

# Journal of Environmental Sciences Studies (JESS)

Journal homepage: [www.jess.ir](http://www.jess.ir)

## Rapid Catalytic Cracking of Municipal Waste with Simultaneous Hydrogenation to Produce Liquid Fuel

Hossein Vahidi<sup>a</sup>, Morteza Riyazinejad<sup>b</sup>, Bahador Abolpour<sup>c,\*</sup>

a. Department of Environment, Institute of Science and High Technology and Environmental Sciences, Graduate University of Advanced Technology, Kerman, Iran

b. Health, Safety and Environment, Faculty of Environment, University of Tehran, Tehran, Iran

\*c. Department of Chemical Engineering, Sirjan University of Technology, Sirjan, Kerman, Iran

\*Email address : [bahadorabolpor1364@yahoo.com](mailto:bahadorabolpor1364@yahoo.com)

### ARTICLE INFO

Received: 24 November 2019

Accepted: 26 December 2019

### Keywords:

Pyrolysis; Catalytic cracking; simultaneous hydrogenation; municipal waste; gasoline

### A B S T R A C T

Simplest methods of the municipal waste disposal are exploitation and abandoning this national wealth in the environment. In this study, a new method of cracking municipal waste and producing useful products with a suitable thermal value and quality for consumption has been developed. For this purpose, a hydrogen gas flow has been injected into a predesigned rotational pyrolysis reactor. Reducing the process time and cost and also increasing the product quality are specifications of this innovation. Sample analyzing of the pilot study products determines the presence of a wide range of hydrocarbons with 5-14 carbons in their molecular structures. This approves the presence of the paraffinic, naphthenic, olefin (lower than the common refinery gasoline) and aromatic compounds, which are the main compositions of gasoline.

### 1. Introduction

Attending the increment of the population and industry, solid and liquid waste production has also been increased. Traditional charcoal production kilns have received a bad environmental reputation as they vent volatiles in to the atmosphere as they operate [1]. This increment has reached its critical point in some areas. During recent years, some countries have tried to utilize appropriate ways of waste disposal with high efficiency and reasonable cost based on the quality and quantity of their waste [2]. A modern method for the solid and liquid waste disposal has been based on the

received high attention due to its efficient products and energy production [3]. The methods based on the transforming waste into energy, such as waste incinerators, pyrolysis units, cracking and RDF/SRF, have different products, such as electricity, solid fuels or liquid fuels with various qualities. The pyrolysis and cracking processes produce energy with a cleaner method than the waste incinerating process. This cleanliness can be observed both in the chimney outputs and also in the solid leftovers in the reactor and crucible, such that the concentration of nitrogen dioxide (NO<sub>x</sub>) and

sulfur dioxide (SO<sub>2</sub>) are less in the output of the pyrolysis unit than similar incinerator units. Also solid accessories in the pyrolysis reactors have higher quality for use or burial compared to the ash produced in incinerator units. Furthermore, it is possible to incorporate filtration systems to reduce pollution concentration during the pyrolysis method [4]. The pyrolysis process has been described as thermal decomposition of material in the absence of oxygen. According to the general equations of the solid waste pyrolysis, the acquired products from this process include char, oil, liquid fuel (if complementary procedures take place) and flammable gases. Considering these products and the recycling of energy with considerable efficiency compared to routine municipal waste incinerators, pyrolysis is one the most cost-effective, efficient methods of municipal waste disposal suggested [5]. From a city management perspective, another advantage of pyrolysis and cracking units compared to incinerators is flexibility of their function capacity and relative investment requirement. Based on the experience acquired over recent years, waste incinerators should have high capacities to be economically justified and practical. Whereas, pyrolysis units have economic justification even with small capacities and do not face problems in operation with these capacities [5]. Because of this, smaller cities are more inclined towards establishing pyrolysis and cracking units and therefore do not need to transfer their waste to larger cities to convert them into energy and can do this with a good rate of efficiency locally. This issue relieves the pressure on larger cities to receive waste from smaller cities and prevents problems in large cities such as rapid expansion of landfills and waste incinerators. From a transport efficacy point of view, the transport expenses are reduced to the minimum [5-8]. One of the most important advantages of the pyrolysis waste disposal system is the high quality of the products, such as gas and liquid fuels, instead of thermal energy (that produced in incinerators) in various capacities and compatible with a variety of waste from different cities. Municipal waste is the main feed of the pyrolysis reactors which include

various items with different composition percentages and their variability depends on the location, time, culture and lifestyle of people in different areas [2]. For example, waste in Middle Eastern countries varies vastly from European countries and is made up of a higher organic matter percentage [9]. The majority of municipal waste includes paper, cardboard, textiles, iron metal and non-iron metal, glass, rubber, nylon, wood, organic material and other material. The pyrolysis process can use all material with a hydrocarbon and organic base. The important point in using waste in the pyrolysis system is the percentage of moisture of the waste. A pyrolysis process with a low value of the moisture takes place with a high efficiency and quality of the final product. Moreover, the percentage of the moisture of the waste has an inverse relationship with the thermal energy required to heat the reactors, such that the lower the moisture the less thermal energy required to break bonds of material in pyrolysis reactors, therefore less moisture means saving energy [10-12]. Thus it can be stated that mechanical preprocessing in order to reduce unusable waste and reduce moisture is necessary. In some studies, stricter preprocessing is preformed and in some cases it has been managed to produce accessory fuels such as SRF and RDF from waste [13,14]. However, an increment in cost, because of the preprocessing stage, can pose a challenge in economically justifying the efficiency of this system. This has led to some people contemplating using the municipal waste as a whole in the pyrolysis procedure [15,16]. Based on the obtained results from various studies, the most important factors effecting the efficacy and quality of the product of the pyrolysis and cracking procedure include temperature, heating rate, duration of pyrolysis, engineering of input, variety of primary waste material and size of input load of the reactors. BP polymer cracking, Fuji and Hamburg processes recycled basic pyrolytic oils successfully [17,18]. In cracking and pyrolysis systems in order to make a product with a quality suitable to be distributed to worldwide markets, the process of production is carried out in two stages. The first stage is producing the basic pyrolytic oil and the second

stage is cracking and changing the heavy hydrocarbons into products such as gasoline. Various types of these processes have been analyzed and a summary of them can be studied in Masuda and Tago's (2006) research [19]. It has been pointed out in some studies that catalytic hydrolysis reactors with steam as a carrier gas and FeOOH, as a catalyst, followed by a catalytic cracking reactor with zeolite, as a catalyst, improve the product quality [5]. Pyrolysis of solid wastes in requires more heat compared to biomass and the majority of this thermal energy is used for two purposes: 1) higher moisture 2) larger variety of material available in municipal waste [5]. As a general concept, increasing the temperature and using the catalysts lead to an increment in the gas yield and a decrement in the char [20]. In recent years, some studies have been carried out in this area, such as, investigations of concerning pyrolysis of tires and plastics, quality of pyrolysis products, various pyrolysis and cracking technologies and also general approaches regarding management concepts in utilizing pyrolysis systems [17,21-22]. Some studies have also been carried out on the quality of products of the pyrolysis and cracking process, especially the quality of basic oils produced in the first phase of the process and also methods of improving their quality and properties [23,24]. Heating systems and other factors effecting the quality of the products of the pyrolysis process have been examined in order to enhance their properties [25]. Some studies have focused on the kinetic of the reactions and identifying mechanisms that take place in the pyrolysis process [23,26]. The focus of the presented study is designing a new process in pyrolysis of municipal waste, called Rapid Catalytic Cracking (RCC), and simultaneous hydrogenation in order to increase efficiency and quality of pyrolytic products.

## 2. Materials and Methods

The regulation of processing and separation of waste and excluding material which aren't necessary for the process and also controlling the percentage of the rest of the composition in order to fixate the quality of the reactor's input material is referred to as input engineering. The

material used in the initial reactor of this pyrolysis pilot include, a grinded mixture of routine solid municipal waste in Iran. However, metal, glass and construction waste were separated from municipal waste and the remainder, which includes hydrocarbon based and organic waste, were entered into the reactor as small particles (with 5 cm equal radius) with remained moisture. A preprocessing was carried out on the waste based on engineering the input and regulating the input items of the reactor for increasing the efficiency of the reactor and also the quality of the products. The composition of the reactor's input waste has been presented in Table 1.

**Table 1- Physical characterization of input wastes**

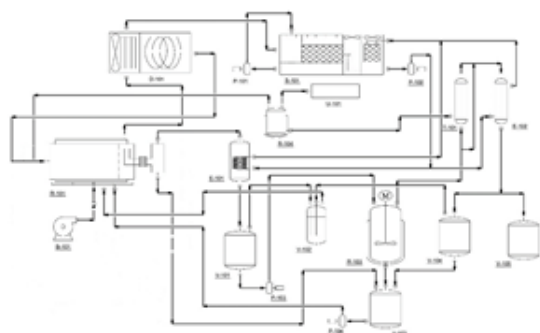
Pyrolysis System Type	Major equipment
Fixed-bed reactor and pyrolysis system	N <sub>2</sub> bottle Reactor Heat exchanger Separation unit Water trap Gas flow meter Rotameter
Fixed bed pyrolysis system	Furnace Pyrolysis reactor Thermocouple Temperature controller N <sub>2</sub> pipe Liquid gathering tank Thermometer Condenser Pressure gauge Sampling vent
Rotary kiln pyrolysis system	Thermometer Bearing Gear transmission Electrical furnace Rotary kiln Temperature controller Seal Two-steps condenser filter Accumulative flowmeter Computer Gas sampling device Feed and discharge opening speed adjustable Electrical machinery

Rejected dried waste was mixed at the same time as entering the reactor with hot solvent that had a high flash point. This was the first stage of breakage in polymers present in the rejected waste and their transformation into a soft paste. After the loading finishes the

catalysts related to the input were added and the input engineering finishes, rejected waste, catalyst and solvents were mixed and readied for the procedure. Hydrogen was added after the loading stage and at the same time as increasing the temperature, this hydrogen was made in a process which was part of innovations of this study.

**2.1. Pilot**

In many studies, various pilots and experimental setups have been designed for examining the pyrolysis reactions with a more accuracy and improving the process carried out on waste. The major equipment of these pilots has been presented in Table 2 [15-16,27-30]. The pilot designed and made in this study has been shown in Figure 1, schematically, and Figure 2 shows a picture of this pilot. Table 3 presents a list of the components of the pilot. After production and storing the product in a specialized sampling container, samples were sent to a laboratory for GC-Mass analysis.



**Fig. 1- Experimental pilot for RCC**



**Fig. 2- A photograph of pilot and the product**

**Table 2- Major equipment of the previous pyrolysis pilots [15-16,27-30]**

Rejected waste composition	%
Nylon bags	59.6
Polica tube & Oil containers	1.2
Polypropylene containers such as yogurt	15.8
Other disposable utensils	2
Unilite and foam	6
Wood	1.2
Leather, textile, clothing and cloth	14.3
Total	100

**Table 3- Introducing different units designed in the RCC pilots**

	Reactor units	Unit code
1	Cracking reactor	R-101
2	Distillation reactor with mixer	R=103
3	Hydrogen gas reactor	R=104
4	Waste dryer	D=101
5	Coiled condenser	E=101
6	Shield and tube condenser	E=102
7	Wet scrubber	S=101
8	Aluminum bar production unit	U=101

9	Air blower	B=101
10	Reforming catalytic tower	T=101
11	Primary crude oil storage	V=101
12	Water seal	V=102
13	Procedure fuel storage	V=103
14	Initial product storage	V=104
15	Secondary product storage	V=105
16	Scrubber water circulation pump	P=101
17	Cooling tower water circulation pump	P=102
18	Initial product transfer pump to the reactor	P=103
19	Transfer pump for fuel to the cracking reactor	P=104

### 3. Results & Discussion

#### 3.1. Input engineering

Municipal waste first entered a separation process and decay-able material that can transform into compost was separated. Metals and glasses, which are presented in waste, were separated in this stage. In predicted input engineering, valuable material, such as PET, can also be separated in this stage. The rest of the material the remains after preprocessing, is named rejected material (the main input material for the pilot), was guided to the dryer. The dryer's heat was provided using the hot gases exiting from the pyrolysis reactor. After a thermal transaction, the gases exited the dryer head towards the scrubber. The rejected waste material entered the pyrolysis reactor. In this stage, other material can be added to increase the quality of the product. The rejected dried waste material was mixed with a hot solvent at the same time it entered the reactor and this was the first stage of breaking up the polymers presented in the waste and transforming the waste into a soft paste. After loading, the related catalysts were added. Some of these catalysts included lick to control the hydrochloric acid produced during pyrolysis of PVC waste, or sodium hydroxide to control sulfur containing compounds. After this stage of input engineering terminates the waste and

catalysts and solvent are mixed so the procedure can start. Separated material, such as metals and glasses, which cannot be inherently, cannot undergo pyrolysis, can be recycled.

#### 3.2. Pyrolysis reactors

After input engineering, municipal waste entered pyrolysis cylindrical reactors, which had been placed horizontally on a frame. The reactor was 1.2 meters long and had a diameter of 0.5 meters. It was made from the steel 304. The volume of these reactors was 0.250 meters cubed and can process 200 to 250 kilos of waste input (dependent on the volumetric weight of the waste) every 6 hours. The reactor had a port for importing hydrogen gas at one end and at the other side it had a U shaped pipe, which exported the gas produced from the procedure. The U shaped pipe had two mechanical seals connecting the reactor and wax gear and these mechanical seals enabled the pyrolysis reactors to process liquid inputs, up to 70% of their capacity in volume. This reactor had an air jet under its frame, which injected cool air under the reactor at the end of the process for a rapidly cooling of the reactor. The thermal energy of the process was provided using the product of the procedure and incondensable gases. These gases had polluting compounds with excess oxygen and were heated to 1400 degrees centigrade in a furnace under the reactor. The reactor had two walls, the internal wall was the main wall of the reactor and was placed on 4 main ball bearings, gears and a dynamo enable the circular motion of the reactor to mix the waste, catalysts and the injected hydrogen. Spiral blades inside the reactor facilitated mixing and also pushed the material inwards in the reactor, which prevented the exit of non-pyrolyzed material. The outer wall was covered with thermal insulators to prevent energy loss.

#### 3.3. Hydrogen gas producing reactor and electrochemical recycling of aluminum

This reactor was made from steel 304, which is resistant against corrosion and heat. A double walled cylindrical unit was placed vertically with safety valves for emergency gas release and emergency liquid ejection. The process of hydrogen gas production used in this pilot was a classic reaction among sodium hydroxide,

water and recycled aluminum from the waste. This reaction produces hydrogen gas and sodium aluminate [27,28]. As designed, the hydrogen gas was directed towards the reactor and the sodium aluminate was neutralized after the reaction and ended up as an electrolysis solution, which can be recycled into pure aluminum through an electrochemical process. This procedure provided the needed hydrogen for pyrolysis and pure aluminum. The important points in producing hydrogen gas in this process are regulating the concentration of sodium hydroxide, the interaction surface of sodium hydroxide and aluminum, controlling the reaction's temperature and controlling the overall synthetics of the reaction, which leads to a constant flow of hydrogen over the 6 hour pyrolysis procedure in each reactor. This issue has been examined experimentally through the experiments carried out on the pilot and requires accurate engineering calculations to estimate quantities.

### 3.4. Wet scrubber and refinery

After thermal transaction, the output gases exiting from bottom of the reactor were directed towards rejected waste to dry them and increasing its temperature to 70 degrees centigrade. The hot air, which dried the rejected waste, was also transferred to the scrubber. The scrubber unit in this pilot was a steel tank with a height of 2 meters and diameter of 40 centimeters, which had water outlets at the top that sprayed water on the hot gases and these gases cooled down after contacting with the water and were returned to the system after cooling down.

### 3.5. Primary product purification

The gases liquefied after passing through the condenser and accumulated in the initial product storage unit. The primary product which was reduced with hydrogen and input engineering, was in the form of crude oil but more dilute. This product was black in color and had impurities and pollutants such as soot and sulfur compounds. To clarify the product and reduce the amount of sulfur and the amount of energy used, nano material was used to precipitate and clarify. The sulfur of the product was reduced by about 200 mg/l. Then the petrol, gasoline and mazut were separated in the

reforming process with hydrogen gas and catalysts through part by part distillation. By adding additives, such as octane booster material, the produced petrol can achieve consumable standards.

### 3.6. Product

In other methods of waste pyrolysis, when the polymer molecules of nylon, plastic and rubber are broken down by heat, due to lack of hydrogen, the broken down hydrocarbons produce olefins, circular compounds and organic compounds with large auxiliary branches. However, in this procedure the ends of broken down carbons are reduced with hydrogen and rarely produce undesirable compounds and mostly organic paraffin based material are made. Results of the PONA test, which was carried out to verify this issue, have been presented in Table 4. Also the results of the GCMass test of the product have been presented in Table 5. This GCMass analysis obtained a wide range hydrocarbons (with 5-14 carbons in its main chain). The different percentage of hydrocarbons in this analysis shows a uniform growth in the number of carbons, which proves the presence of paraffin, naphthenic, olefin and aromatic compounds that are the main components of gasoline.

**Table 4- Results of the distillation test of the product**

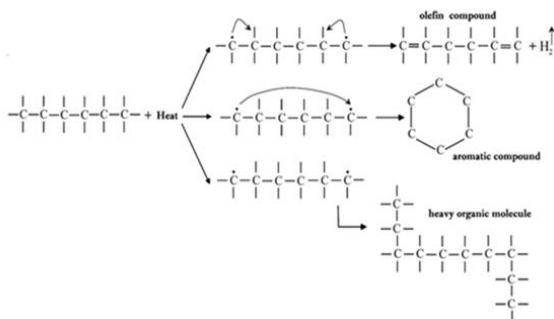
Sample Test	Municipal waste diesel	50% municipal waste diesel 50% refinery diesel
Density@15 °C	788.0	813.0
<b>Distillation</b>		
IBP °C	126	154
10% °C	180	190
20% °C	188	202
30% °C	197	213
40% °C	204	223
50% °C	211	236
60% °C	219	249
70% °C	229	267
80% °C	239	294
90% °C	256	330
F.B.P °C	313	363
Recovery Vol%	98.8	98.4
Residue Vol%	0.8	1.3
Loss Vol%	0.4	0.3
Recovered@250 °C Vol%	82	61
Recovered@350 °C Vol%	--	93.5
95%Recovered	279	365
Sulfur ppm	95	482

Propene	0.30	Cyclohexane, propyl	0.62	Dimethyl, 2,3-Heptene-3	1.13
1-Propen,2-methyl	0.51	3-Methylnonane	1.42	2-Tetradecane, (E)	0.38
1-Pentene	0.81	Heptane, 3-ethyl-2-methyl	0.85	Tetradecane	0.91
1,4-Pentadiene	0.07	Benzene, propyl	0.31	Cyclohexane, 1-ethyl- 2-propyl	0.33
1-Pentene,2-methyl	0.03	Benzene, 1-ethyl -2-methyl	1.90	Tetradecane	0.26
2-Butene,2,3-dimethyl	0.14	Nonane,2-methyl	0.64	Heptadecane	0.74
1-Pentene,2-methyl	0.79	Benzene, 1,2,3-trimethyl	0.82	Dodecane, 2,6,11-trimethyl	0.26
2-Pentene,2-methyl	0.19	Nonane,3-methyl	0.73	4-Methyltridecane	0.34
Cyclopentene,3-methyl	0.05	Benzene, 1-ethyl -2-methyl	0.45	3-Octadecene,(E)	0.73
Cyclopentene,1-methyl	0.28	3-Nonyn-1-ol	0.31	Octadecane	1.02
Benzene	0.34	Benzene, 1,2,3-trimethyl	1.65	Benzyl(dideuterated)methyl ether	0.25
Hexane,3-methyl	0.17	Decane	2.99	Cyclopentane, 1-ethyl-2propyl	1.81
1-Heptane	0.38	Heptane, 3,3,5-trimethyl	0.40	Cyclopentane, hexyl	0.76
Heptane	0.88	Undecane, 4,6-dimethyl	0.43	Undecane, 5-methyl	0.49
Methyl cyclohexane	1.09	Benzene, 1,4-diethyl	0.48	Cyclooctane, 1,4-dimethyl, trans	1.37
1,2,4,Trimethylcyclopentane	0.28	Nonane, 2,6-dimethyl	0.59	6-Tridecene, 7-methyl	0.42
Hexane,2,3,-dimethyl	0.37	Cyclohexane, butyl	0.55	Transdimethyl-2,2hepten3-3	0.74
Heptane,2-dimethyl	1.32	3,7-Dimethylnonane	0.34	1-Hexadecene	0.26
Toluene	1.13	Benzene, 1-methyl-3-propyl	0.56	Cyclopropanol, 1-(3,7-dimethyl-1-octenyl)	0.40
2-Ethylhexane	1.07	Benzene,4-ethyl-1,2dimethyl	0.57	Hexadecane	0.92
Cyclohexane,1,3-dimethyl,cis	1.42	Decane,4-methyl	0.25	Cyclohexane, 1,1,2-trimethyl	0.41
Cyclohexane,1,1-dimethyl	0.24	Decane, 2-methyl	0.83	Cyclopentane, 1-butyl-2propyl	0.32
Cyclopentane,1-ethyl-2-methyl	0.47	Decane, 3-methyl	0.42	Hexadecane,2,6,11,15-tetramethyl	0.26
Octane	4.22	2-Undacane, 4-methyl	0.76	1-Tetradecene	0.27
Cyclohexane,1,4-dimethyl,trans	0.37	Benzene,1-ethyl-2,4dimethyl	0.88	1-Heptadecene	0.33
Heptane,2,4-dimethyl	0.38	1-Undecane	0.51	Heptadecane	0.53
Heptane,2,6-dimethyl	0.90	Undecane	2.65	2-Methylcyclohexanone	1.52
Cyclohexane, ethyl	0.25	Decane, 3,7-dimethyl	0.61	Tetracontane,3,5,24-trimethyl	1.69
2,5-Dimethylheptane	0.19	2,3,7-Trimethyl-2octene	0.51	Hexadecane, 1-chloro	0.40
Cyclohexane, 1,1,3-trimethyl	0.26	Prehnitene	0.26	Pentadecane	0.72
2,4-Dimethyl-1-heptene	1.83	Nonadecane	0.47	Octadecane	0.87
Cyclohexane, 1,2,4-trimethyl	0.50	Undecane, 3-methyl	0.26	3-Decane, 2,2-dimethyl	0.27
Heptane, 2,3-dimethyl	0.80	1-Dodecene	0.36	Cyclohexane, 1-ethyl-2-propyl	0.24
Benzene, ethyl	0.55	Dodecane	1.40	Nonadecane	0.39
2-Methyloctane	1.90	1-Pentadecene	0.85	Heneicosane	1.00
Benzene, 1,3-dimethyl	3.09	Tridecane	1.26	1,2,4-Trimethylcyclohexane	0.55
Isononane	0.76	1,2,3-trimethylcyclohexane	2.65	Eicosane	0.63
1-Ethyl-4-methylcyclohexane	0.34	2-acetylcyclopentanone	1.52	Heneicosane	0.27
p-Xylene	2.36	4-Isopropyl-1,3-cyclohexanedione	2.63	4,5-Dimethylnonane	0.44
Hexane, 1-(hexyloxy) -2-methyl	0.45	3-Decene, 2,2-dimethyl	1.78	Nonane	4.17
Cyclohexane, 1-ethyl2-methyl, tra	0.30	2-Decene, 7-methyl, (z)	0.25		

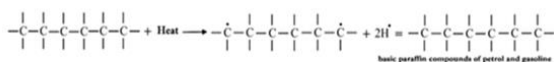
Table 5- The obtained percentages of composition of the product using the GCMass analysis

he gasoline produced from municipal waste cracking, which has the analysis results seen in Table 5, due to simultaneous hydrogenation and cracking, has little olefin (see Figure 3). This type of gasoline has a good quality after one stage of blending, especially because it has less sulfur than refinery produced gasoline in Iran. Figure 4 compares the TIC (Total Ion Chromatogram: a chromatogram created by summing up intensities of all mass spectral peaks belonging to the same scan) of the produced gasoil with and without hydrogenation with a standard sample of the refinery produced gasoline in Iran. This Figure approves the improvement of the quality of produced gasoil from the municipal waste with simultaneous hydrogenation injection. Because of the distillation start point from 126 degrees to 313 degrees centigrade for gasoline produced from waste, it can be concluded that it is a light gasoline and its sulfur levels are adequate such that they can achieve euro standards after one stage of refining. Also the gasoline produced from waste produces less ash when burnt.

non hydrogenous cracking:



Simultaneous cracking and hydrogenation:



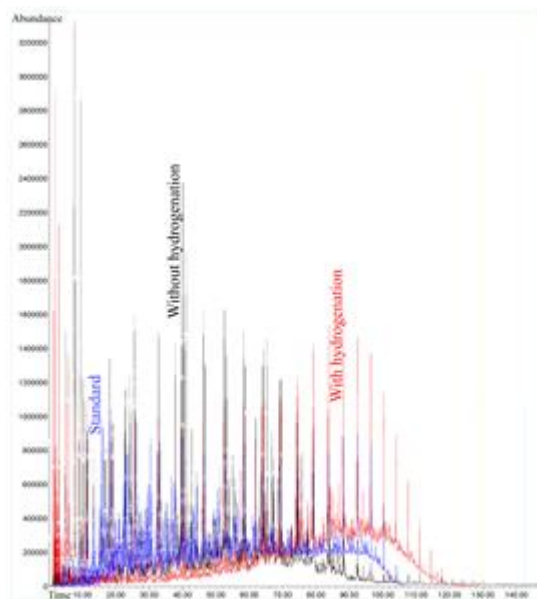
**Fig. 3- A comparison between the products of the non-hydrogenous cracking and the simultaneous hydrogenation and cracking**

### 3.7. Other outputs of the pilot

This process not only extracts the stored energy inside the municipal waste, it also produces coke and leaves no waste to be buried. Only about 2 to 5 percent of the input material and that is only if there is construction waste such

as sand, will need burying. The incondensable gases in the pyrolysis process which make up about 10 to 15 percent of the product, are passed through sodium hydroxide chemical and peroxide and water and directed towards the reactor. They are then heated with the help of excess oxygen to 1400 degrees centigrade. In this stage all of the polluting compounds are ionized and provide some of the thermal energy needed for pyrolysis reactors. In an industrial model of the pilot the burnt gases under the reactor can be transferred to a thermal transformer so the heat can be used to dry waste. Also in the industrial model the gases can be transferred into the scrubber after being cooled down, so that the air exiting the reactor is completely clean and free of pollutants.

**Fig. 4- Comparison of the obtained TIC from the produced gasoil with and without hydrogenation, with a standard sample of the refinery produced gasoline in Iran**



### 3.8. Remainder material in the reactor

Coke remains at end of the process. This substance due to its molecular structure cannot be used as industrial soot, because it needs to receive an electron to break carbon-carbon bonds. If this happens, the produced coke turns into amorphous carbon and becomes industrial soot, which can be used in the painting industry, rubber industry and other industries. If the procedure to make industrial soot is not



conducted, the produced coke can be directly used to reduce iron ore in the steel industry, or as an additive in the cement industry in order to make harder cements and cement blocks. If this coke has enough thermal energy, it can also be used as fuel.

#### 4. Conclusions

Redesigning rotary pyrolysis reactors in order to inject hydrogen gas and enable the input of liquid waste and reduce the cooling, extraction and loading times or use coupled catalytic pyrolysis reactors has been achieved in this project. By analyzing the percentage of different material in the pyrolysis the improvement of product quality was observed. Therefore, using the input engineering has been suggested in pyrolysis as another step in improving final product quality. Using a traditional and classic process to build a hydrogen producing reactor using the aluminum compounds available in the recyclable waste and sodium hydroxide produced hydrogen, which can be transferred into the pyrolysis reactor to reduce polymer material in waste that are broken down by heat, was an innovation in this project. GC/MS analysis of the samples from the pilot shown a wide range of hydrocarbons, ranging from 5 to 14 carbons, which proved the presence of paraffin, olefin, naphthenic and aromatic compounds, which are the main components of gasoline. The gasoline produced by cracking municipal waste in this study has lower olefin levels which is due to simultaneous hydrogenation with cracking. This results in having a product with a good quality and lower sulfur levels than refinery gasolines in Iran, after just one stage of blending. Also pollutant gases, such as dioxin and furan, have been reduced in this process due to hydrogen reduction.

#### Acknowledgements

This work was supported by Science based Cooperation of Pak Petro Zist Khavaran. The authors thanked the cooperation for funding and providing necessary equipment.

#### References

- D.A. Laird, R.C. Brown, J.E. Amonette, J. Lehmann (2009) Review of the Pyrolysis Platform for Coproducing Bio-Oil and Biochar. *Biofuels, Bioproducts and Biorefining*, 3, pp. 547-562.
- H. Vahidi, H. Nematollahi, A. Padash, B. Sadeghi, M. RiyaziNejad (2017) Comparison of Rural Solid Waste Management in Two Central Provinces of Iran, *Environmental Energy and Economic Research*, 1(2), pp. 195-206.
- T. Malkow (2004) Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal, *Waste management*, 24(1), pp. 53-79.
- A. Saffarzadeh, T. Shimaoka, Y. Motomura, K. Watanabe (2006) Chemical and mineralogical evaluation of slag products derived from the pyrolysis/melting treatment of MSW, *Waste Management*, 26(12), pp. 1443-1452.
- D. Chen, L. Yin, H. Wang, P. He (2014) Pyrolysis technologies for municipal solid waste: a review, *Waste management*, 34(12), pp. 2466-2486.
- F. Shams Fallah, H. Vahidi, M. Pazoki, F. Akhavan-Limudehi, A. Aslemand, R. Samiee Zafarhandi (2012) Investigation of solid waste disposal alternatives in Lavan Island using life cycle assessment approach, *International Journal of Environmental Research*, 7(1), pp. 155-164.
- H. Hoveidi, A. Aslemand, H. Vahidi, F. Limodehi (2013) Cost emission of Pm10 on human health due to the solid waste disposal scenarios, case study; Tehran, *Journal of Earth Science and Climatic Change*, 4, p. 139.
- H. Vahidi, H. Hoveidi, J.K. Khoie, H. Nematollahi, R. Heydari (2018) Analyzing material flow in Alborz industrial estate, Ghazvin, Iran, *Journal of Material Cycles and Waste Management*, 1.
- Y. Dhokhikah, Y. Trihadiningrum (2012) Solid waste management in Asian developing countries: Challenges and opportunities, *Journal of Applied Environmental and Biological Sciences*, 2(7), pp. 329-335.
- J. Dong, Y. Chi, Y. Tang, M. Ni, A. Nzihou, E. Weiss-Hortala, Q. Huang (2016) Effect of Operating Parameters and Moisture Content on Municipal Solid Waste Pyrolysis and Gasification, *Energy & Fuels*, 30(5), 3994-4001.

- R. Miandad, M.A. Barakat, A.S. Aburizaiza, M. Rehan, I.M.I. Ismail, A.S. Nizami (2017) Effect of plastic waste types on pyrolysis liquid oil, *International Biodeterioration & Biodegradation*, 119, pp. 239-252.
- X. Zheng, C. Chen, Z. Ying, B. Wang (2016) Experimental study on gasification performance of bamboo and PE from municipal solid waste in a bench-scale fixed bed reactor, *Energy Conversion and Management*, 117, pp. 393-399.
- S. Al-Salem, A. Antelava, A. Constantinou, G. Manos, A. Dutta (2017) A review on thermal and catalytic pyrolysis of plastic solid waste (PSW), *Journal of Environmental Management*, 197, pp. 177-198.
- E. Ranieri, C. Montanaro, A.C. Ranieri, V. Campanaro, L.I. Cioca (2017) Municipal solid wastes in the South-Eastern Mediterranean region: Quality, quantity and management *Quality, Calitatea*, 18, pp. 162-169.
- F. Ates, N. Miskolczi, N. Borsodi (2013) Comparison of real waste (MSW and MPW) pyrolysis in batch reactor over different catalysts. Part I: product yields, gas and pyrolysis oil properties, *Bioresour. Technol.*, 133, pp. 443-454.
- N. Miskolczi, F. Ates, N. Borsodi (2013) Comparison of real waste (MSW and MPW) pyrolysis in batch reactor over different catalysts. Part II: contaminants, char and pyrolysis oil properties, *Bioresour. Technol.*, 144, pp. 370-379.
- X. Yang, L. Sun, J. Xiang, S. Hu, S. Su (2002) Pyrolysis and dehalogenation of plastics from waste electrical and electronic equipment (WEEE): a review, *Waste Management*, 33, pp. 462-473.
- S. Ali, A. Garforth, D. Harris, D. Rawlence, Y. Uemichi (2002) Polymer waste recycling over "used" catalysts, *Catalysis Today*, 75, pp. 247-255.
- [19] T. Masuda, T. Tago (2006), Development of a Process for the Continuous Conversion of Waste Plastics Mixtures to Fuel, Feedstock Recycling and Pyrolysis of Waste Plastics: Converting Waste Plastics into Diesel and Other Fuel, pp. 161-192.
- I.H. Hwang, J. Kobayashi, K. Kawamoto (2014) Characterization of products obtained from pyrolysis and steam gasification of wood waste, RDF, and RPF, *Waste management*, 34(2), pp. 402-410.
- E. Sannita, B. Aliakbarian, A.A. Casazza, P. Perego, G. Busca (2012) Medium-temperature conversion of biomass and wastes into liquid products, a review, *Renewable and Sustainable Energy Reviews*, 16(8), pp. 6455-6475.
- P.T. Williams (2013) Pyrolysis of waste tyres: A review, *Waste Management*, 33(8), pp. 1714-1728.
- A. Quek, R. Balasubramanian (2013) Liquefaction of waste tires by pyrolysis for oil and chemicals-A review, *Journal of Analytical and Applied Pyrolysis*, 101, pp. 1-16.
- A. Quek, R. Balasubramanian (2012) Mathematical modeling of rubber tire pyrolysis, *Journal of Analytical and Applied Pyrolysis*, 95, pp. 1-13.
- J.D. Martínez, N. Puy, R. Murillo, T. García, M.V. Navarro, A.M. Mastral (2013) Waste tyre pyrolysis—a review, *Renewable and Sustainable Energy Reviews*, 23, pp. 179-213.
- S. Al-Salem, P. Lettieri, J. Baeyens (2010) The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals, *Progress in Energy and Combustion Science*, 36, 103-129.
- L. Aimin, L. Xiaodong, L. Shuiqing, Y. Jianhua, C. Kefa (1999), *Journal of Chemical Industry and Engineering (China)*, 50, p. 101.
- A.M. Li, X.D. Li, S.Q. Li, Y. Ren, N. Shang, Y. Chi, J.H. Yan, K.F. Cen, (1999) Experimental studies on municipal solid waste pyrolysis in a laboratory-scale rotary kiln, *Energy*, 24(3), pp. 209-218.
- P.T. Williams, E.A. Williams (1999) Fluidised Bed Pyrolysis of Low Density Polyethylene to Produce Petrochemical Feedstock, *Journal of Analytical and Applied Pyrolysis*, 51, pp. 107-126.
- P.T. Williams, E.A. Williams (1999) Interaction of Plastics in Mixed-Plastics Pyrolysis, *Energy & Fuels*, 13(1), pp. 188-196.
- K. Hirose (2010) Handbook of hydrogen storage: new materials for future energy storage, John Wiley & Sons.
- C. Schmitz (2006) Handbook of aluminium recycling, Vulkan-Verlag GmbH.