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Energy and Exergy Analysis of Hydrogen Production on Co-Gasification of Municipal Solid Waste and Coal

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ABSTRACT

Hydrogen energy is considered one of the cleanest sources of energy due to its high efficiency. The only combustion product of hydrogen is water. Gasification can be used for the conversion of wastes into other fuels, and it presents an engaging renewable replacement for fossil fuels. This study aims to produce hydrogen as a result of the co-gasification of municipal solid waste (MSW) with coal to generate energy during its disposal. The importance of the system has been emphasized by making energy and exergy analyses. Gasification performance and the importance of hydrogen production of municipal solid blended with coal at different ratios (10%, 30%, 50%, 70%, and 90%) were also determined. A numerical model was developed for the co-gasification system. At the end of the study, a reduction in HHV can be seen as the coal concentration is increased. Also, with an increase in coal content of the MSW, it was found that the exergy values in syngas composition decreased. This study implies that gasification can be used for the evaluation of coal with the disposal of MSW and conversion of these wastes into energy, without harming the environment.

1. INTRODUCTION

In recent years, municipal solid waste (MSW) disposal has been one of the most important environmental problems for all countries. MSW is a system that includes social, economic, and environmental factors [1]. Generating energy in the process of waste disposal is important for the economy. In the last decade, the amount of MSW in Turkey increased by 32% with population growth [2]. MSW is divided into two categories; organic and inorganic. The composition of municipal solid waste in Turkey is given in Table 1. These wastes consist of organic wastes in the range of 40%-65% [3].

Commonly, MSW is disposed of as open dumping and sanitary landfilling. According to the Turkish State Statistical Institute's 2018 database [2], 67% of MSW is disposed of as sanitary landfilling. Recovery and composting are other disposal methods. MSW disposal is also applied in thermal methods such as pyrolysis, incineration, and gasification.

Gasification can be used for the conversion of wastes into other fuels, and it presents an engaging renewable replacement for fossil fuels. It is also an effective method for the disposal of waste. Most of the hydrogen gas formed is produced by physicochemical processes.

TABLE 1
COMPOSITION OF MSW IN TURKEY [3]

Components	Range (%) in weight
Organics	40–65
Paper/cardboard	7–18
Plastics	5–14
Metal	1–6
Glass	2–6
Others	7–24

However, these processes are not economical and are not preferred as they require external energy sources [4]. Thermochemical and biological processes can also be applied practically to produce hydrogen gas [5]. The greatest advantage of gasification is its effects on the environment. It can have a significant role in the reduction of landfill disposal. Besides, the emission tests for gasification confirm its acceptance [6].

Xydis et al. analyzed the electricity produced exergetically, from a landfill in the area of Volos, Greece, and discussed how the extension of the landfill influences electricity production. They also reported that the exergy efficiency of the operation is at a level of 33% [7].

Cabuk et al. investigated the effect of fuel blend composition on hydrogen yield in the co-gasification of coal and non-woody biomass. The authors reported that the yields of hydrogen depend on the volatile content of raw biomass, in the co-gasification of lignite with biomass. Also, it was reported that hydrogen yields of 84 and 75 mol/kg fuel were obtained from lignite and torrefied biomass, respectively [8].

Gai et al. reported that the steam gasification of hydrochar obtained from sewage sludge produced a higher hydrogen yield than direct steam gasification of sewage sludge under the same conditions. They also reported that hydrothermal carbonization effectively pretreated sewage sludge to produce hydrogen-rich gas via steam gasification [9].

Seyitoglu et al. conducted energy and exergy analyses to investigate system performances for different coal types and they reported that the overall energy and exergy efficiencies of the entire system became 41% and 36.5%, respectively [10].

The study aims to produce hydrogen gas as a result of the co-gasification of MSW with coal to generate energy during its disposal. The importance of the system has been evaluated by energy and exergy analyzes. Gasification performance and the importance of hydrogen production of municipal solid blended with coal at different ratios (10%, 30%, 50%, 70%, and 90%) were also determined. In this study, it is discussed whether coal can be disposed of without harming the environment by gasification and whether these wastes can be converted into energy.

2. MATERIALS AND METHODS

A two-stage water gas shift (WGS) reactor was used to obtain the syngas from a gasifier and a bypass line was used to control the composition of syngas at the exit of the cascade reactor as shown in Figure 1.

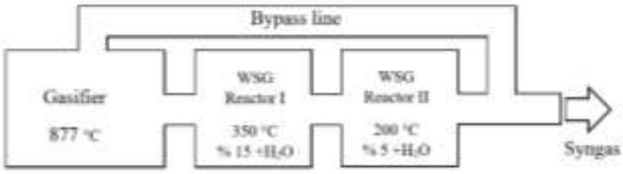

Figure 1. Schematic view of the cascade WGS reactor system

The properties of coal and municipal solid waste used in the study are given in Table 2. A numerical model was developed for the gasification system. Then, an optimum working condition was defined for H_2/CO ratio, which is equal to 2, at the gasification system exit. In the model, a combined relaxation Newtone Raphson method is used, using Visual Basic Net. The flowchart of the computations in the model is presented in Figure 2.

TABLE 2
PROPERTIES OF COAL AND MUNICIPAL SOLID WASTE [11], [12]

	MSW	Coal
C (%)	47.90	41.81
H (%)	6.00	4.28
O (%)	32.90	8.09
N (%)	1.20	2.16
Moisture (%)	30.00	13.51

It is quite difficult to obtain the best synthesis gas composition for H_2 production from MSW. For a reliable gasification model, the parameters and reactions of the gasification process should be well-determined. In this study, a co-gasification model was developed based on seven simultaneous reactions (Table 3). Equals show the reactions used in the model. The equilibrium constants of these reactions are given in Table 4.

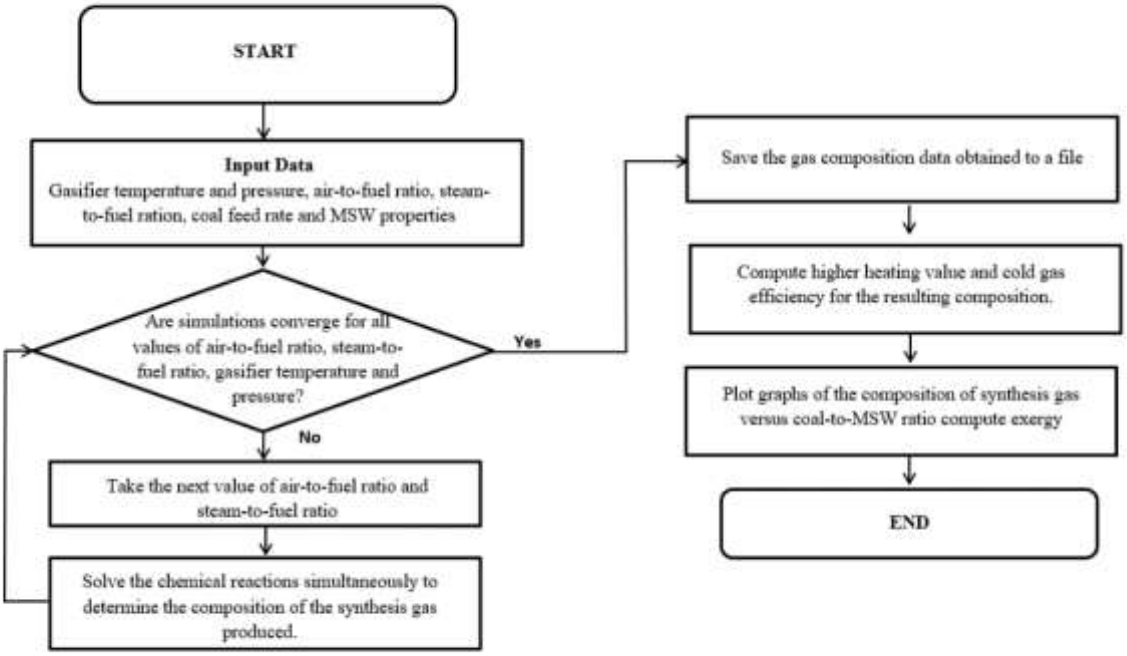

Figure 2. Flowchart of MSW gasification model.

TABLE 3
CHEMICAL REACTIONS INVOLVED IN THE GASIFICATION SYSTEM [13]

No	Reactions	Equals
1	Oxidation I	$C+O_2=CO_2$ (−394.5 kJ/mol)
2	Oxidation II	$C+12O_2=CO$ (−111.5 kJ/mol)
3	Steam gasification	$C+H_2O=CO+H_2$ (+131.4 kj/mol)
4	Boudouard reaction	$C+CO_2=2CO$ (+172.6 kj/mol)
5	Methanation reaction	$C+2H_2=CH_4$ (−74.9 kJ/mol)
6	Steam reforming reaction	$CH_4+H_2O=CO+3H_2$ (+206.2 kj/mol)
7	Water-gas shift reaction	$CO+H_2O=CO_2+H_2$(−41.2 kJ/mol)

TABLE 4
EQUILIBRIUM CONSTANTS USED IN THE MODEL

Temperature (K)	$K_{p,w}$ Eq. (5)	$K_{p,b}$ Eq. (6)	$K_{p,m}$ Eq. (7)
400	7.7×10^{-11}	5.2×10^{-14}	2.99×10^{5}
600	5.1×10^{-5}	1.9×10^{-6}	9.24×10^{1}
800	4.4×10^{-2}	1.1×10^{-2}	1.34×10^{0}
1000	2.62×10^{0}	1.90×10^{0}	9.6×10^{-2}
1500	6.08×10^{2}	1.62×10^{3}	2.5×10^{-3}

TABLE 5
VARIATION OF THE EQUILIBRIUM CONSTANT, $K_{P,S}$ WITH TEMPERATURE FOR THE WGS REACTION [14]

Temperature (K)	$K_{p,s}$
400	4050.00
600	27.00
800	4.04
1000	1.38
1500	0.37

2.1. Modeling and validation

The model requires syngas composition to be known at the beginning of the calculation and after entering the operation parameters such as steam/fuel ratios, air/fuel ratios, and reactor temperatures. The model performs calculations for the H_2/CO ratio. If the calculations converge to a solution, the program saves the results to a file and stops. Otherwise, perform the following operations; updating the values of the H_2/CO ratio and giving an initial value to the bypass ratio, the WGS reaction is solved to get a syngas composition. As a final step, the desired H_2/CO ratio is checked. If this ratio satisfies the criteria, the program computes the higher heating value (HHV) of the resulting syngas composition and, hot and cold gas efficiencies of the system.

The developed model was confirmed by experimental data for the co-gasification of pelletized wood residues in the literature [15], and the hydrogen gas content produced by the model is less than 2.77%.

It is emphasized in the literature that the gasifier temperature should be in the range of 700-850 °C. At lower temperatures, the gasification efficiency decreases, and the tar content increases [16]. The gasifier temperature of the model developed is 877 ° C (1150 K).

2.2. Energy and exergy analysis

To analyze the production of syngas from the co-gasification of MSW and coal, and to be able to make an assessment of the efficiency of the process, an energy and exergy analysis was performed.

Energy analysis is the main method to study gasification systems. System efficiency can be calculated according to the sum of H_2, CO, and CH_4 ratios that can be used from the syngas components resulting from gasification. The exergy rate can be expressed as the sum of the physical exergy and chemical exergy rates [17].

$$Ex = Ex_{ph} + Ex_{ch} \tag{1}$$

$$Ex_{ph} = \sum_i n_i \left[(h - h_0) - T_0(s - s_0)\right] \tag{2}$$

$$Ex_{ch} = \sum_i n_i \left(e_{0_i} + RT_0 \ln \frac{n_i}{\sum n_i}\right) \tag{3}$$

where “n_i” is the molar yield of gas component (mol/kg), “R” is the ideal gas constant and “e_{0i}” is the standard chemical exergy of a pure chemical compound, “s” is entropy and “h” is enthalpy, these values are for the given temperatures. Also, specific enthalpy (h_0) and entropy (s_0) values of the system at ambient temperature (25 °C) and pressure (1 atm) are given in Table 6.

TABLE 6
SPECIFIC ENTHALPY, ENTROPY, AND STANDARD CHEMICAL EXERGY VALUES OF SOME GASES [6].

Gas	h_0 (kJ/kmol)	s_0 (kJ/kmol K)	e_{0i} (kJ/kmol)
H_2	8468	130.574	236 100
CO	8669	197.543	275 100
CO_2	9364	213.685	19 870
H_2O (g)	9904	188.72	9500
CH_4	-	-	831 650

Exergy values of solid carbon, methane, and hydrogen gases in coal were taken into account while making exergy calculations. The specific heat value of solid carbon was calculated from the equation given below by Abbott and Van Ness [18];

$$c_{p_C} = 17.166 + 4.271 \frac{T}{1000} - \frac{8.79 * 10^5}{T^2} \tag{4}$$

$$h - h_0 = \int_{T_0}^{T} c_p dT \tag{5}$$

$$s - s_0 = \int_{T_0}^{T} \frac{C_p}{T} dT - R \ln \frac{P}{P_0} \tag{6}$$

where c_p is the constant pressure-specific heat capacity which can be calculated by the equations given in Table 7.

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TABLE 7
VARIATION OF SPECIFIC HEAT VALUES (C_P) AT CONSTANT PRESSURE WITH TEMPERATURE [14].

Gas	$c_p = \frac{kJ}{kmolK}, \theta = \frac{T(Kelvin)}{100}$
N_2	$c_p = 39.060 - 512.79\theta^{-1.5} + 1072.7\theta^{-2} - 820.40\theta^{-3}$
O_2	$c_p = 37.432 + 0.020102\theta^{1.5} - 178.57\theta^{-1.5} + 236.88\theta^{-2}$
H_2	$c_p = 56.505 - 702.74\theta^{-0.75} + 1165.0\theta^{-1} - 560.70\theta^{-1.5}$
CO	$c_p = 69.145 - 0.70463\theta^{0.75} - 200.77\theta^{-0.5} + 176.76\theta^{-0.75}$
H_2O	$c_p = 143.05 - 183.54\theta^{0.25} + 82{,}751\theta^{0.5} - 3.69890\theta$
CO_2	$c_p = -3.7357 + 30.529\theta^{0.5} - 4.1034\theta + 0.024198\theta^2$
CH_4	$c_p = -672.87 + 439.74\theta^{0.25} - 24.875\theta^{0.75} + 323.88\theta^{-0.5}$

3. RESULT AND DISCUSSION

During the first stage, syngas from the gasifier was fed into the system and mixed with steam at the WGS Reactor 1. Some portion of the syngas from the gasifier was mixed with the exiting stream via a bypass line connecting inlet and outlet streams. During the second stage, syngas at the exit of WGS Reactor 1 was mixed with a second stream of steam. Syngas at the exit of WGS reactor 2 was mixed with a bypass stream to produce the resulting composition.

The result in Figure 3 shows that a decrease in the H_2 gas content in syngas composition can be observed with an increase in the coal content of the MSW. The main reason for this is that MSW has a high moisture content. At the same conditions, CH_4 content was observed to increase. The CO content was seen to decrease negligibly. As shown in Figure 4, a decrease in HHV can be observed with an increase in the coal content.

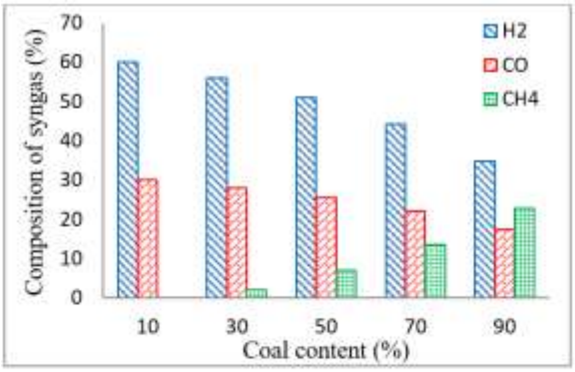

Figure 3. Effect of coal content in the composition of syngas (H_2, CO, CH_4) from co-gasifier with MSW

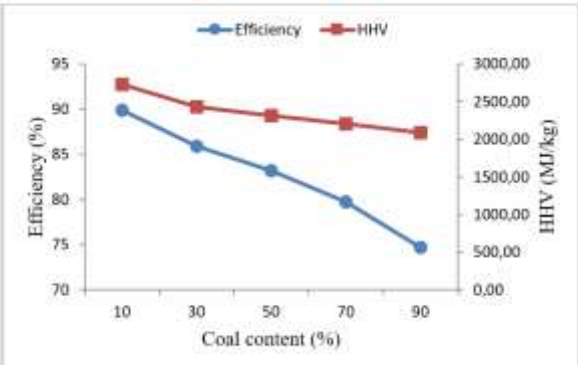

Figure 4. Effect of coal content on efficiency and HHV from co-gasifier with MSW

Figure 5 illustrates the effect of coal content on syngas exergy values from the co-gasifier with MSW. According to Zhang et al. [17], exergy values are determined by their temperature and yield. Also, a decrease in the exergy values in syngas composition was observed with an increase in the coal content of the MSW.

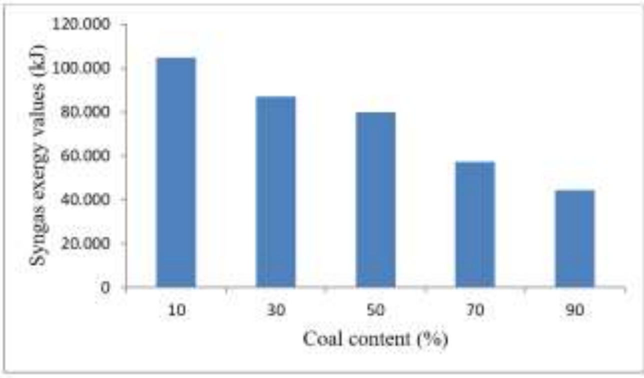

Figure 5. Effect of coal content on syngas exergy values from co-gasifier with MSW

4. CONCLUSION

Hydrogen production is important in terms of the energy economy. MSW and coal potentials are reliable sources of energy in hydrogen production. Gasification is important to evaluate the existing coal without harming the environment. It is also important for the disposal of MSW and conversion of it into energy.

In the present study, energy and exergy analyses of hydrogen production on the co-gasification of MSW and coal were evaluated. Also, gasification performance and the importance of hydrogen production of municipal solid blended with coal at different ratios (10%, 30%, 50%, 70%, and 90%) were determined. A numerical model was developed for the co-gasification system.

The results produced from the study showed that hydrogen gas can be used for the evaluation of coal with the disposal of MSW and conversion of these wastes into energy, without harming the environment.

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BIOGRAPHIES

Abdulkadir Kocer was born in Bolvadin, Afyonkarahisar in 1981. He graduated from the Mechanical Education Department of Gazi University Technical Education Faculty in 2002. In 2005, he obtained his MSc degree from the Mechanical Education Department of Gazi University in Ankara, Turkey. In 2018, he obtained his Ph.D. degree from the Farm Machinery Department of Akdeniz University. He is also an Assistant Professor at Vocational School of Technical Sciences of Akdeniz University. His main research fields are gasification, solar energy, computer programming, and biomass energy.

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