



Performance Modelling of Co-Fired Palm Kernel Shell -Pulverized Coal Blend in Steam Power Plant

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ABSTRACT: This study investigates the performance of co-firing palm kernel shell (PKS) and pulverized coal in a steam power cycle. The process simulation software Aspen Hysys was used in the simulation. The study analyzed the various emitted combustion product gases. The cycle efficiency and Power output for each fuel sample blend was carried out. This provided the basis for the performance comparison of each fuel sample. The Sample D with mix ratio 80 (coal)-20 (PKS) came out the best fuel blend having a CO₂ emission of 1844.198854 Kgmol/h, an SO₂ emission of 8.830612928 kgmol/h, a cycle efficiency of 0.41 and an estimated power of 104, 076 kW. It was concluded that coal blended with palm kernel shell at a mix ratio of 80-20 has a suitable heating value for steam generation which promotes a cleaner coal usage with a significant reduction in the emission levels of greenhouse gases.

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Access to energy specifically electricity is vital for economic and social development. Coal remains an essential fuel for global energy systems and the release of toxic products of combustion into the air is the major challenge in its usage. Coal power plant are some of the largest single point source emitters; a typical 1,000 MW coal-fired power plant emits over 6 million tons of CO₂ per year (IEA, 2006). Experts agree that one of the viable options which can be explored to reduce the greenhouse gas emissions is the use of renewable sources such as biomass (Alie (2004), Assadi (2009), Diaz-Somoama (2003), Budianto (2015)). Biomass co-firing entails a process of supplementing base fuel with dissimilar fuel. It is a low-cost option for efficiently and cleanly converting biomass to electricity by adding biomass as a partial substitute fuel in high efficiency coal boilers. The primary reason for co-firing coal with biomass is as a means of reducing the potential environmental

impacts associated with the combustion of fossil fuels. It is important to be conversant with the types of co-firing techniques available in order to be on the right course as regards the choice of co-firing technique suited for the study. Direct co-firing is a more 'economic' and the preferred option as both fuels can be used in the boiler at the same time. Zulfiqar et al (2005) found that it is possible to reach a 10% co-firing ratio without any modification to the plant. According to Baxter (2005) in his review on opportunities for affordable renewable energy, he claims that co-firing installation cost ranges between \$50/KW and \$300/KW depending on the capacity of biomass. Low cost is achievable because biomass co-firing uses an existing coal infrastructure with minimal changes. As of 2011, co-firing biomass contributed 55GW in Europe and North America. This is expected to grow to 270GW in 2030, which will represent a 10% in renewable energy contribution to the total world

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energy consumption (Irena, 2012). Indirect co-firing systems are usually complex and expensive solutions as the biomass is converted to gaseous fuel before firing in the same boiler with coal but they reduce problems related with corrosion, fouling and slagging caused by inorganic compounds present in the secondary fuel. Parallel co-firing might not be economically feasible as separate boilers are required for each fuel. There are some studies in regards co-firing of coal and biomass materials aimed at promoting a cleaner coal usage. Boylan (1996), (2009) evaluated the impact of co-firing wood waste with pulverized coal on plant performance. Nicholls and Zerbe (2012) conducted a comprehensive research on Co-firing Biomass and Coal for Fossil Fuel Reduction and other Benefits – Status of North American Facilities. Zulfiqur, et al (2005) carried out

a pilot scale co-firing of coal and biomass: combustion results from a boiler simulation furnace. Eyad Mohammed (2018) carried out A Techno-Economic study of the reduction of greenhouse gas emissions through biomass co-firing. However, studies on co-firing are scanty in Nigeria, hence, the objective of this study was to evaluate the performance of co-firing palm kernel shell (PKS) and pulverized coal in a steam power cycle in Nigeria using the simulation software Aspen Hysys

MATERIALS AND METHODS

The seven fuel pellets produced in the study by Ighodaro et al (2020) were subjected to Rankye cycle simulation using the commercial software Aspen Hysys version 11.

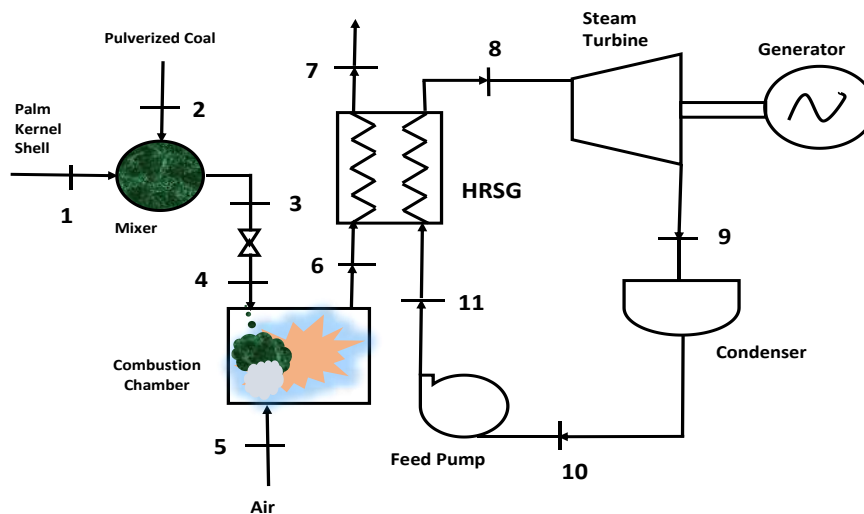


Fig 1: Schematic of Fuel Combustion Process used in the Simple Rankine Cycle

As shown in Figure 1, the palm kernel shell and pulverized coal is first mixed before passing through a Let-down Valve where it is depressurized before going into the Gibbs combustor where it mixes with air in the combustion process. The combusted gases enter the Heat Recovery Steam Generator (HRSG) where high quality steam is generated. The generated steam enters the turbine where work is extracted by the expanding steam. The steam passes through the condenser where heat is rejected, the condensate is then channeled to the pump to continue to cycle. The fuel, air and combusted exhaust were modelled using Peng-Robinson Equation of State. Stream was modelled as pure water using property correlations consistent with the ASME steam tables. For every state point on the steam cycle, at least three state properties need to be defined such as pressure, vapour fraction and fluid package for other state properties i.e. molar flow, molar entropy, molar enthalpy, density, temperature, mass flow e.t.c.

to be computed. The selected fluid package could either be Basis I or Basis II for either of ASME Steam model or Peng-Robinson Equation of state model respectively depending on the type of fluid.

RESULTS AND DISCUSSION

The seven fuel pellets produced in the study by Ighodaro *et al.* (2020) is presented in table 1. The property of each of the fuel samples used in the simulation is presented in Table 2

Table 1: Fuel Pellets

SAMPLE	%PKS	%COAL
A	100	-
B	-	100
C	10	90
D	20	80
E	30	70
F	40	60
G	50	50

Table 2: Summary of Ultimate Analysis

Fuel Pellets	A	B	C	D	E	F	G
Mix Ratio	100	100	90-10	80-20	70-30	60-40	50-50
% Carbon	62.11	65.52	54.14	51.52	55.74	59.34	60.94
% Hydrogen	5.09	5.12	5.14	5.27	5.19	5.32	5.23
% Nitrogen	0.849	0.803	0.103	0.980	0.921	0.889	0.833
% Sulphur	0.84	0.76	0.67	0.70	0.73	0.82	0.88
% Moisture	4.69	4.38	4.49	4.80	4.09	4.60	4.10
% Oxygen	26.421	23.417	35.457	36.730	33.329	29.031	28.017

Table 3: Combustion Products

Fuel sample	MIX RATIO	H ₂ O Kgmol/h	O ₂ Kgmol/h	CO Kgmol/h	CO ₂ Kgmol/h	SO ₂ Kgmol/h	NO ₂ Kgmol/h	N ₂ O Kgmol/h	NO Kgmol/h
A	100	1144.65441	6770.89861	2.82875E-06	2106.641969	10.04082516	0.088968217	0.000208563	2.775067189
B	100	1113.329024	6672.623123	4.5662E-06	2182.436542	4.68E-44	0.092252373	0.000235269	3.168933215
C	90-10	1202.514024	7063.98619	9.14657E-07	1923.174909	8.3875718	0.08241443	0.000158079	2.044749217
D	80-20	1247.274418	7145.137164	5.36598E-07	1844.198854	8.830612928	0.078790624	0.00013797	1.760007196
E	70-30	1190.229228	6996.911866	1.24239E-06	1956.756956	9.031371305	0.084391247	0.000171027	2.229721251
F	60-40	1194.144963	6865.527767	2.12864E-06	2021.64134	9.84535399	0.08773258	0.000195902	2.590092887
G	50-50	1161.426973	6813.393927	2.91833E-06	2069.356075	10.53116372	0.090038711	0.000212345	2.830455356

From table 3, fuel sample D (80-20) has the least CO₂ emission of 1844.198854 kgmol/h amongst all the fuel samples with an SO₂ emission of 8.830612928 kgmol/h. Thus, this fuel sample is the most environmentally friendly as regards CO₂ and SO₂ emissions. A typical sample calculation as used by Aspen Hysys in the simulation for Fuel sample E (70-30) in the simple steam cycle is illustrated below

Assumptions: Heat loss by combustion gas = Heat gain by High Pressure water.

Combustion gas temperature, $T_{cg} = 776.2^{\circ}C$

For the Gas side of the HRSG:

$$\Delta T = 656.2^{\circ}C$$

Temperature of the expelled flue gas = $120^{\circ}C$
i.e. $T_{cg} - \Delta T$ on gas side of HRSG (Heat Loss)

Fluid Package – Basis II (Peng-Robinson)

For Steam side of the HRSG:

$$\Delta T = 307.6^{\circ}C$$

Pressure drop = 0 kPa

For the Pump: The Input parameters were as follows:

- Vapour fraction = 0.000
- Pressure = 125 bar i.e. Pressure of water entering the boiler inlet, $P_{11} = 125$ bar
- Fluid package – Basis I (ASME Steam)

The output parameters at entry to the boiler were computed thus:

- Temperature of water entering the boiler; $T_{11} = 20.2^{\circ}C$
- Molar enthalpy of water entering the boiler, $h_{11} = -2.852 \times 10^5$ kJ/kgmol

Turbine Inlet: The Input parameters were as follows:

- Vapour Fraction = 1
- Fluid package - Basis I

The output parameters of the steam exiting the HRSG, going into the steam turbine were computed thus:

- Temperature of steam exiting the boiler, $T_8 = 327.8^{\circ}C$ i.e. $T_{11} + \Delta T$ on steam side of HRSG (Heat gain)
- Pressure of steam exiting the boiler, $P_8 = 125$ bar
- Molar enthalpy of steam exiting the boiler, $= h_8 - 2.386 \times 10^5$ kJ/kgmol
- Molar flow of steam = 2.030×10^4 Kgmol/h
- Mass flow of steam, $m = 101.29$ kg/S
- Temperature of wet steam exiting the turbine, $T_9 = 20^{\circ}C$
- Molar enthalpy of the wet steam exiting the turbine, $h_9 = -2.581 \times 10^5$ kJ/kgmol
- Temperature of condensate exiting the condenser, $T_{10} = 20^{\circ}C$
- Pressure of condensate exiting the condenser, $P_{10} = 2.337 \times 10^{-2}$ bar
- Molar enthalpy of condensate exiting the condensate, $h_{10} = -2.854 \times 10^5$ kJ/kgmol
- Isentropic efficiencies of pump and turbine = 100 % (Assumed)

For each fuel samples, the above set of parameters are obtained for each combustion process and steam cycle following the same sequence of operation. An analytical approach using Steady-Flow Energy Equation was adopted to validate the heat supplied by the boiler, work done by the turbine, Net Work and cycle efficiency obtained from the process simulation. The results obtained are recorded in table 4. The major parameters used in the analysis are:

Mass Flow of Steam, $m_s = 101.29$ kg/S

Temperature of steam exiting the boiler, $T_8 = 327.8$ °C

Pressure of steam exiting the boiler, $P_8 = 125$ bar

Temperature of condensate exiting the condenser, $T_{10} = 20$ °C

Pressure of condensate exiting the condenser, $P_{10} = 2.337 \times 10^{-2}$ bar

The accuracy of this simulation carried out on the Aspen Hysys software is validated by using analog Programming. This is because when a simulation case is set up, there are 1 of 3 possible results. The results could have Syntactic errors – case didn't run. The results could have Semantic errors – case ran but didn't give the right results. The results could be completely devoid of errors as this was the case because the analytical method using the Steady Flow Energy Equation which is valid for all the seven tested fuel samples simply affirmed the simulation results obtained.

Table 4: Cycle Efficiency and Power

Fuel sample	Mix ratio	Turbine power KJ/S	Pump power KJ/S	Net Power KJ/S	Boiler KJ/S	Condenser KJ/S	Efficiency
A	100	113700.00	1321	112379.00	272388.89	160027.78	0.41
B	100	116200.00	1350	114850.00	278611.11	163638.89	0.41
C	90-10	107900.00	1254	106646.00	258638.89	151944.44	0.41
D	80-20	105300.00	1224	104076.00	252361.11	148250.00	0.41
E	70-30	109500.00	1272	108228.00	262388.89	154166.67	0.41
F	60-40	112300.00	1305	110995.00	269138.89	158111.11	0.41
G	50-50	114000.00	1325	112675.00	273166.67	160472.22	0.41

All the fuel samples were tested on a Simple Steam cycle and the results are tabulated in Table 4

From table 4, fuel sample with the highest power output might not be environmentally friendly. Considering this criterion, sample D (80-20) is the best fuel sample having a power output of 104,076 kW.

Conclusion: Biomass co-firing with coal is believed to be able to enhance the domestic energy security through renewable energy utilization as well as improve the utilization of power plants. The products of combustion, cycle efficiency and estimated power generation per fuel sample were key indices taken into consideration in choosing the most suitable fuel at the end of the performance simulation on Aspen Hysys. Sample D with mix ratio 80-20 came out the best fuel blend as it promotes a cleaner coal usage with a significant reduction in the emission levels of greenhouse gases.

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