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Techno-Environmental Assessment of Co-Gasification of Low-Grade Turkish Lignite with Biomass in a Trigeneration Power Plant

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Abstract **– Trigeneration or Combined Cooling, Heat and Power (CCHP) which is based upon combined heat and power (CHP) systems coupled to an absorption chiller can be recognized as one of the best technologies recovering biomass effectively to heat, cooling and power. Co-gasification of the lignite and biomass can provide the possibility for safe and effective disposal of different waste types as well as for sustainable and environmentally-friendly production of energy. In this article, a trigeneration system based on an IC engine and gasifier reactor has been simulated and realized using Thermoflex simulation software. Performance results suggest that utilization of sustainably-grown biomass in a Tri-Generation Power Plant (TGPP) can be a possibility for providing cooling, heat and power demands with local renewable sources and reducing the environmental impacts of the energy conversion systems.**

Keywords **– Trigeneration, biomass, co-gasification, emission, IC engine.**

I. Introduction

In recent years, the growing need for energy recovery from renewable sources along with the necessity to mitigate environmental impact and supply costs has resulted in an increased interest in the thermal conversion of biomass/wastes. Biomass is one of the most promising resources which can serve as an alternative to fossil fuel-generated energy. Biomass offers an alternative remedy for reducing emissions, if it may be replaced by part or in full in place of the fossil fuels of energy conversion systems, and would probably be the cheapest and lowest risk alternative for energy generation [1,2]. Biomass absorbs carbon dioxide from the atmosphere during growth and then releases it during combustion; therefore, biomass cannot be considered as a disturbance that could affect the balance of carbon dioxide and does not contribute to the net greenhouse effect [3, 4].

Trigeneration (i.e. CCHP) which is based upon combined heat and power (CHP) systems coupled to an absorption chiller can be recognized as one of the best technologies to recover biomass effectively to heat, cooling and power. Several previous studies in literature show that the trigeneration system is able to generate three useful energy forms with only a single fuel source [5–13]. However, trigeneration systems have been utilized for decades only in a small number of food manufacturing and retail facilities with limited fuel sources [14]. Nevertheless, there are some newer studies on different types of renewable fuel such as; jatropha oil [13], wood [15], biogas from sewage [16], willow, rice husk and miscanthus [17] showing that they are all highly potential fuels for trigeneration systems.

By taking these facts into consideration, if a trigeneration system based on a fluidized bed gasifier and IC engine is co-fired with biomass, it would allow the utility production at lower fossil fuel consumption, less air and water pollutant production and would reduce overall facility expenditure [18].

The primary objective of this study is to investigate the feasibility of utilizing of biomass in a trigeneration system. The sub-objectives include:

- To design and simulate a trigeneration system based on a gasifier, an internal combustion engine, a steam turbine and a single-effect absorption chiller;
- To examine the performance of the system firing with different fuels like Tunçbilek lignite as the fossil fuel and olive pits, rice husk and pistachio shells as the renewable fuel;
- To investigate the variation of fuel consumption rate, energy efficiency, CO_2 and SO_2 emissions of system with respect to the different blends of Tunçbilek lignite and biomass types.

In this regard, first a trigeneration system firing with Tunçbilek coal has been simulated in THERMOFLEX simulation software [19], and then it is modified for co-firing with lignite and biomass.

II. Turkey's Biomass Energy Potential

Biomass can be considered as one of the most interesting renewable energy sources of Turkey, since its share of the total energy consumption of the country is approximately 10 % (for year 2010), as shown in Table 1. In addition, the required technologies for converting biomass to useful energy are not necessarily complicated.

However, as a matter of fact, the implementation of biomass-based energy programs cannot be a definitive solution to the country's energy problems, but it could bring new insight for efficient energy use in the country, for instance, in the household sector, particularly in rural areas where 40 % of the population lives (26 million). The estimates are based on the recoverable energy potential from the main agricultural residues, livestock farming waste, forestry and wood processing residues, as well as municipal waste [20].

TABLE I

TURKEY'S PRIMARY ENERGY CONSUMPTION IN GOE (BETWEEN 1990 AND 2010)

Fuel source for each year (Goe)	**1990**	**1995**	**2005**	**2010**
Coal	6 150	5 905	12 500	17 000
Lignite	9 765	10 570	30 500	48 000
Asphaltite	123	–	205	250
Natural Gas	3 110	6 218	23 500	31 000
Crude oil	23 901	29 324	39 500	47 000
Hydropower	1 991	3 057	8 500	11 000
Geothermal	85	138	180	350
Fuel wood	5 361	5 512	7 800	13 000
Waste	2 548	1 556	2 500	3 800
Solar	21	52	125	250
Total consumption	53 055	62 332	125 310	171 650

Goe: Gigagrams of oil equivalent
Source: Ref. 21

It has been proved that the generation of electricity from biomass can be a promising method in the near future in Turkey. The electricity produced by direct combustion of biomass, advanced direct combustion, co-combustion with fossil fuels, gasification and pyrolysis technologies are almost ready for commercial-scale use. Turkey's first biomass power project is under development in Adana province, at an installed capacity of 45 MW. Two others, at a total capacity of 30 MW, are at the feasibility study stage in Mersin and Tarsus provinces [22].

III. DESCRIPTION OF THE SYSTEM

The schematic diagrams of the proposed energy system integrated with an 890 kW circulating fluidized bed gasifier and a 260 kW gas fired internal combustion engine, which is the basic primary mover of the system, are illustrated in Figure 1. The trigeneration system considered in this study consists of two main modules; CHP module and absorption chiller module.

The circulating fluidized bed biomass gasifier with an integrated gas cleaning system generates syngas as the main fuel of the IC engine. The engine cooling system is used to produce hot water at a temperature level adequate for domestic hot water or heating (~75°C). The combustion gas from the engine is directed to the absorption chiller for producing chilled water. The absorption system of the simulated facility is a single effect lithium bromide-water system (with capacity of approximately 100 kW) which can deliver chilled water at 7°C.

IV. FUEL CHARACTERISTICS

Fuel properties and their composition have a great effect on the technical and environmental performance of energy conversion systems; therefore, the relevant details of the used lignite and biomasses including proximate analysis, ultimate analysis and calorific values have been given in Table 2.

Tunçbilek lignite has a quite high calorific value of 23 211 kJ/kg (higher heating value, HHV). Other main characteristics of this lignite are; low content of the moisture (7.50 %) and sulphur (1.81 %) and higher content of fixed carbon (41.3 %).

On the other hand, higher levels of volatile matter and lower content of fix carbon are recorded for the all biomass types, which results in lower heating values compared to lignite.

V. RESULTS AND DISCUSSION

In this section, results of the simulation are presented, including technical and environmental performance of the system and assessments of the effects of varying fuel blends on the cycle performance.

For the technical performance of the system, the efficiency for both net electricity and trigeneration are calculated. For environmental performance, the amount of SO_2 and CO_2 emissions are used as indicators for monitoring the environmental impact of the system, considering the fact that sustainably-grown biomass is used as fuel or co-fuel.

The operating conditions taken for the simulation were; ambient temperature and pressure of 25°C and 1.013 bar, respectively, chilled water temperature and mass flow rate of 7°C and 10.44 t/h, respectively, gasifier pressure and temperature of 1.2 bar and 850°C, respectively, hot water temperature leaving the system of 75°C and for all fuel types, COP of the absorption chiller was selected as 0.55.

A. General technical and environmental results of TG system

The proposed energy system operating with Tunçbilek lignite was successfully simulated using Thermoflex, then, in order to investigate the feasibility of using biomass as a fuel or secondary fuel in the trigeneration systems, the designed system was modified and co-fired with three types of biomass.

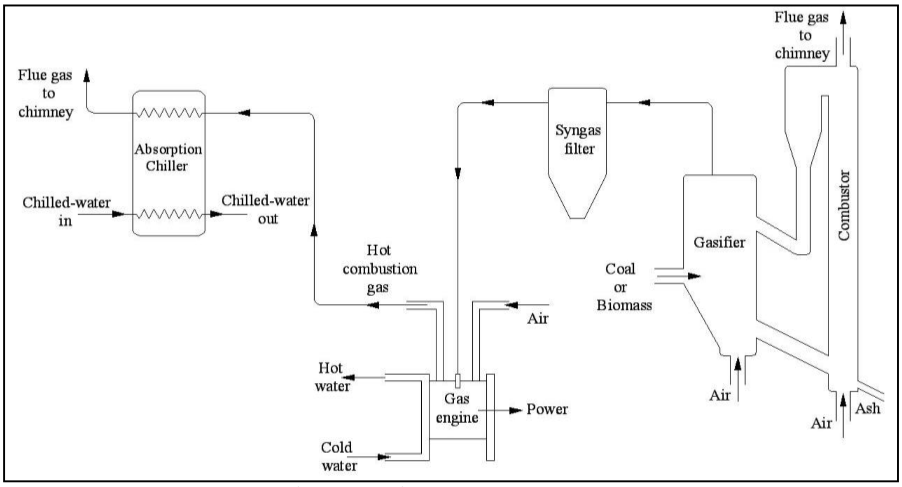

Fig. 1. Process flow sheet of the simulated trigeneration power plan.

TABLE II

THE CHARACTERISTICS OF OLIVE PITS, RICE HUSK, PISTACHIO SHELLS AND TUNÇBILEK LIGNITE (AS RECEIVED)

	Olive pits	**Rice husk**	**Pistachio shell**	**Tunçbilek coal**
Proximate analysis, %				
Moisture	6.08	10.94	7.54	7.50
Volatile matter	77.01	56.57	75.49	27.50
Ash	1.62	18.05	1.3	23.70
Fix carbon	15.29	14.44	15.67	41.30
Ultimate analysis, %				
Carbon	49.57	34.58	46.42	55
Hydrogen	6.28	4.23	5.84	4
Nitrogen	0.42	0.46	0.64	2
Sulphur	0.05	0.05	0.20	1.81
Thermal analysis, kJ/kg				
Higher heating value (HHV)	20 277	14 016	19 698	23 211
Lover heating value (LHV)	18 758	12 916	18 239	22 041

Some of the technical and environmental data of the system are presented in Table 3. As it can be seen from this table, system firing with Tunçbilek lignite has the highest process efficiency and the lowest fuel consumption rate with 80.83 % and 136.8 kg/h, respectively among other fuel types. On the other hand, however, SO_2 emission of the biomass is remarkably lower than lignite due to lower content of sulphur of the biomasses. The same cannot be saidin in regard to CO_2 emissions, since as it is presented in the table, the TG system for the lignite firing mode emits the lowest amount of CO_2 at approximately 2.21 Mt/year. The reason may be the lower amount of fuel consumption in comparison with other biomass types. However, it should be noted that biomass must not be considered as a disturbance which could contribute to the net greenhouse effect [4].

The synthesis gas mainly consists of H_2 and CO and is commonly known as syngas. After the gasification process, the syngas passes through a cleaning system to remove undesirable pollutants such as tar and solid particles [23]. Table 4 summarizes the syngas composition produced after gasification for used lignite and biomass types.

When coal is used as the main fuel, the CO, H_2, and CO_2 contents in the syngas are approximately 24.1 %, 16.4 %, and 4.6 %, respectively, and a considerable quantity of N_2, i.e. about 51.0 %, is produced. Meanwhile, when olive pit is used, the contents of CO, H_2, and CO_2 in the product gas changed to 18.0 %, 18.0 %, and 9.1 %, respectively. And when rice husk is supplied, the obtained syngas composition is similar to that of olive pits -- H_2 and CO contents are somewhat low. For pistachio shell, the contents of CO, H_2, CO_2 and N_2 in the syngas are obtained as approximately 20.8 %, 21.3 %, 8.7 % and 39 %, respectively. Moreover, lower heating values of the produced syngas from each fuel type are calculated as 3 947 kJ/kg, 3 970 kJ/kg, 4 813 kJ/kg and 4 886 kJ/kg, respectively. In other words, syngas with an increased heating value is obtained with higher amounts of CO and lower amount of CO_2.

TABLE III

TECHNICAL AND ENVIRONMENTAL DATA OF THE SIMULATED TRIGENERATION SYSTEM FOR DIFFERENT TYPES OF FUEL

Parameter	**Unit**	**Value**
Operating with olive pits		
Net power	kW	252.7
Net electric efficiency	%	30.6
TG efficiency	%	80.46
Fuel consumption rate	kg/h	162
Heat recovered from water-cooled condenser	kW	314.5
SO_2 emission	t/year	1.31
CO_2 emission	t/year	2 326.5
CO_2 emission	kg/GJ	96 618
Operating with rice husk		
Net power	kW	251.3
Net electric efficiency	%	30.0
TG efficiency	%	78.67
Fuel consumption rate	kg/h	237.6
Heat recovered from water-cooled condenser	kW	311.5
SO_2 emission	t/year	1.93
CO_2 emission	t/year	2 394.3
CO_2 emission	kg/GJ	97 864
Operating with pistachio shell		
Net power	kW	253.2
Net electric efficiency	%	30.63
TG efficiency	%	80.47
Fuel consumption rate	kg/h	165.6
Heat recovered from water-cooled condenser	kW	314.7
SO_2 emission	t/year	5.37
CO_2 emission	t/year	2 240.1
CO_2 emission	kg/GJ	92 952
Operating with Tunçbilek lignite		
Net power	kW	253.2
Net electric efficiency	%	30.51
TG efficiency	%	80.83
Fuel consumption rate	kg/h	136.8
Heat recovered from water-cooled condenser	kW	320.4
SO_2 emission	t/year	40.46
CO_2 emission	t/year	2 209.4

TABLE IV

SYNGAS COMPOSITION (VOLUME PERCENT %) FOR DIFFERENT FUEL TYPES

Component	***Olive pits***	***Rice husk***	***Pistachio shell***	***Tunçbilek coal***
CO	17.92	16.6	20.74	24.07
H_2	17.94	19.08	21.27	16.35
CO_2	9.085	11.08	8.722	4.612
CH_4	0.0031	0.0024	0.006	0.009
H_2S	0.0101	0.0149	0.047	0.3447
H_2O	9.874	13.83	9.713	3.401
COS	0.0003	0.0004	0.0015	0.0162
N_2	44.63	38.92	39.03	50.6
Ar	0.5363	0.4668	0.4679	0.6039
LHV, kJ/kg	**3.947**	**3.970**	**4.813**	**4.886**

B. Effect of varying fuel blends on system performance

In this section, the simulation results obtained through the variation of some essential parameters of the trigeneration system for different blends of Tunçbilek coal and biomasses are presented.

The motivation for utilizing trigeneration technology and biomass is not only financial. Other parameters, such as system efficiency and reduction in emissions should also be taken into account [23]. In this regard, besides the amount of fuel saved, the variation of the system efficiency and CO_2 emission are investigated.

Figure 2 shows the fuel consumption rate against fuel types at different fuel blends. For all biomass types, the fuel consumption rate increases notably when the coal share in fuel blends reduces from 100 % to 0 %. However, in all four cases, the fuel consumption of the rice husk is the highest. This is because of the lower calorific value of the rice husk in comparison with other biomass types.

Figure 3 illustrates the variation of energy efficiency of the TG system with different blends of Tunçbilek coal and biomass types. It can be observed that an increase of the biomass share in the fuel blends from 0 % to 100 % results in a slight decrease of the energy efficiency of the system for olive pits and pistachio shells. For both fuel types, energy efficiency decreases from 80.83 % to 80.46 %. The same cannot be seen for rice husk, where an increase of rice husk share in the fuel blend results in a considerable reduction of efficiency from 80.83 to 78.67.

The effect of the different blends of lignite and biomass types on CO_2 emission of the trigeneration system is illustrated in Figure 4. As it can be seen from this figure, the increase of biomass share in fuel blends has different effects on CO_2 emissions of lignite-biomass blends. The increase of the biomass share in fuel blends from 0 % to 100 % causes an approximate 117 t/year increase of CO_2 emissions for the system co-firing with olive pits and approximately 185 t/year increase for the system co-firing with rice husk. For the system co-firing with pistachio shell, CO_2 emissions increase very slightly and remain nearly constant.

Figure 5 displays the variation of SO_2 emissions of the TG system with different blends of Tunçbilek lignite and biomass. It is clear that for all investigated samples, SO_2 emissions of the TG system reduces significantly when the lignite share in fuel blends decreases from 100 % to 0 %.

VI. CONCLUSION

The comprehensive simulation and thermodynamic analysis of a trigeneration system for electricity generation, heating and cooling has provided useful insight.

From the results and discussions, it can be concluded that:

- Trigeneration system firing with Tunçbilek lignite has the highest process efficiency and lowest fuel consumption rate in comparison to other fuels with 80.83 % and 136.8 kg/h, respectively. In this mode, the system also emits the lowest amount of CO_2 with approximately 2.21 Mt/y. On the other hand, it also emits a much higher amount of SO_2 at 40.46 t/year.
- Lower heating values of the produced syngas from each fuel types are obtained as 3 947 kJ/kg, 3 970 kJ/kg, 4 813 kJ/kg and 4 886 kJ/kg, respectively. It is shown that, syngas with higher amounts of CO and lower amount of CO_2 has the higher heating value.
- Decrease of the coal share in the fuel blends from 100 % to 0 % results in a decrease of the fuel consumption rate of all biomass types. However, in all four fuel cases, the fuel consumption of the rice husk is the highest.
- For olive pits and pistachio shells, the decrease of the lignite share in the fuel blends results in a very slight decrease of the energy efficiency of the TG system, but for the rice husk it results in a considerable reduction.
- The increase of the biomass share in fuel blends has different effects on CO_2 emissions.
- For all investigated samples, SO_2 emissions of the TG system reduces numerously when the lignite share in fuel blends decreases.

VII. ACKNOWLEDGEMENTS

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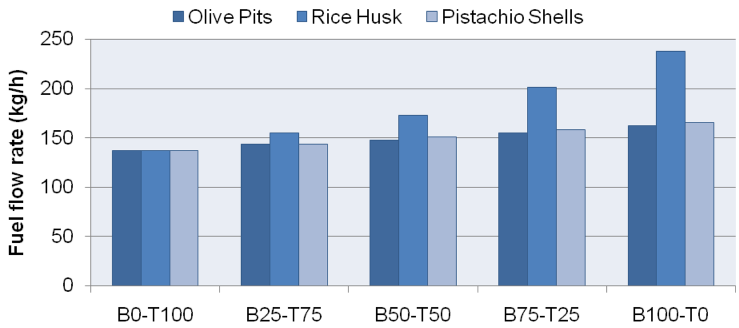

Fig. 2. Variation of fuel flow rate of the system with different blends of Tunçbilek coal and biomass types.

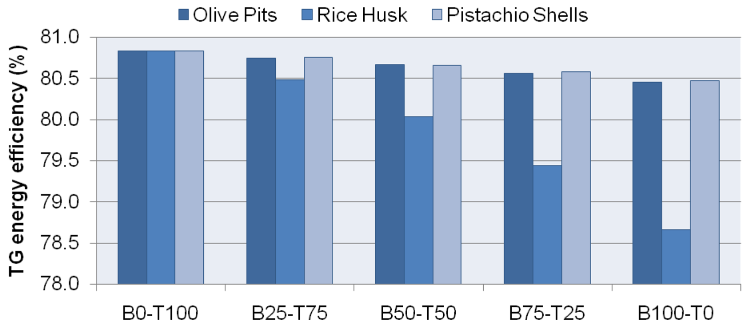

Fig. 3. Variation of the system energy efficiency with different blends of Tunçbilek coal and biomass types.

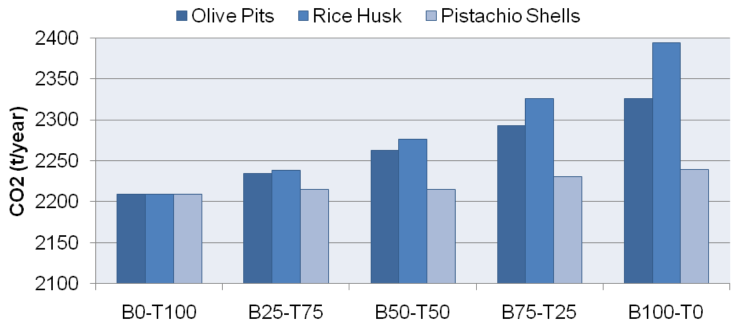

Fig. 4. Variation of the CO_2 emission of the system with different blends of Tunçbilek coal and biomass types.

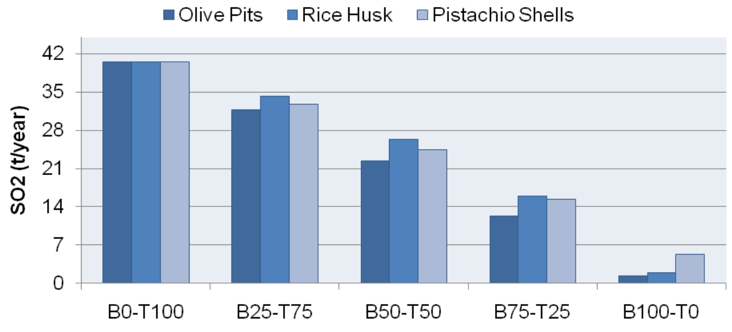

Fig. 5. Variation of the SO_2 emission of the system with different blends of Tunçbilek coal and biomass types.

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