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Exergy Analysis and Optimization of Gasifier-Solid Oxide Fuel Cell-Gas Turbine Hybrid System

Dev Nandwana*, Amrit Raj*, Tejas Deepak Kakkade* and Manavalla Sreekanth*¹

Abstract – In this paper, different systems based on integrated gasifier-solid oxide fuel cells (SOFC)-gas turbine hybrid system are modelled to carry out their thermodynamic analysis. The thermodynamic flowsheet software Cycle-Tempo is used to analyze the performance of the modelled systems. Influence of fuels viz. coal and cow manure on the performance of the integrated hybrid system is studied. It is observed that the efficiency of the system changes with change in fuel. The electrical efficiency is found to be 40.2% when coal was used as fuel, and the efficiency increased to 48.2% when coal was replaced by cow manure as fuel. Exergy analysis of the integrated hybrid base case system is performed to find out the components responsible for the poor efficiency of the system. Based on the exergy analysis of the base case system, a new optimized system was designed with the critical operating parameters remaining the same. The system efficiency increased from 40.2% to 49% with coal as fuel and from 48.2% to 56.9% with cow manure as fuel in the optimized system. Exergy analysis of the optimized system depicts that there is a reduction in total relative exergy loss percentage when compared to the base case system.

Keywords – exergy analysis, gas turbine, gasifier, optimization, solid oxide fuel cell (SOFC).

1. INTRODUCTION

In today's world, the development of any country directly depends on its ability to produce electricity in an efficient and sustainable manner. The most conventional method of generating electricity is with the help of coal powered thermal power plants which have a number of drawbacks. Thermal power plants result in a large amount of CO₂ emissions across the world. Apart from CO₂, other harmful gases like NO_x and SO_x are also generated leading to environmental degradation. So, a cleaner, efficient and more sustainable electricity generating system is required [1]-[4].

Solid oxide fuel cells (SOFC) are electrochemical devices which convert the chemical energy of a fuel into electricity and heat [5]. They have electrical efficiencies up to 70% in hybrid configuration [6]. Hydrogen is used as a fuel which is not combusted but rather electro-oxidized at the anode by oxygen ions conducted across the electrolyte. Electrons which are liberated pass through an external circuit to arrive at the cathode where reduction of molecular oxygen takes place to form oxide ions. At the anode, the water vapor is produced which helps in diluting the fuel [7].

SOFC operates at temperatures between 1,073 K and 1,273 K [8]. Major advantages of SOFC over other fuel cells are high power density, fuel flexibility and the ability to reform internally. Alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC) and proton exchange membrane fuel cell (PEMFC) which are low temperature fuel cells require additional processing of fuel since they work with hydrogen only whereas molten

carbonate fuel cell (MCFC) and SOFC which are high-temperature fuel cells are capable of handling hydrocarbons as fuel. Experiments conducted by Li *et al.*, [9] on the economic feasibility of hydrogen production through gasification for PEM (proton-exchange membrane) application, show that energy generated from PEM is lower than combined heat and power (CHP) of the gasifier. Reason for this is that the gasification process produces a clean syngas (H₂, CO, and CH₄) but PEM fuel cell uses the energy of hydrogen gas for power generation. Whereas in SOFC, due to high operating temperature hydrocarbons are reformed internally to form H₂ and CO inside MCFC and SOFC. Carbon monoxide which is considered poison for AFC, PAFC and PEMFC are oxidized in MCFC and SOFC. MCFC, when compared to SOFC, has relatively lesser advantages. MCFC have problems associated with the molten electrolyte corrosion and electrolyte loss whereas SOFC being solid construction has no such losses. Furthermore, the requirement of CO₂ at the MCFC cathode adds to system complexity [9]-[13].

Gasification is a process where partial oxidation of carbonaceous material takes place by limiting the supply of oxygen. Gasification is carried out around 1,173 K which is also the operating temperature of SOFC, which makes gasifier and SOFC integration completely viable. As in the SOFC system, high heat is generated which helps in cogeneration and combined cycle systems. Hence, SOFC is best suited for use with biomass gasifier compared to other types of the fuel cell, but there is a need for cleaning of the producer gas before feeding into the SOFC [14]. Aravind and de Jong have carried out experiments on the influence of biomass-derived contaminants on the SOFC [15]. The contaminants studied are tar, particulates, H₂S, HCl and alkali compounds. They claimed that it is possible to achieve effective gas cleaning at a temperature range of 1,023-1,223 K with existing methods. Based on experiments

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and equilibrium studies they have put forward a conceptual design for gas cleaning.

Colpan *et al.*, [16] carried out a study to understand the effect of gasification agent on the performance of integrated biomass gasification and SOFC system. They tested three (3) agents: air, steam and enriched oxygen. The steam had maximum efficiency but minimum fuel utilisation, while air had the second-highest efficiency and highest fuel utilisation. Enriched oxygen had the lowest efficiency and second-highest fuel utilisation.

Experiments conducted by Douvrtzides *et al.*, [17] indicate that energy losses in the stack of SOFC are responsible for low system efficiency. Thus, the thermal efficiency of SOFC is vital. The efficiency of the system can be increased by addition of components that reduce the energy loss in stack of SOFC. Pierobon and Rokni [18] have modelled integrated SOFC plant with simple Kalina cycle and compared its efficiency with integrated SOFC steam turbine plant. Results indicate that simple Kalina cycle has an efficiency of 50.6% while steam cycle has higher efficiency of 52.5%. Rokni [19] has developed an integrated biomass gasification SOFC Stirling engine system. Thermodynamic analysis indicated it has low efficiency of about 41%. The author also highlights the need for proper optimization of the parameter in order to achieve higher efficiency. Bang-Moller and Rokni [20] have carried out thermodynamic performance study of three (3) systems: gasifier-micro gas turbine (MGT), gasifier-SOFC and gasifier-SOFC-MGT [20]. Gasifier-SOFC system is more efficient in converting biosyngas into energy as compared to gasifier-MGT. Electrical efficiency of gasifier-SOFC is 36.4% while electrical efficiency of gasifier-MGT is 28.1%. When gasifier, SOFC, and MGT were integrated into a single system, the electrical efficiency of the system increased to 50.3%. In order to obtain higher energy efficiency, gas turbine operated by SOFC exhaust should be combined with gasifier [21]. Such systems offer an opportunity for realizing sustainable, highly efficient and practically carbon-neutral electricity generation.

In this paper, the thermodynamic properties of the integrated gasifier-SOFC-gas turbine hybrid system are studied. The fuels used in our study are coal and cow manure. Coal is selected because it is the most widely used fuel in thermal power plants. By using coal as fuel the efficiency of our designed system with that of the thermal power plants is compared. The reason behind using cow manure as an alternative fuel is because of its abundant presence in rural areas of India. The total amount of fresh cow dung produced in India amounts up to 800 million tons. Also, coal is a fossil fuel which is a non-renewable source of energy but cow manure is a renewable source of energy. A base case system is initially modeled in cycle-tempo software and then energy and exergy analyses of the base case system are performed for different fuels with the help of the same software. After performing the energy and exergy analyses of the base case system, potential recommendations for optimization of the base case system are suggested. Based on the recommendations, an optimized hybrid system is designed so as to improve

the base case system. Energy and exergy analyses of the optimized system are also performed in order to show that the optimized system is better than the base case system.

2. BASE CASE SYSTEM

The proposed systems (base case system and optimized system) consist of a biomass gasifier, a solid oxide fuel cell and a gas turbine system as major components. In the base case model, producer gas is generated in a gasifier which is cleaned and fed into the anode of solid oxide fuel cell (SOFC). The cathode exhaust air along with the anode exhaust gases are fed into the combustor and after the combustion process, the hot flue gases are expanded in the gas-turbine. The flue gases coming out from the turbine outlet are used to heat the cathode inlet air and the inlet air to gasifier before sending it to stack. Pressure ratio for gas turbine *i.e.*, 10 have been taken from the literature [6]. Variation of electrical efficiency of the gasifier-SOFC-gas turbine hybrid system with a pressure ratio of the turbine has been discussed in the literature [6].

2.1 Descriptions of Subsystems Employed

2.1.1 Gasifier subsystem

Gasifier considered here is fixed bed, downdraft gasifier operating at elevated pressure. The output pressure of gasifier with oxidant-fuel ratio as three (3) is set at 10 bar and the output temperature of bio syngas is set at 1,173 K. These parameters are kept constant. The compositions of coal and cow manure which are used as fuels in the base case system and optimized system for energy and exergy analysis are mentioned in Table 1.

Table 1. Composition of coal and cow manure which are used as fuels.

Elements (%)	Coal	Cow manure
C	59.9	45.39
O	16.95	30.98
SiO ₂ (S)	15	0
H	5.34	5.35
N ₂	1.15	0
S(S)	1.35	0.39
F	0.02	0
Cl	0.3	17.07
N	0	0.96

2.1.2 Solid oxide fuel cell

The cathode and anode inlet temperature is set at 1,173 K. These temperatures are achieved through partial recirculation of cathode and anode exhaust of the SOFC. Pressure drop for cathode and anode of SOFC is assumed to be 0.05 bar [6]. The cell operates at 10 bar pressure. Parameters such as cell resistance, fuel utilization ratio, *etc.* are taken from literature.

2.1.3 Gas turbine and heat recovery

In the base case model, cathode inlet air is heated to 893 K by turbine outlet and is further increased to 1,173 K

with the help of recirculation of cathode outlet air. The turbine exhaust flue gases are used to preheat the air

supply of gasifier to 773 K after which the flue gases are sent to the stack.

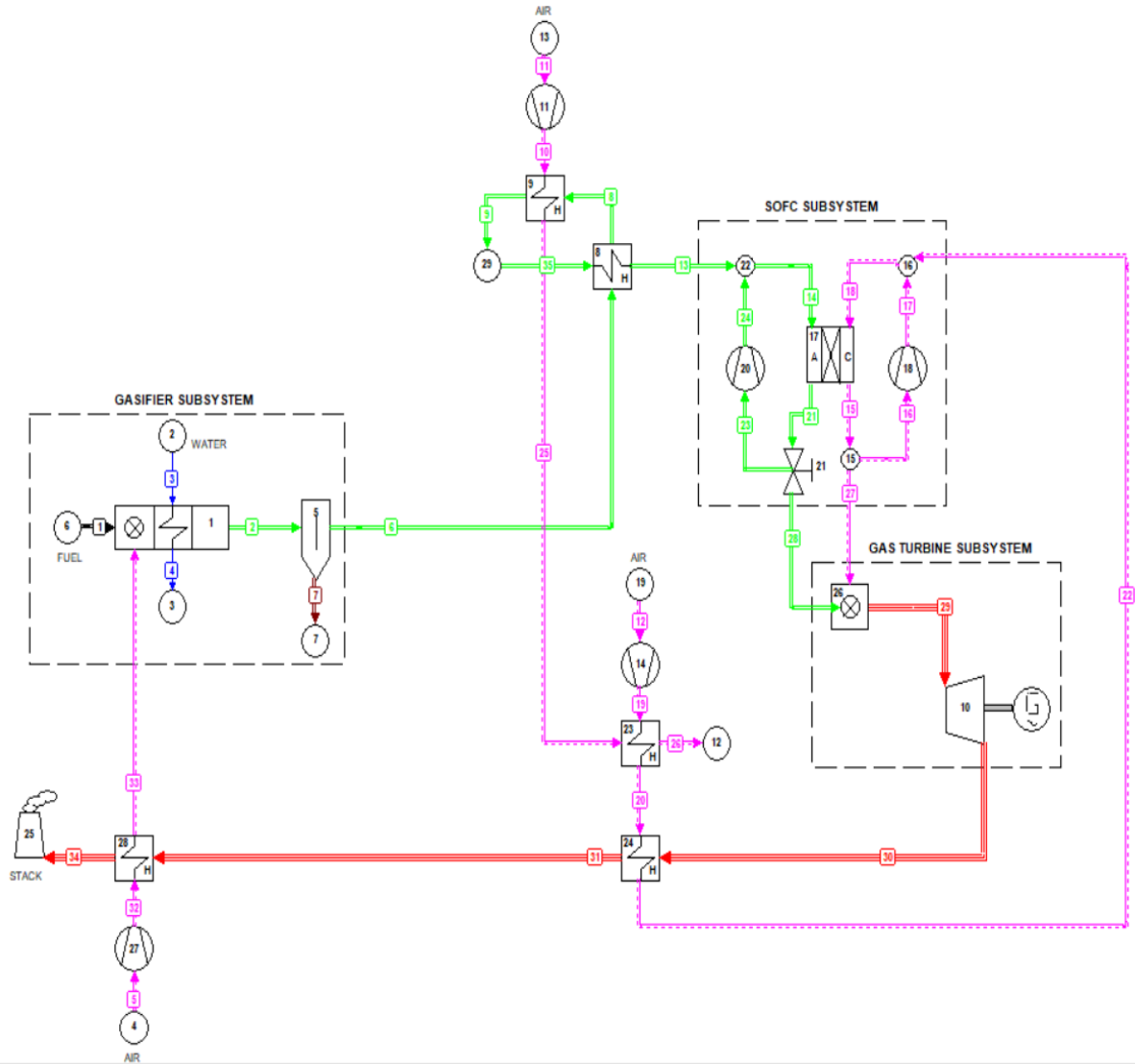


Fig. 1. Base case system.

3. CALCULATIONS

Mass, energy, and exergy related calculations are performed based on standard concepts of mass and energy conservation and exergy balance. The following equations and notation were adapted from Cengel and Boles [22]. All calculations are done using Cycle-Tempo software based on input parameters of various apparatus.

3.1 Mass Balance in a Steady Flow System

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (1)$$

3.2 Energy Balance in a Steady Flow System

$$\sum_{in} \dot{E} = \sum_{out} \dot{E} \quad (2)$$

For multiple streams:

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m} \left(h + \frac{V^2}{2} + gz \right) - \sum_{in} \dot{m} \left(h + \frac{V^2}{2} + gz \right) \quad (3)$$

For single streams:

$$\dot{Q} - \dot{W} = \dot{m} \left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right] \quad (4)$$

3.3 Exergy Balance in a Steady Flow System

$$\underbrace{\dot{X}_{in} - \dot{X}_{out}}_{\text{is rate of net exergy transfer by heat, work and mass}} - \dot{X}_{destroyed} = 0 \quad (5)$$

$$\dot{X}_{heat} = \left(1 - \frac{T_0}{T} \right) \dot{Q} \quad (6)$$

$$\dot{X}_{work} = \dot{W}_{usefull} \quad (7)$$

$$\dot{X}_{mass} = \dot{m}\psi \quad (8)$$

$$\psi = (h - h_0) - T_0(S - S_0) + \frac{V^2}{2} + gz \quad (9)$$

$$\dot{X}_{destroyed} = T_0\dot{S}_{gen} \quad (10)$$

In the combustion process which does not involve any work, the maximum possible work, also known as reversible work is equal to the exergy destroyed and is calculated as follows:

$$\begin{aligned} \dot{W}_{rev} = \dot{X}_{destroyed} & \quad (11) \\ & = \sum N_r (\bar{h}_f^o + \bar{h} - \bar{h}^o - T_0\bar{s})_r \\ & - \sum N_p (\bar{h}_f^o + \bar{h} - \bar{h}^o - T_0\bar{s})_p \end{aligned}$$

$$\eta_I = \frac{W_{useful}}{Q_{input}} \quad (12)$$

$$\eta_{II} = \frac{W_{useful}}{W_{reversible}} = \frac{\eta_I}{\eta_{I,reversible}} = \frac{X_{recovered}}{X_{supplied}} \quad (13)$$

4. RESULTS AND DISCUSSION

4.1 Energy Analysis

4.1.1 Coal as fuel

In the base case system, initially, coal was taken as fuel. The composition of standard coal has been mentioned in Table 1. After the gasification process in the gasifier, the composition of bio-syngas produced is given in Table 2. The bio-syngas is later fed to the SOFC.

Table 2. Composition of bio-syngas produced with coal as fuel.

Elements	% Mole fraction
C(S)	6.02
H ₂	12.39
N ₂	50.57
H ₂ O	3.33
SiO ₂ (S)	1.56
Ar	0.6
CO ₂	6.41
CH ₄	0.62
CO	18.18
COS	0.01
HCl	0.05
H ₂ S	0.25
NH ₃	0.01

The absorbed power in the system is 2461 kW which is obtained by multiplying mass flow rate of fuel with the lower heating value (LHV) of fuel. The power delivered by the fuel cell (apparatus 17) is 693.68 kW

and that of the generator (apparatus 1) is 576.39 kW which makes a total of 1,270.07 kW of gross power delivered. The total auxiliary power consumption in the system is 279.87 kW which occurs in the five compressors used in the base case system (apparatus 11, 14, 18, 20 and 27). The net power delivered by the system is 990.2 kW which is obtained by subtracting auxiliary power consumption from gross power delivered by the system. The gross and net efficiencies of the system are found to be 51.6% and 40.2%, respectively.

Table 3. Gross and net efficiencies with coal as fuel.

Parameter	Value
Absorbed power (kW)	2461
Gross delivered power (kW)	1270.07
Auxiliary power consumption (kW)	279.87
Net delivered power (kW)	990.2
Gross efficiency (%)	51.6
Net efficiency (%)	40.2

4.1.2 Cow manure as fuel

The composition of cow manure which is used as an alternative fuel has already been mentioned in Table 1. When using cow manure as fuel, the composition of bio-syngas produced is shown in Table 4.

Table 4. Composition of bio-syngas produced with cow manure as fuel.

Elements	% Mole fraction
H ₂	10.32
N ₂	54.13
H ₂ O	6.25
Ar	0.64
CO ₂	11.18
CH ₄	0.13
CO	14.06
HCl	3.22
H ₂ S	0.06
NH ₃	0.01

The absorbed power in the system is 1,619 kW. The power delivered by the fuel cell (apparatus 17) is 572.01 kW and that of the generator (apparatus 1) is 472.78 kW which makes a total of 1044.8 kW of gross power delivered. The total auxiliary power consumption in the system is 265.10 kW. The net power delivered by the system is 779.70 kW. The gross and net efficiencies of the system are found to be 64.6% and 48.2%, respectively.

It can be inferred from Figure 2 that net efficiency of a base-case system that uses cow manure as fuel was higher than net efficiency of a base-case system that uses coal as the fuel. This is because SOFC generates only 121.67 kW higher and generator develops only 103.61 kW higher in the case of coal. However, the input energy from coal is 842 kW higher than cow manure and hence results in lower efficiency.

Using a higher heating value (HHV) fuel, energy losses in stack increases. These losses may be responsible for the lower overall efficiency of the integrated system.

Table 5. Gross and net efficiencies with cow manure as fuel.

Parameter	Value
Absorbed power (kW)	1619
Gross delivered power (kW)	1044.8
Auxiliary power consumption (kW)	265.1
Net delivered power (kW)	779.7
Gross efficiency (%)	64.6
Net efficiency (%)	48.2

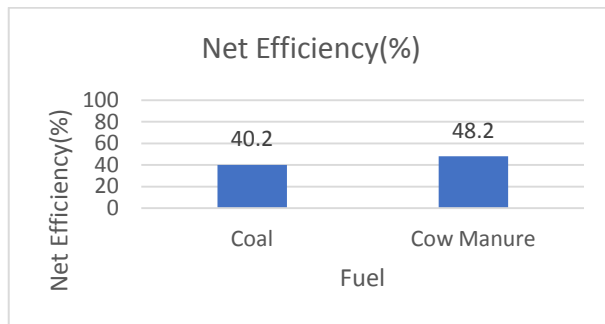


Fig. 2. Comparison of net system efficiency with coal and cow manure as fuel.

4.2 Exergy Analysis

Exergy analysis of the base case system has also been performed so as to determine the components responsible for the poor efficiency of the system. The environmental conditions are chosen to be like Baehr at 298 K for exergy calculations. For the exergy analysis the entire system is divided into different subsystems *i.e.*, (1) gasifier, (2) gas cleaning loop, (3) SOFC, (4) gas turbines, compressor and pump, (5) heat recovery and (6) stack. The apparatus included in each of the subsystems is discussed in Table 6. Exergy loss in each sub-system is equal to the sum of exergy loss in apparatuses that form the sub-system.

Table 6. Apparatuses included in each sub-system.

Subsystems	Apparatuses included
Gasifier	1, 5
Gas cleaning loop	8, 9, 11
SOFC sub-system	15, 16, 17, 18, 20, 21, 22
Gas turbine, compressor and pump	10, 14, 26, 27
Heat recovery	23, 24, 28
Stack	25

The relative exergy loss graphs shows similar trend when coal and cow manure are used alternatively as fuel with maximum relative exergy loss occurring in gasifier subsystem (25.32% in case of coal and 34.65% in case of cow manure as fuel) and minimum exergy loss occurring in heat recovery subsystem (0.65 % in case of coal and 0.44 % in case of cow manure as fuel). Apart

from the gasifier subsystem, a significant amount of exergy destruction takes place in the stack subsystem (10.85% in the case of coal and 9.95% in the case of cow manure). Results obtained in Ref [6] and Ref [23] show the same trend, with maximum exergy destruction taking place in gasifier and stack. It can be deduced that the total relative exergy destruction with coal as fuel is 62.59% and that of the system with cow manure as fuel is 57.24%.

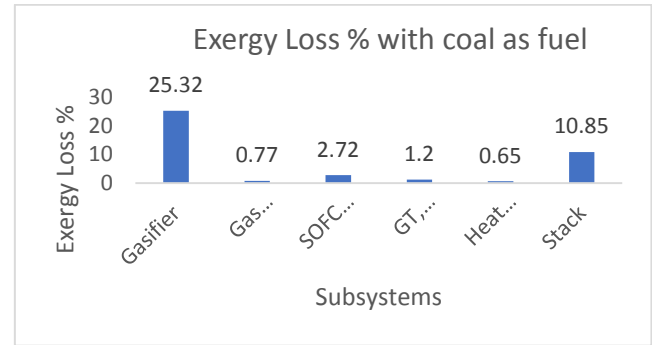


Fig. 3. Relative exergy loss percentages in different subsystems with coal as fuel.

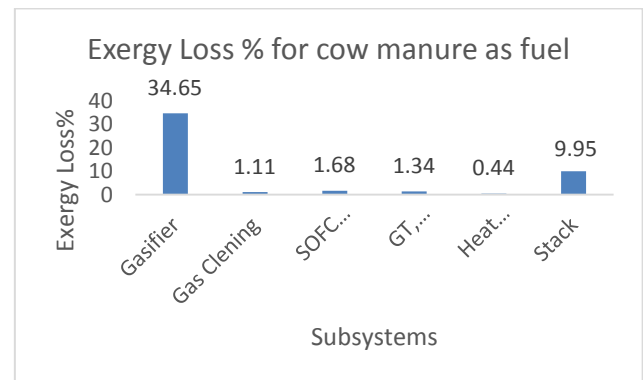


Fig. 4. Relative exergy loss percentages in different subsystems with cow manure as fuel.

Relative exergy loss is given by the percentage value of exergy loss/ exergy input ratio. As relative exergy loss is high in gasifier and stack, improvements must be made in these systems.

5. RECOMMENDATIONS FOR OPTIMIZATION

From the energy and exergy analyses of the base case system, the following recommendations are suggested to enhance the performance of the base case system: -

5.1 Reduction in Auxiliary Power Consumption

The base case system included five compressors with a total power consumption of 279.87 kW (coal as fuel) and 265.10 kW (cow manure as fuel).

The gas cleaning process is difficult at temperatures above 1,173 K. So, we reduced the temperature of bio syngas to 923 K in order to effectively accomplish gas cleaning. In the base case system, a supply of air at 10 bar is used to initially reduce the temperature of bio-syngas to 923 K and is later used for heating of cathode inlet air from 570 K to 673 K. To raise the pressure of air to 10 bar, a compressor (apparatus 11) is used which

consumes a power of 98.46 kW.

In the base case system, partial recirculation of anode and cathode exhaust is done to increase the inlet temperature of anode and cathode respectively. For anode, the inlet temperature of 1,173 K and mass flow rate of 0.605 kg/s in case of coal (0.626 kg/s in case of cow manure) is achieved by mixing of anode exhaust gas after compressor (apparatus 20) at 1425 K and mass flow rate of 0.216 kg/s in case of coal (0.226 in case of cow manure) with low temperature inlet at 1,030 K and mass flow rate of 0.388 kg/s in case of coal (0.4 kg/s in case of cow manure). The pressure at the outlet of the anode is 9.95 bar and in order to increase the pressure to 10 bar, a compressor (apparatus 20) which consumes 0.58 kW power for coal (0.61 kW for cow manure) was employed. Similarly for cathode, the inlet temperature of 1,173 K and mass flow rate of 0.6 kg/s in case of coal (0.49 kg/s in case of cow manure) is achieved by mixing of cathode exhaust gas after compressor (apparatus 18) at 1,423 K and mass flow rate of 0.312 kg/s in case of coal (0.256 kg/s in case of cow manure) with low temperature inlet of 893 K and mass flow rate of 0.288 kg/s in case of coal (0.237 kg/s in case of cow manure). The pressure at the outlet of the cathode is 9.95 bar and in order to increase the pressure to 10 bar, we are using a compressor (apparatus 18) which consumes 0.9 kW power for coal (0.74 kW for cow manure).

Since compressors are work consuming devices which decreases the net efficiency of the system, efforts have been made in the optimized model to eliminate the above discussed three compressors (apparatus 11, 18 and 20) and efficiently utilize the high-temperature exhaust of different components with the help of heat exchangers.

5.2 Flue Gas leaving the Plant

From the exergy analysis, it has been found that substantial amount of relative exergy loss occurs in

stack *i.e.*, around 10.85 % with coal as fuel) and 9.95 % (with cow manure as fuel). The stack temperature in the base case system is quite high *i.e.*, around 966 K (with coal as fuel) and 738 K (with cow manure as fuel). So, efforts have been made in the optimized model to properly utilize the excess heat of hot flue gases before sending it to stack and thereby decreasing the stack temperature.

6. OPTIMIZED SYSTEM

In the optimized model, important parameters of the system such as mass flow rates of input fuel, the temperature of bio-syngas exiting from the gasifier, the inlet temperature of cathode and anode at SOFC, pressure ratio of gas turbine, *etc.* are kept unchanged when compared to the base case system. In this system, the output of gasifier *i.e.*, bio-syngas is used to heat the cathode inlet air supply with the help of two heat exchangers (apparatus 23 and 24) and as a result its temperature reduces to 923 K. Then gas cleaning is carried out and cleaned gas is fed into heat exchanger (apparatus 16) and its temperature is increased to 1,173 K before its entry to SOFC with the help of anode exhaust gases. The cathode air supply is heated in 3 stages. In stage 1, the temperature is raised to 673 K with the help of bio-syngas. In stage 2, the temperature is raised to 773 K with the help of turbine exhaust flue gases. Then in stage 3, the temperature is increased to 1,173 K with the help of cathode exhaust air by incorporating heat-exchanger (apparatus 18). Cathode and anode exhaust is then fed into the Combustor (apparatus 26) and after combustion, the exhaust is fed into gas turbine (apparatus 10). The gas is then expanded in the gas turbine from 10 bar to 1 bar. Then the exhaust gases are used to heat gasifier air supply to 623 K with the help of a heat exchanger (apparatus 28).

Table 7. Key data for the base case and optimized system.

Parameters	Base case system	Optimized system
Gasifier subsystem		
Air-fuel ratio	3	3
Gasifier output pressure (bar)	10	10
Reaction temperature (K)	1023	1023
SOFC subsystem		
The inlet temperature of the anode (K)	1173	1173
The inlet temperature of the cathode (K)	1173	1173
Pressure drop in anode (bar)	0.05	0.05
Outlet temperature anode and the cathode (K)	1423	1473
Efficiency of DC/AC conversion	0.95	0.95
The pressure at which electrochemical processes occur (bar)	10	10
The temperature at which electrochemical processes occur (K)	1173	1173
Fuel utilization	0.85	0.85
Cell resistance (ohm m ²)	7.50E-05	7.50E-05
Gas turbine		
The pressure at the inlet of the turbine (bar)	9.95	9.95
The pressure at the outlet of the turbine (bar)	1	1

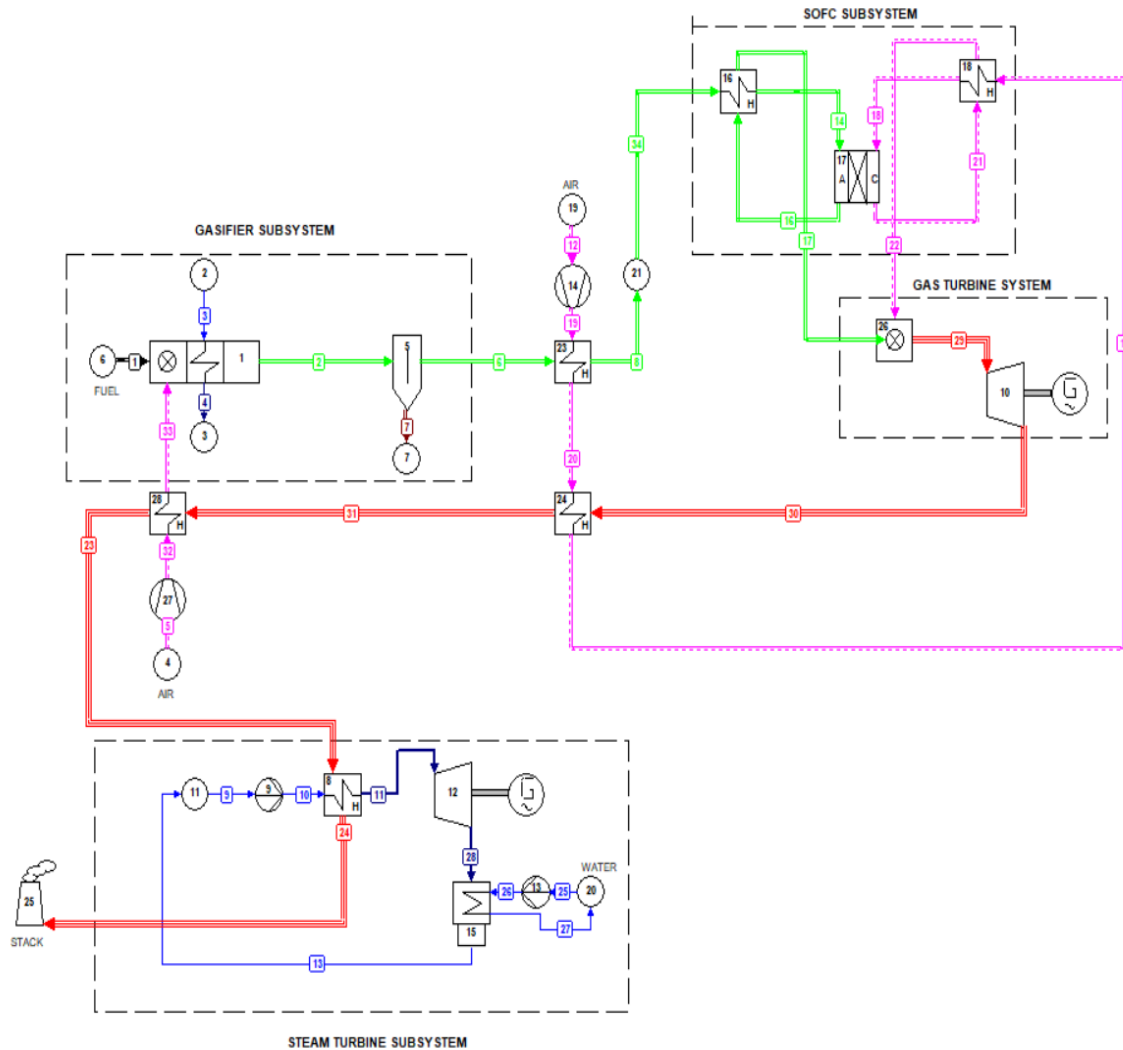


Fig. 5. Optimized system.

In order to properly utilize the excess heat of hot flue gases, a steam turbine cycle has also been incorporated in the optimized plant. The exhaust gases, after passing through a heat exchanger (apparatus 28), are used for generation of steam in the heat exchanger (apparatus 8), which is then fed into a steam turbine (apparatus 12) that delivers a power of 60 kW. The exhaust flue gases after passing through the heat exchanger (apparatus 8) are released to the stack at a much lower temperature when compared to the base case model.

7. RESULTS AND DISCUSSIONS

7.1 Energy Analysis

7.1.1 Coal as fuel

The absorbed power in the optimized model is 2,461 kW, which is the same as that of the base case system with coal as fuel. The delivered gross power of the optimized system increased to 1,468.80 kW due to the use of the additional steam turbine in the optimized model. There is a reduction in the total auxiliary power consumption of the system to 262.62 kW, when compared to the base case system due to the elimination of three compressors from the base case system. The

gross and net efficiencies of the system increased to 59.7% and 49% respectively.

Table 8. Gross and net efficiencies with coal as fuel.

Parameter	Value
Absorbed power (kW)	2461
Gross delivered power (kW)	1468.8
Auxiliary power consumption (kW)	262.62
Net delivered power (kW)	1206.18
Gross efficiency (%)	59.7
Net efficiency (%)	49

7.1.2 Cow manure as fuel

A similar trend is observed in the energy analysis of the optimized system with cow manure as fuel due to the same reasons as discussed in the case with coal as fuel. The absorbed power of the system is 1,619 kW. The delivered gross power of the system is 1,145.45 kW. The auxiliary power consumption in the system is 223.56 kW. The gross and net efficiencies of the system are 70.8% and 56.9%, respectively.

Optimization increased the efficiency of the coal-based system by 21.89% and of cow manure-based system by 18.05%. Comparison between the new efficiency of coal and cow manure-based system is

shown in Figure 6. Cow manure yields better efficiency than coal probably due to its organic nature.

Table 9. Gross and net efficiencies with cow manure as fuel.

Parameter	Value
Absorbed power (kW)	1619
Gross delivered power (kW)	1145.45
Auxiliary power consumption (kW)	223.56
Net delivered power (kW)	921.89
Gross efficiency (%)	70.8
Net efficiency (%)	56.9

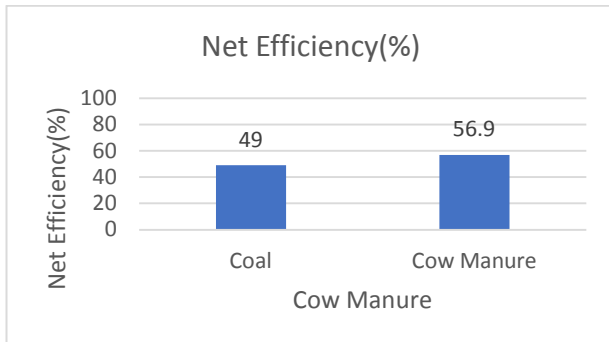


Fig. 6. Comparison in net system efficiency with coal and cow manure as fuel.

7.2 Exergy Analysis

Exergy analysis of the optimized system is performed in a similar manner it was performed for the base case system. The optimized system is divided into different subsystems *i.e.*, (1) gasifier, (2) SOFC, (3) gas turbines, compressor and pump, (4) heat recovery and (5) stack. The apparatus included in each of the subsystems is discussed in Table 10. It should be noted that there is no separate gas cleaning subsystem in the optimized system as it is incorporated in other subsystems.

Table 10. Apparatuses included in each sub-system.

Subsystems	Apparatuses included
Gasifier	1, 5
SOFC sub-system	16, 17, 18
Gas turbine, compressor and pump	9, 10, 12, 13, 14, 26, 27
Heat recovery	8, 15, 23, 24, 28
Stack	25

Table 11. Comparison of output results between base case system and optimized system with coal and cow manure as fuel.

Parameters	Base case system		Optimized system	
	Coal	Cow manure	Coal	Cow manure
Gross efficiency (%)	51.6	64.6	59.7	70.8
Net efficiency (%)	40.2	48.2	49	56.9
Total relative exergy loss (%)	62.59	57.24	54.4	49.41

The relative exergy losses in different subsystems have been depicted in Figures 7 and 8 with coal and cow manure as fuel respectively. Although the maximum relative exergy loss percentage in an optimized system is still occurring in gasifier sub-system (same in case of base case system) there is a substantial decrease in the relative exergy loss percentage in the stack subsystem due to the effective integration of steam turbine cycle before the stack which lowers the temperature of flue gases entering the stack and thereby decreasing the exergy loss percentage.

Also, it can be noted that there is a reduction in total relative exergy loss percentage from 62.59% to 54.4% with coal as fuel and from 57.24% to 49.41% with cow manure as fuel.

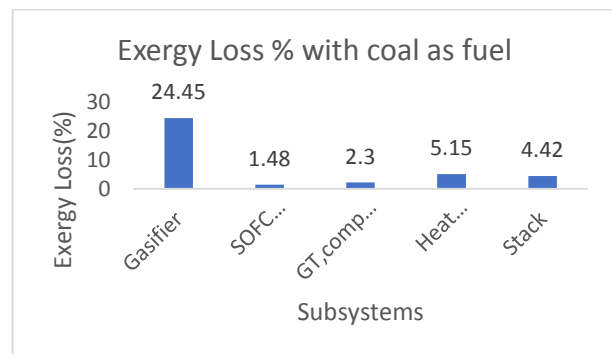


Fig. 7. Relative exergy loss percentage in different subsystems with coal as fuel.

Relative exergy loss in the stack was reduced by 59.26%. This can be seen by comparing Figures 3 and 7.

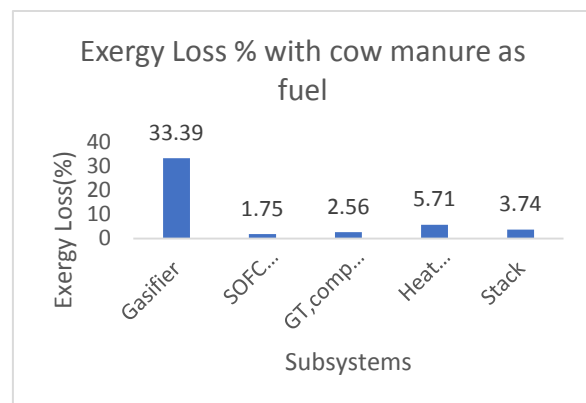


Fig. 8. Relative exergy loss percentage in different subsystems with cow manure as fuel.

Relative exergy loss in the stack of cow-manure based system has been reduced by 62.41%. (from comparing Figures 4 and 8).

From the table, it can be seen that the efficiency of the system for both fuels has been increased in the optimized system. Exergy loss % has decreased in the optimized system as compared to the base-case system.

8. CONCLUSION

In this study, an integrated gasifier-SOFC-gas turbine hybrid system has been modeled using Cycle-Tempo software and influence of different fuels such as coal and cow manure was studied. Energy and exergy analyses of the hybrid system have been performed to look out for potential recommendations for modifications in the base case system. Based on the energy and exergy analyses of a base case system, an optimized system was developed. The following conclusions can be drawn from the study: -

1. The net efficiency of the base case system is about 40.2% with coal as fuel and 48.2% with cow manure as fuel.
2. The relative exergy loss percentage is 62.59% with coal as fuel and 57.24% with cow manure as fuel for the base case system with maximum exergy loss occurring in the gasifier subsystem.
3. Important modeling parameters such as gasifier reaction temperature, air fuel ratio, pressure ratio for gas turbine, etc. were kept constant while designing the optimized system. The net efficiency of the optimized system increased from 40.2% to 48.2% with coal as fuel and from 48.2% to 56.9% with cow manure as fuel.
4. The relative exergy loss percentage of the optimized system decreased from 62.59% to 54.4% with coal as fuel and from 57.24% to 49.41% with cow manure as fuel.

Increment in system efficiency and decrement in relative exergy destruction percentage for the optimized system when compared to base case system was achieved by proper utilization of high-temperature exhaust of different components and incorporation of an additional steam turbine plant in the optimized system.

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NOMENCLATURE

\dot{E}	Rate of energy transfer (power), kW
g	Acceleration due to gravity=9.81 m/s ²
h	Enthalpy, kJ/kg
h_0	Enthalpy at dead state, kJ/kg
\dot{m}	Mass flow rate, kg/s
\dot{Q}	Rate of heat transfer, kW
S	Entropy, kJ/kg-K
S_0	Entropy at the dead state, kJ/kg-K
T	Temperature, K
T_0	Temperature at the dead state, K
V	Velocity, m/s
\dot{W}	Rate of work(power), kW
\dot{X}	Rate of exergy transfer, kW
z	Height, m
η	Efficiency
η_I	First law efficiency or thermal efficiency
η_{II}	Second law efficiency