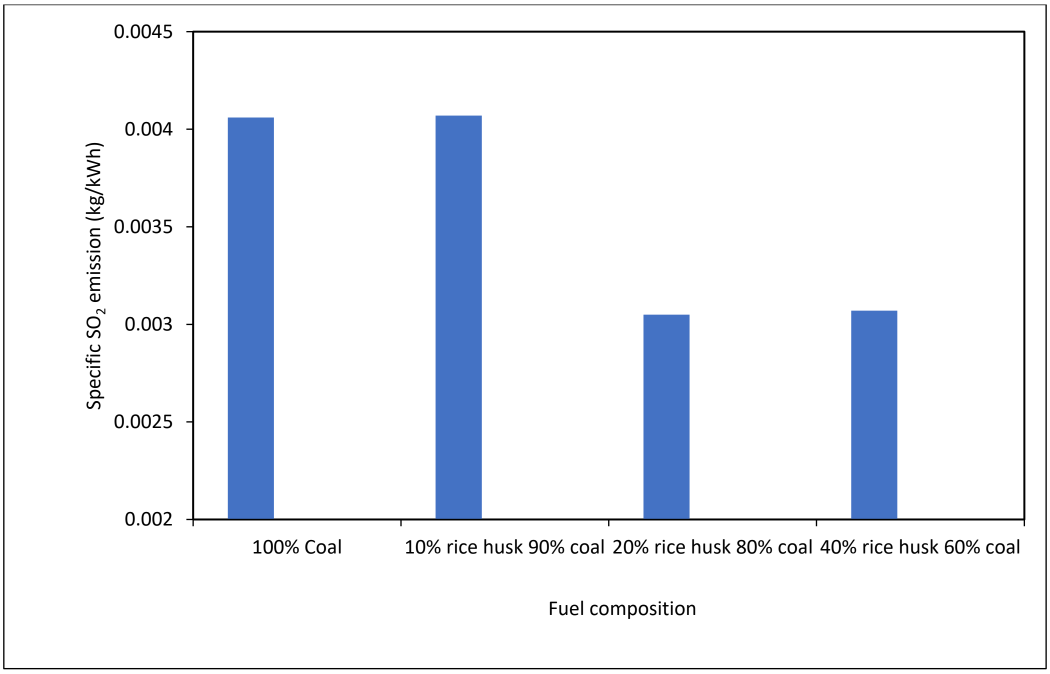

Fig.3. Specific SO_2 emission (kg/kWh) for different composition of fuel

Parametric Analysis of the proposed plant

Effect of Steam fuel ratio (SFR) on the syngas composition (%)

According to figure 4, increasing the amount of steam supplied to the gasifier, i.e., increasing the steam fuel ratio, causes an increase in H_2 synthesis; this is due to endothermic reactions that take place during the gasification process, this occurs. Nevertheless, in the presence of steam, CO is converted to CO_2 and H_2, and the H_2/CO ratio increases as the SFR increases. The conclusion is also drawn that as SFR rises, the slope of the curve depicting H_2 synthesis decreases. The increase in H_2 synthesis is more pronounced between SFRs of 0.1 and 0.5, while it becomes less pronounced beyond 0.5. This is due to a decrease in the gasifier core reaction temperature as more steam is introduced into the gasifier. As a result, the endothermic reactions inside the gasifier don't favour product creation, thereby reducing H_2 synthesis. This graph is plotted for 60% coal and 40% rice husk.

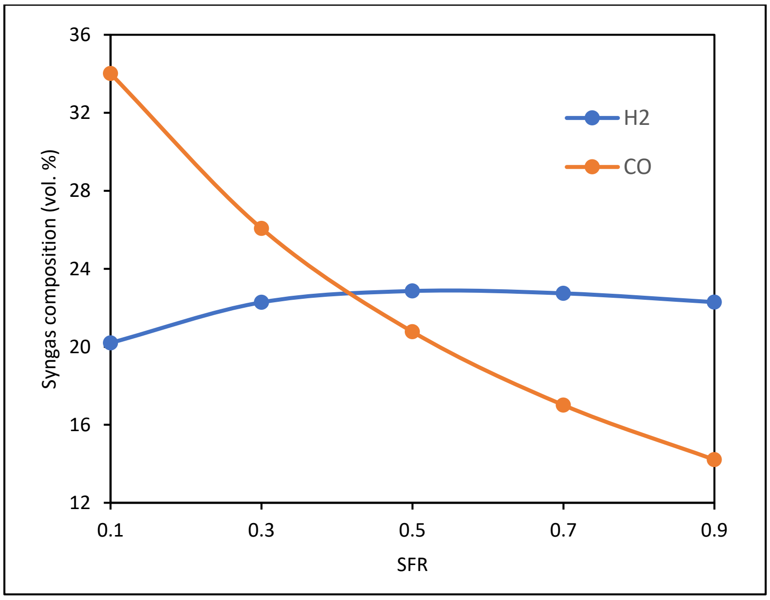

Fig.4. Effect of SFR on the syngas composition (Vol %).

Effect of SFR on the HHV of Syngas Produced.

The graph (Fig.5) plotted for 20% rice husk and 80% coal shows that the HHV of the syngas produced by the gasifier decreases as the steam fuel ratio (SFR) increases. This is due to lower CO concentrations and higher CO_2 levels in syngas as a result of enhanced water gas shift reaction at higher SFR values.

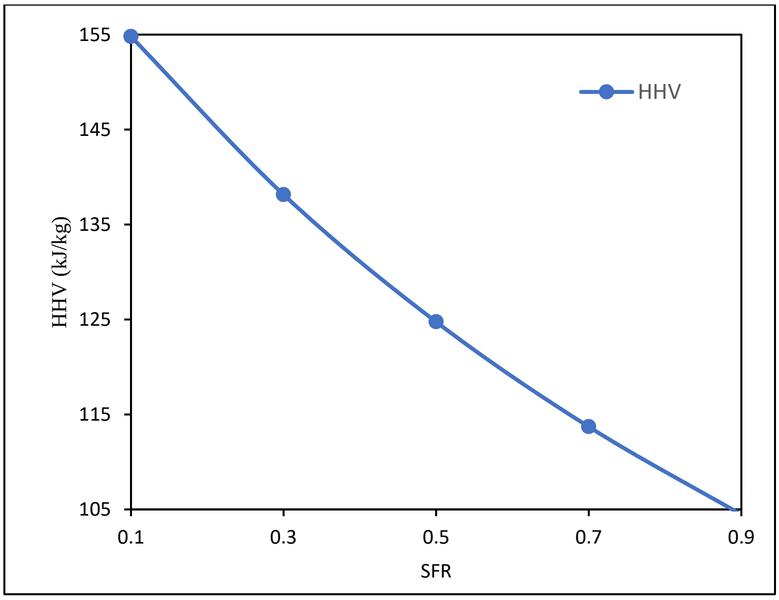

Fig.5. Effect of SFR on the HHV of syngas produced

CONCLUSIONS

- Due to the co-gasification of coal and rice husk mass of coal used reduces as the blending ratio increase, i.e. the minimum amount of coal is used when the blending ratio is 40%.
- The amount of SO_X emitted from the plant also reduces and is at its minimum when 20% rice husk is blended with 80% Indian coal.
- Maximum energy efficiency is obtained when 20% rice husk is blended with 80% coal, and maximum exergy efficiency is obtained with 100 % coal.
- Water requirement in the plant's condenser reduces because only a small portion of power is obtained from the Rankine cycle.

Nomenclature

HHV_{fuel}	Higher heating value of fuel	W_{gross}	Gross power output of plant
SFR	Steam to fuel ratio	W_{net}	Net power output of plant
$\dot{m}$	Mass flow rate of the fuel	SOFC	Solid oxide fuel cell
IGFC	Integrated gasification fuel cell		
M_{gas}	molecular mass of the flue gas leaving through stack		
y_{SO_2}	molar fraction of the SO_2 leaving through stack		

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