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Experimental and Numerical Investigation of Pyrolysis of Municipal Solid Waste with Using Computational Fluid Dynamics

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Abstract: In this study, experiments have been carried out to investigate the effect of temperature on the final product yield of pyrolysis of municipal solid waste. Also, the rotary kiln is numerically modeled, mass, energy, and momentum equations are derived. At the same time, a finite element model was constructed for a pyrolysis reactor designed at three different aspect ratios. A total of 81 computational fluids dynamics analyzes were carried out by using different values for inlet temperature, particle size, and rotation speed with data from Kocaeli province environmental situation report' 2015. According to the analysis conditions, where the maximum methane gas yield is obtained, the energy potential that can be obtained from the municipal solid wastes was calculated. It has been observed that the experimental data overlaps with the analysis in terms of methane yield.

Keywords: CFD, Energy Production, FEA, Municipal Solid Waste, Pyrolysis,

Hesaplamalı Akışkanlar Dinamiği Kullanılarak Kentsel Katı Atıkların Pirolizinin Deneysel ve Nümerik İncelenmesi

Öz: Bu çalışmada, sıcaklığın kentsel katı atık pirolizinin nihai ürün verimi üzerindeki etkisini araştırmak için deneyler yapılmıştır. Ayrıca döner fırın sayısal olarak modellenmiş, kütle, enerji ve momentum denklemleri türetilmiştir. Aynı zamanda, üç farklı en-boy oranında tasarlanmış bir piroliz reaktörü için sonlu elemanlar modeli oluşturulmuştur. Kocaeli ili çevre durum raporu 2015'ten alınan verilerle giriş sıcaklığı, tane boyutu ve dönüş hızı için farklı değerler kullanılarak toplam 81 adet hesaplamalı akışkanlar dinamiği analizi gerçekleştirilmiştir. Maksimum metan gazı veriminin elde edildiği analiz şartlarına göre, kentsel katı atıklarından elde edilebilecek enerji potansiyeli hesaplanmıştır. Metan verimi açısından deneysel verilerin analiz ile örtüştüğü görülmüştür.

Anahtar Kelimeler: CFD, enerji üretimi, sonlu elemanlar analizi, kentsel katı atık, piroliz

1. Introduction

In parallel with the rapid growth of the world population and the developing technology, the energy demand is constantly increasing. Besides, the fact that fossil energy resource reserves will be consumed in a limited and near future necessitates the evaluation of alternative energy sources more efficiently nowadays. Many countries in the world are taking advantage of new and renewable energy sources instead of consumable energy sources. New and renewable energy sources are mainly, biomass, sun, hydraulics, wind, geothermal, tide, wave energy. And most of these energy sources are widely used in the world. One of the most widespread uses in developed and developing

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countries is the energy that biomass has. Biomass is of great importance in both developed and developing countries due to its contribution to environmental protection, electricity generation, and fuel availability for vehicles in particular. The share of this energy source in primary energy consumption in industrialized countries is generally around 3%. In developing countries, the share of biomass energy in the form of wood and dung among energy sources ranges between 20-90% [1–8]. With the increase in population, migration from villages to cities, and industrialization, the amount of municipal solid waste produced per person is increasing rapidly and this increase is becoming an inevitable problem especially for metropolitan cities. The method of disposal of urban solid wastes in landfill areas, which has a great danger in terms of the environment and human health previously applied, is becoming increasingly lost its popularity in the new world order. Nowadays, it is tried to try different technologies in the disposal of urban solid wastes, especially in thermal disposal, and to improve the existing technologies. Municipal solid wastes are considered as raw material, which is an energy source. However, the technologies that will process urban solid wastes and transform them into energy are not sufficient. Landfill and incineration technologies have been used in the disposal of urban solid waste since the 1970s. However, these systems are not much preferred today due to the negative impacts on the environment. In the 1990s and 2000s, gasification and anaerobic digestion systems started to take their place in waste disposal technologies. Among all these methods, the pyrolysis method is environmentally friendly but needs to be technologically developed. The need for technological development is highlighted by scientific circles and users worldwide [4,9–28].

In this study, the effect of temperature on final product yield in pyrolysis of municipal solid waste was investigated. Also, the rotary kiln was modeled numerically, and mass, energy, and momentum equations were derived. At the same time, a total of 81 computational fluid dynamics analyzes were carried out using different values for inlet temperature, particle size, and rotation speed with the data obtained from Kocaeli province environmental status report '2015.

2. Experimental Methods

2.1. Installation of the Thermal Processing Plant

In the thermal processing plant, there is one precision shredder, one drying unit, and one pyrolysis unit. It has been reported in many studies that particle sizes to be used in the pyrolysis process significantly affect the final product distribution obtained [10,13,22,29–32]. The growth of the particle size increases the yield of the solid product by reducing the heating rate, while the efficiency of the gas product increases when working at smaller particle sizes. Therefore, in the shredder, the samples are reduced to the smallest possible levels to achieve a high gas yield [33].

In the pyrolysis and drying units, thermocouples are placed in 5 different regions and temperature values in these regions are obtained by these thermocouples. In this way, the temperature of the system can be kept under control and it is ensured that the optimum temperature at which pyrolysis takes place. The settlement of the dryer and pyrolysis unit is shown in Figure 1. and the flow chart of the thermal processing plant prepared for the test is shown in Figure 2.

Figure 1. Settlement of the dryer and pyrolysis unit.

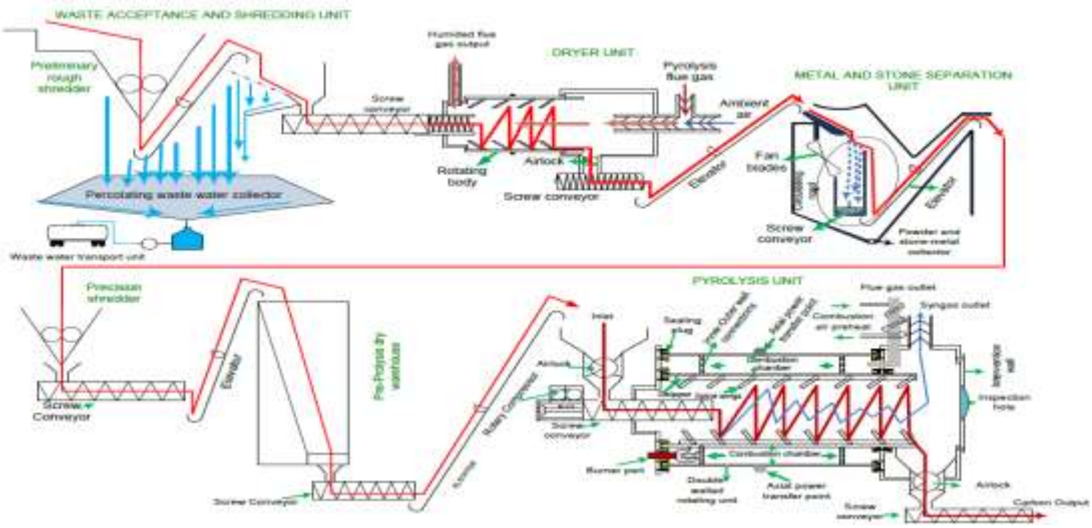

Figure 2. Schematic diagram of the thermal processing plant.

The temperature data obtained from both units can be measured and controlled instantly with the help of a touch-screen database mounted on the wall. In addition to the temperature measurement and control features, the following operations can also be checked with the data bank;

- Operation of the burner, which is the heat source in the pyrolysis unit,
- Sample input speed to pyrolysis unit (feed rate)
- Sample input speed to drying units (feed rate)
- Rotation speed of the feed units in the pyrolysis and drying units (rpm)

2.1.1. Pyrolysis Unit

A pyrolysis reactor is a unit with a burner that has an operating temperature of 450-750 °C. To carry out the studies, the design and manufacture of the pyrolysis unit were completed and installed in the plant. The pyrolysis unit which takes place at the plant is shown in Figure 3 and the schematic diagram of the pyrolysis unit is shown in Figure 4.

Figure 3. Pyrolysis unit.

2.2. Experimental Studies

The steps performed in the experiments are as follows:

- Municipal solid wastes are primarily reduced to 20-40 mm in the shredder unit and maximum gas product yield is aimed.
- After the shredder unit, the samples which reach the desired dimensions are transferred to the dryer unit via conveyor. Moisture amounts of samples drying at 100-130 ^{o}C in the drying unit are reduced in a controlled manner.
- The moisture values are measured at the outlet of the dryer unit and the municipal wastes, which have reached the desired temperature and humidity value, are transferred to the pyrolysis unit via closed conveyor.
- The municipal solid wastes transferred to the pyrolysis unit are subjected to pyrolysis at a temperature of 450 - 750 ^{o}C and the amount of gas obtained as a result of the process is measured employing a gas analyzer. The solid product is transferred from the bottom of the pyrolysis unit to the storage tank.

Primarily, the menus to be used in experimental studies were prepared according to the solid waste composition specified in the provincial environmental status report of Kocaeli province for 2015, and pyrolysis was performed at 500, 550, 600, 650, and 700 ^{o}C. According to the obtained values, the maximum CH_4 yield was found and this value was defined as the boundary condition for the finite element analysis, and CFD analysis was performed.

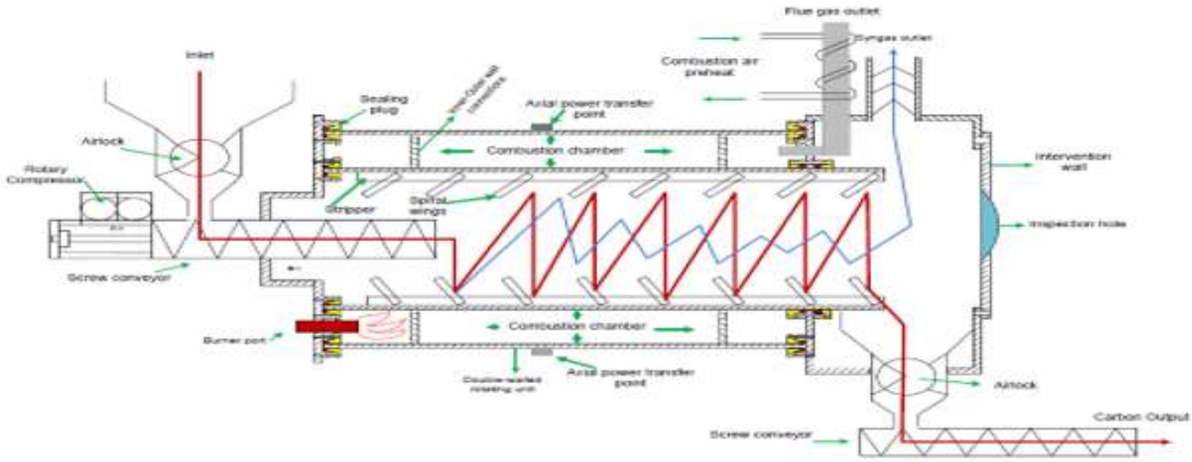

Figure 4. Schematic diagram of the pyrolysis unit.

2.3. Numerical Modeling of Pyrolysis Reactor

The main considerations for modeling the rotary kiln pyrolysis reactor are the material flow, gas-solid mass transfer, and reaction kinetics. In the rotary kiln pyrolysis reactor modeling, not only heat transfer in the reactor but also pyrolysis reactions should be considered. Therefore, the mass, energy, and momentum balance equations are derived for the rotary kiln pyrolysis reactor. All material types, including reactant and product materials, flow to a control volume as shown in Figure 5, and leave the control volume with mass and energy change.

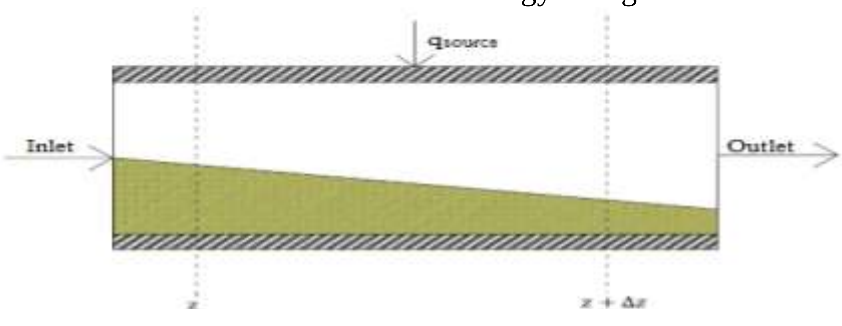

Figure 5. Control volume of rotary kiln pyrolysis reactor.

In accordance with Figure 5, the particle i enters the control volume in the z-direction with mass flow rate m_i (kg / s), density ρ_i (kg / m^3), enthalpy value h_i (kJ/kg) and cross-sectional area A_i (m^2). The mass flow of particle i during the flow in the control volume will vary with chemical reactions (reaction rate of municipal solid waste r_a and individual stoichiometric coefficient υ_i) [34-36]. After the necessary intermediate operations, the total mass balance and the total energy balance on the control volume in cartesian coordinates can be written as follows:

$$\left(\frac{\partial}{\partial t}(\rho_a A_a) + \frac{\partial}{\partial t}(\rho_c A_c) + \frac{\partial}{\partial t}(\rho_g A_g)\right) = -\left(\frac{\partial m_a}{\partial z} + \frac{\partial m_c}{\partial z} + \frac{\partial m_g}{\partial z}\right) + r_a A_a(\upsilon_a + \upsilon_c + \upsilon_g) \tag{1}$$

$$\begin{aligned}&\left[\left(\rho_a A_a C_{p_a} + \rho_k A_k C_{p_k}\right)\frac{\partial T_y}{\partial t} + \rho_g A_g C_{p_g}\frac{\partial T_g}{\partial t} + \rho_w A_w C_{p_w}\frac{\partial T_{wall}}{\partial t}\right] \\ &= -\left[\left(m_a C_{p_a} + m_k C_{p_k}\right)\frac{\partial T_y}{\partial z} + m_g C_{p_g}\frac{\partial T_g}{\partial z}\right] \\ &- r_a A_a\left[\upsilon_a h_a T_y + \upsilon_k h_k T_y + \upsilon_g h_g T_g\right]\end{aligned} \tag{2}$$

Mass balance equations and energy balance equations require mass flow to complete the set of equations. Therefore, the momentum balance should be used to derive the exchange equation of the mass flow. The total momentum balance for each phase can be obtained from the following equation.

$$\frac{\partial m_a}{\partial t} = -2\left(\frac{m_a}{\rho_a A_a}\right)\frac{\partial m_a}{\partial z} + \left(\frac{m_a}{\rho_a A_a}\right)^2 \frac{\partial}{\partial z}(\rho_a A_a) - \frac{\partial}{\partial z}(P_a A_a) \tag{3}$$

2.4. CFD Analysis of Rotary Kiln Pyrolysis Reactor

The following steps were taken to perform the computational fluid dynamics analysis of the rotary kiln pyrolysis reactor:

- Design of model geometry,
- Creation of model mesh structure,
- Running the appropriate analyzer for the two- or three-dimensional model,
- Analyzer selection,
- Determining material properties, and modeling of new materials if necessary,
- Determination of boundary conditions,
- Arrangement of solution control parameters,
- Performing the first analysis,
- Evaluation of results,
- Improving the grid structure if necessary or reviewing the numerical/physical model and repeating the transactions,
- Recording of results.

The process steps for the FEA of the rotary kiln pyrolysis reactor are shown in Figure 6. In this study, the provincial environmental status report of Kocaeli province for 2015 was used and material modeling was made according to these data.

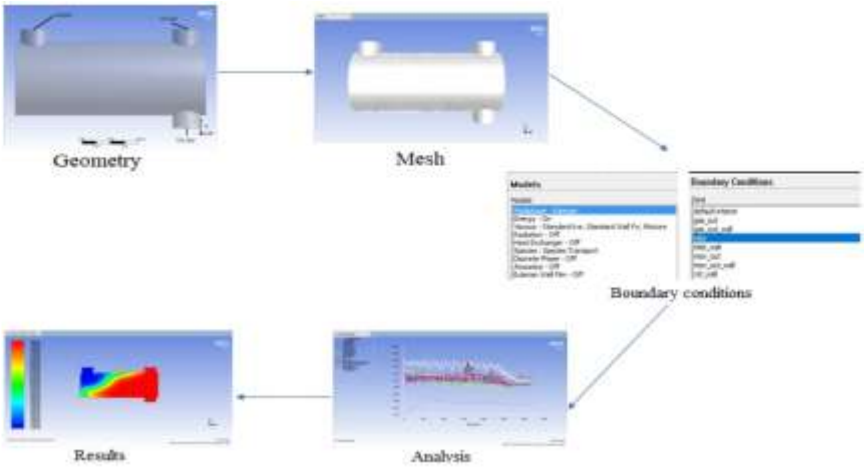

Figure 6. Flow chart of the computational fluid dynamics process.

The solid waste composition of Kocaeli province in 2015 is as shown in Figure 7 [37].

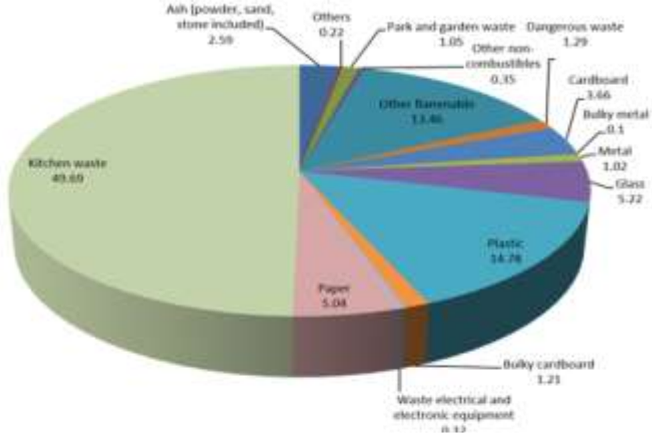

Figure 7. Waste composition of Kocaeli province in 2015.

2.4.1. Information on Municipal Solid Waste of Kocaeli Province in 2015

The population of Kocaeli province in 2015, the amount of solid waste collected, and the amount of waste produced per person are summarized in Table 1.

Table 1. MSW information of Kocaeli in 2015.

Total people	1.780.055	**Wet waste density**	155,350 kg/m^3
Total solid waste	1.090.962,41 kg/day	**Amount of waste**	0,006 m^3/day/person
Water in waste	664.037,60 kg/day	**Wet waste volume**	11297,094 m^3/day
Amount of wet waste	0,986 kg/day/person		
Total waste amount (daily).	1.755.000,00 kg/day	**Total amount of waste (annually)**	641.013,750 ton/year

For municipal solid waste composition, the total wet and dry volumes of each different species are calculated and shown in Table 2.

The density of wet waste was calculated as 155,350 kg / m^3 and the density of dry waste was calculated as 199,923 kg / m^3. The number of elements in the average chemical composition from the literature data is given in Table 3.

Table 2. Wet and dry volumes of MSW in Kocaeli annually.

Waste type	Mass (% kg)	Water (% kg)	Density (kg/m^3)	Dry mass (kg)	Wet waste volume(m^3)	Dry waste volume(m^3)
Ash (powder, sand, stone included)	4,42	8	480	4,0664	0,00920833	0,00847167
Park and Garden Waste	1,05	60	100	0,4200	0,01050000	0,00420000
Other Non-combustibles	0,35	4	1420	0,3360	0,00024648	0,00023662
Other Flammable	13,46	8	360	12,3832	0,03738889	0,03439778
Cardboard	4,87	5	50	4,6265	0,09740000	0,09253000
Metal	1,12	3	150	1,0864	0,00746667	0,00724267
Glass	5,22	2	195	5,1156	0,02676923	0,02623385
Plastic	14,78	2	65	14,4844	0,22738462	0,22283692
Paper	5,04	6	90	4,7376	0,05600000	0,05264000
Kitchen Waste	49,69	70	290	14,9070	0,17134483	0,05140345
TOTAL	**100**	**-**	**-**	**62,163**	**0,64400000**	**0,50000000**

Table 3. Average chemical composition of MSW.

Solid waste components	Chemical composition (% in dry mass)					
	C	**H**	**O**	**N**	**S**	**Ash**
Ash (powder, sand, stone included)	26,3	3	2	0,5	0,2	68
Park and Garden Waste	47,8	6	38	3,4	0,3	4,5
Other Non-combustibles	4,5	0,6	4,3	0	0	90,5
Other Flammable	66,9	9,6	5,2	2	0	16,3
Cardboard	44	5,9	44,6	0,3	0,2	5
Metal	4,5	0,6	4,3	0,1	0	90,5
Glass	0,5	0,1	0,4	0,1	0	98,9
Plastic	60	7,2	22,8	0	0	10
Paper	43,5	6	44	0,3	0,2	6
Kitchen Waste	48	6,4	37,6	2,6	0,4	5

According to the 2015 environmental status report of Kocaeli province, the amount of elements in the waste for each solid waste component is calculated as in Table 4.

Table 4. The number of elements in MSW within the year 2015 in Kocaeli province.

Solid waste components	Dry mass (kg)	Wet waste (kg)	C	H	O	N	S	Ash
Ash	4,0664	0,35	1,07	0,12	0,08	0,02	0,01	2,77
Park and Garden Waste	0,4200	0,63	0,20	0,03	0,16	0,01	0,00	0,02
Other Non-combustibles	0,3360	0,01	0,02	0,00	0,01	0,00	0,00	0,30
Other Flammable	12,3832	1,08	8,28	1,19	0,64	0,25	0,00	2,02
Cardboard	4,6265	0,24	2,04	0,27	2,06	0,01	0,01	0,23
Metal	1,0864	0,03	0,05	0,01	0,05	0,00	0,00	0,98
Glass	5,1156	0,10	0,03	0,01	0,02	0,01	0,00	5,06
Plastic	14,4844	0,30	8,69	1,04	3,30	0,00	0,00	1,45
Paper	4,7376	0,30	2,06	0,28	2,08	0,01	0,01	0,28
Kitchen Waste	14,9070	34,78	7,16	0,95	5,61	0,39	0,06	0,75
TOTAL	**62,16**	**37,84**	**29,59**	**3,90**	**14,02**	**0,70**	**0,09**	**13,86**

According to these values, the anhydrous and sulfur-free chemical formula of municipal solid waste for Kocaeli province was found as given in Table 5.

Table 5. The anhydrous and sulfur-free chemical formula of MSW within the year 2015 in Kocaeli.

Component	Anhydrous rates	Atomic weight	Anhydrous mol	Anhydrous mol rate (N=1)
C	29,59	12,01	2,464	49
H	3,90	1,010	3,865	77
O	14,02	16,00	0,876	17
N	0,70	14,01	0,050	1
S	0,09	32,07	0,003	~~0~~
Ash	13,86			
Total	**62,16**			
Anhydrous and sulfur-free chemical formula (N=1)				$C_{49}H_{77}O_{17}N$

To run the analysis, the materials required for the pyrolysis process, if exist in the library, were taken from there. But, as already mentioned, it is almost impossible to find such a ready-made material model for municipal solid waste. Therefore, the municipal solid waste and the materials that emerged as char at the end of the reaction are modeled by entering the required properties in the Fluent.

The Eulerian multiphase flow model was chosen to model the pyrolysis process. Some of the reasons for choosing this model are as follows [1,38–42]:

- It allows the modeling of multiple and interacting phases.
- The phases can be solid, liquid, or gas in almost any combination.
- A single pressure is shared by all stages.
- Momentum and continuity equations are solved for each phase.
- All k-ϵ turbulence models are allowed.
- Following the various types of multi-phase regimes, there are friction coefficient formulations between phases.

Finite element analysis of the pyrolysis process of the municipal solid wastes in the rotary kiln reactor was carried out using different aspect ratios, different inlet temperatures, different particle sizes, and different rotational speeds. As shown in Table 6, 27 different setups were applied for reactors modeled at 3 different aspect ratios and a total of 81 analyzes were performed. The effects of these variables on the yield of gas products were seen comparatively and the optimum values for the pyrolysis process were found according to the percentage of methane generated from the analysis. Then, the energy potential which can be produced annually from municipal solid waste was calculated by using the maximum methane gas yield.

Table 6. Boundary conditions for finite element analysis.

Analysis number	Inlet Temp (K)	Particle size(mm)	Rotation speed (rpm)	Analysis number	Inlet Temp (K)	Particle size (mm)	Rotation speed (rpm)
A1	353	20	5	A15	373	30	15
A2	353	20	10	A16	373	40	5
A3	353	20	15	A17	373	40	10
A4	353	30	5	A18	373	40	15
A5	353	30	10	A19	393	20	5
A6	353	30	15	A20	393	20	10
A7	353	40	5	A21	393	20	15
A8	353	40	10	A22	393	30	5
A9	353	40	15	A23	393	30	10
A10	373	20	5	A24	393	30	15
A11	373	20	10	A25	393	40	5
A12	373	20	15	A26	393	40	10
A13	373	30	5	A27	393	40	15
A14	373	30	10				

3. Results and Discussion

According to the data obtained from the test results, the effect of temperature on pyrolysis product quantities is shown in Figure 8.

According to the results, when the amount of urban solid waste decay is examined, as in the literature, the amount of urban solid waste decomposition increased with increasing temperature value and therefore the amount of solid product decreased.

As the temperature increased, the amount of gas production increased and a significant increase was observed in the amount of gas product, especially after the fragmentation of some of the liquid products after 600 ^oC.

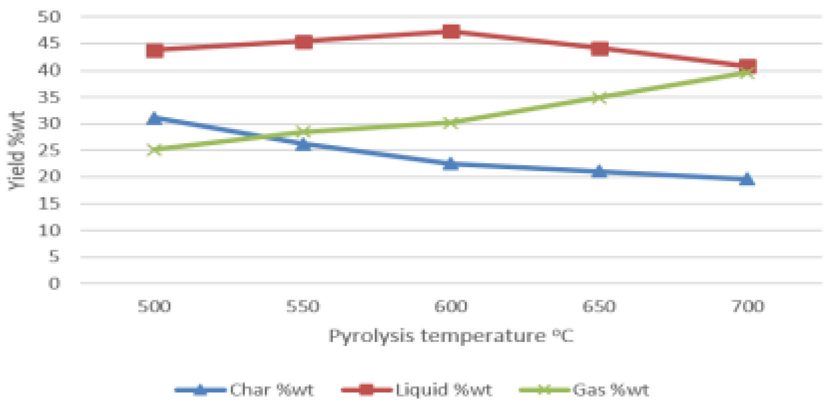

Figure 8. Effect of temperature on pyrolysis's product yields.

As the temperature value increased, the yield of the gas production increased and, in particular, after 600 ^oC, a significant increase in the amount of gas product was observed by fragmenting some of the liquid products. According to the obtained gas composition, the maximum yield of CH_4 was obtained at 600 ^oC and with increasing temperature, the amount of CH_4 decreased while the CO and CO_2 amount increased. The mass of gas product obtained at 600 ^oC was 4,12% CH_4, 9,24% CO, 1,51% H_2 and 10,70% CO_2.

The maximum liquid product yield was observed at 600 ^oC. The percentage of liquid products in mass at this temperature is 47.29%. While the yield of liquid products up to 600 ^oC increased, it started to decrease at temperatures above 600 ^oC.

According to the results of the finite element analysis, mass percentages of 5 different gases, CH_4, CO, CO_2, H_2, and H_2O were found and the values for CH_4 are shown in the figures between Figure 9 and Figure 11.

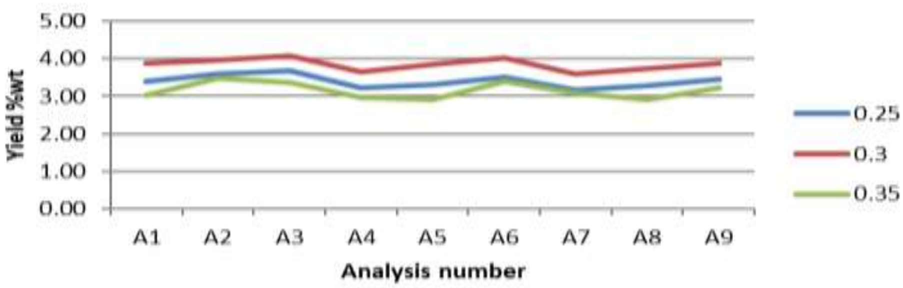

Figure 9. Mass fraction of CH_4 produced in 3 different reactors at an input temperature of 353 K.

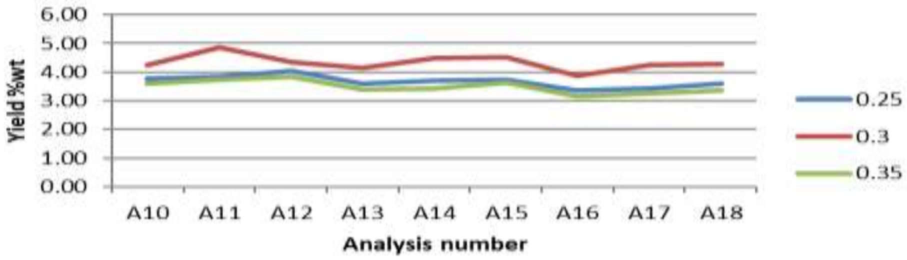

Figure 10. Mass fraction of CH_4 produced in 3 different reactors at an input temperature of 373 K.

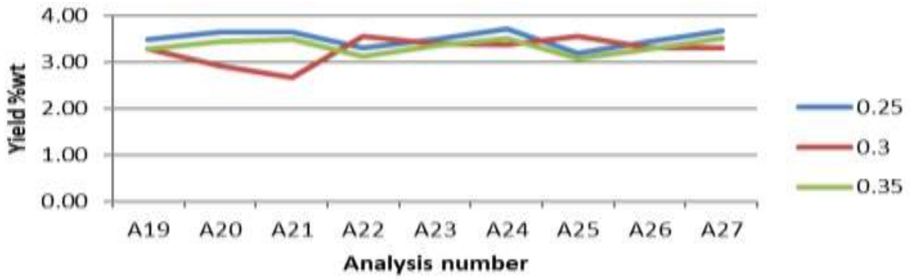

Figure 11. Mass fraction of CH_4 produced in 3 different reactors at an input temperature of 393 K.

As can be seen from Figure 3.3, the maximum amount of CH_4 was obtained in the A11 analysis, ie 0.3 diameter/aspect ratio, 373 K inlet temperature, 20 mm particle size, and 10 rpm rotation speed. According to these observed values, as a result of pyrolysis of 100 kg urban solid waste, 4,85 kg CH_4, 10,80 kg CO, 1,81 kg H_2, 6,12 kg H_2O and 8,70 kg CO_2 in total, 32% by mass gas product was obtained. Contours of mass fraction obtained from the finite element analysis of the A11 are also shown in Figure 12.

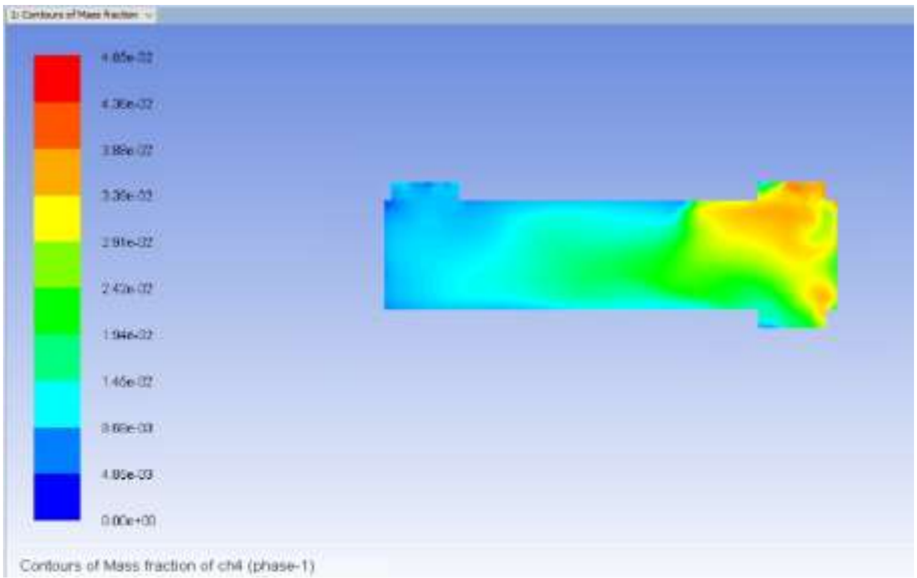

Figure 12. Contours of mass fraction of CH_4 produced in the pyrolysis reactor.

3.1. Calculation of Energy Potential

7.39 m^3 CH_4, 8,64 m^3 CO, 0,02 m^3 H_2, 7,65 m^3 H_2O, and 4,58 m^3 CO_2 were obtained according to the analysis data with maximum methane content for the pyrolysis unit. According to these values, the total pyrolysis gas volume to be obtained in the pyrolysis of 100 kg municipal solid waste is 28,28 m^3.

Energy analysis was carried out only for methane gas from pyrolysis gas products. The annual amount of methane gas was calculated in the case that all wastes produced are subjected to pyrolysis. Afterward, if they are converted to electrical energy in internal combustion engines, the potential amount of energy to be obtained in GWh was revealed. In the calculations, the calorific value of the methane gas at 600 ºC was considered as 33,810 kJ / m^3 and the electrical energy production efficiency at the internal combustion engines was accepted as 35%. The results are given in Table 7.

According to TR42 Eastern Marmara Region Renewable Energy Report; Turkey's total electricity consumption per capita is 2,664 kWh. It is concluded that, even if only methane gas is evaluated from the gas products that will occur in the case of pyrolysis of urban solid wastes in Kocaeli, an average of 58,470 people can meet the electricity needs per year.

Table 7. The annual electrical energy potential of the pyrolysis process in Kocaeli.

Amount of waste collected daily	1755	t/day
Amount of waste collected annually	641014	t/year
Amount of gas produced annually	181.278.759,2	m^3
Amount of methane produced annually.	47.386.267,65	m^3
The calorific value of methane	33.810	kJ/m^3
Annual calorific value	1.602.129.709,246	MJ/year
Calorific value to be obtained annually from methane if used in internal combustion engines.	560.745.398,236	MJ/year
Annual electrical energy	155,7626106	GWh

4. Conclusion

Disposal of municipal solid wastes by pyrolysis is an issue that the international scientific community and users have recently focused on. Municipal solid waste, which grows like mountains every day and has a significant amount of calorific value, should be utilized at the maximum rate. As both energy generation and waste disposal are possible, the expansion of the pyrolysis facilities provides a great added value in terms of minimizing the economic and environmental impacts. As the pyrolysis method is used, there will be no need for landfills and the use of these areas for agricultural or other purposes will be contributed.

According to the statements made by the Society for the Protection of Nature, natural resources that have been consumed more rapidly than ever before in human history have been destroyed even more in the last 40 years. In the Energy Report prepared by the World Energy Council's Turkish National Committee, it is clear that the energy resources will be gradually depleted while the electricity demand will increase by 70 percent in the next 25 years. In the following years, our world will be faced with energy problems. For this reason, countries need to reduce their external dependencies to meet their energy needs and to meet their own energy needs, especially with domestic and renewable energy sources. Municipal solid wastes, which have been kept in the waste class for centuries and ignored the enormous amount of energy in their potential, should be transformed into an economic input by evaluating them, especially in pyrolysis units through controlled waste management.

Authors' Contributions

FP, MK and ET wrote up the article. The authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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