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Design, Fabrication and Testing of Waste Plastic Pyrolysis Plant

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Abstract

In recent decades, there has been a dramatic increment in plastic consumption. Used plastic is one of the major wastes in many countries including Nepal. A lot of money is spent in land filling to process plastic wastes which can pose a threat to environment in long run. The incineration of plastic wastes leads to severe air pollution. Plastic pyrolysis process is a widely used technique to handle plastic wastes in many foreign countries. It is a new technology in Nepalese context. It involves melting plastic wastes, vaporizing them, condensing the vapor and distilling to obtain fuel. In the pyrolysis reactor, plastics are heated, vaporized and the vapor thus produced is passed to shell and tube condenser for condensation. The liquid thus obtained is called pyrolysis oil and char remains in pyrolysis reactor as residue. The yields depend on various factors like plastic type used, cracking temperature of plastic, rate of heating, operation pressure of reactor, type of reactor, residence time, use of catalyst, etc. The plant was designed and modeled in 3D CAD software, Solidworks. Batch reactor was employed to pyrolyze Low Density Polyethylene at reactor base temperature of about 600℃ and the vapour produced was directed to horizontal, counter-flow shell and tube condenser. From 10 kg of plastics, the plant yielded 6.63 liters of pyrolysis oil and 2.236 kg of char, on average, in the cost of 3.169 kg of LPG gas.

Keywords

Waste Plastic – Plastic Pyrolysis – Pyrolysis Oil – Shell and Tube Condenser

1. Introduction

Plastics are one of the most commonly used materials in our daily life. They contribute to make our life convenient. They are widely used in packaging and manufacture of products including electronic, automotive, etc [1]. Plastics have light weight and can be simply formed. They can be reused and help to conserve natural resources [2]. In fact, plastics have been used to replace metals and wood. Resultantly, plastic consumption has skyrocketed.

Plastic was invented in 1862 by Alexander Parkes [3]. They are formed by polymerization and have high molecular mass. Other substances may be present in plastics besides polymers to minimize costs and to enhance performance [4]. Desired shape can be given to these polymers by molding or by extrusion [5].

Plastic pyrolysis involves heating and degradation of plastic polymers at temperatures between 350°C and 900°C in an oxygen deficient environment [2]. This results in the formation of carbonized solid residue called char, condensible hydrocarbon oil and non-condensible gas with high calorific value [2]. Scheirs et al. [5] stated that gases formed during the pyrolysis of organic material include carbon monoxide, carbon dioxide, water, hydrogen, methane, ethane, ethene, propane, propene, butane, butene, etc. The temperature and rate of heating can be controlled to produce desired solid, liquid and gas products because they have significant influence in pyrolysis process [5]. Yin et al. [6] have considered pyrolysis of waste plastic as one of the outstanding methods of energy regeneration. This is because waste plastic is an important resource of chemicals, gas and liquid fuels [6].

Mainly there are two types of plastics: thermoplastics and thermosetting polymers. If enough heat is supplied, thermoplastics can be softened and melted repeatedly. On cooling, they are hardened, so that they can be used to form new plastics products. Examples include polyethylene, polystyrene, etc [4]. They are recyclable. Thermosetting plastics can be melted and shaped only once. It is not good to repeatedly heat treat such plastics; therefore they remain in solid state after they have been solidified [4]. Examples: epoxy resin, phenol formaldehyde, etc [7]. Society of Plastics Industry (SPI) has divided plastics into the following groups on the basis of application and chemical structure.

- PET (Polyethylene Terephthalate)
- HDPE (High Density Polyethylene)
- PVC (Polyvinyl Chloride)
- LDPE (Low Density Polyethylene)
- PP (Polypropylene)
- PS (Polystyrene)
- Other

2. Design Procedure

2.1 Design of Pyrolysis Reactor

Determination of the amount of raw materials : The experiment initially aimed towards performing pyrolysis at large scale. For that, the volume occupied by definite mass of plastics at normal market condition was predicted. The volume appeared to be large. Hence, it was chosen to preheat the plastics at low temperature (below melting point) in reactor so that more plastics could be accommodated in reactor. Finally, the volume of reactor was predicted to process 10 kg of plastics.

Determination of vessel geometry : The pyrolysis reactor was designed to have the vertical cylindrical cross section, called as shell. Heads, which are the end caps of the reactor, were chosen to be kept flat to lessen cost of fabrication, to ensure easy maintenance and to allow for greater rate of heat transfer. The reactor was designed to operate at normal atmospheric pressure. Specific spots were located to attach pressure gauge, to connect piping for guiding vapour to condenser and for the removal of char.

Analysis of heat required and selection of heating system : The total amount of heat energy required to heat, melt, boil, pyrolyze and vaporize 10 kg LDPE was calculated. The heat transfer rate required and the LPG fuel feed rate required were calculated. LPG stove was selected based on its calorific value and stove efficiency to meet our requirements. Water boiling test was done to determine stove efficiency. The plastic vapour production rate was thus calculated and was used later for the design of condenser.

2.2 Design of Condenser

Shell and tube condensers are employed for condensation of process vapours and are mostly used in the chemical process industries [8]. Shell and tube condenser with very slight inclination to horizontal was designed to be used in our experiment in order to facilitate proper support and for the liquid oil to flow naturally under the action of gravity for easy collection in the flask. The detailed design procedure for condenser has been given in table 4 in appendix.

All the 3D modeling and design of pyrolysis reactor, condenser and overall plant were done in Solidworks 2016.

3. Fabrication and assembly

3.1 Fabrication of Pyrolysis Reactor

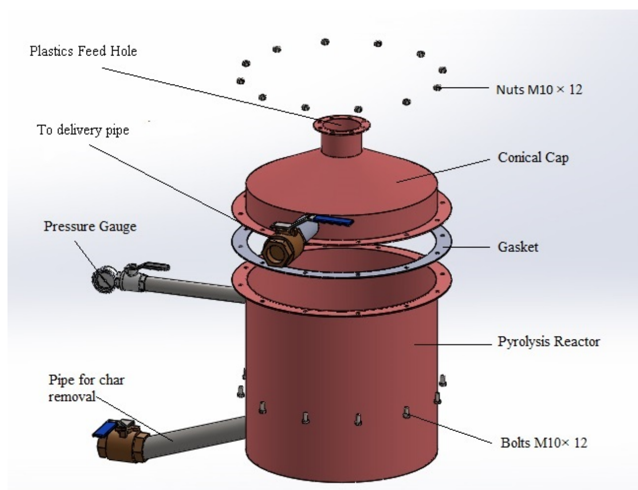

Figure 1: Pyrolysis Reactor

Scrap materials from the project done by Acharya et al. [9] were extensively used for fabrication of reactor and condenser. Locally available mild steel of thickness 3 mm was used for the fabrication of heads, shells and conical cap. Fabrication processes of cutting and welding were used [9]. Various specifications of pyrolysis reactor are listed in table 1.

Table 1: Specifications of Pyrolysis Reactor [9]

Specifications	Value
Outer Diameter	500 mm
Inner Diameter	494 mm
Height of reactor	476 mm
Capacity/Volume	91 liters (approx.)

Two locally available cast iron water pipes of diameters 1.5″ and 2.5″ were welded to the reactor, the former at height of 396 mm and the latter, just above the base. Ball valves were connected to each pipe [9]. The pressure gauge was installed in the former and the latter was used as a pathway for char removal. A water pipe of 2.5″ was also connected at the side of conical cap to allow plastic vapor to enter the condenser shell. Asbestos gasket and high temperature silicone were used to seal reactor and conical cap. Finally, nuts and bolts were used to connect them. Sensor of electronic temperature measuring instrument was inserted inside the reactor via feed hole.

3.2 Fabrication of Condenser

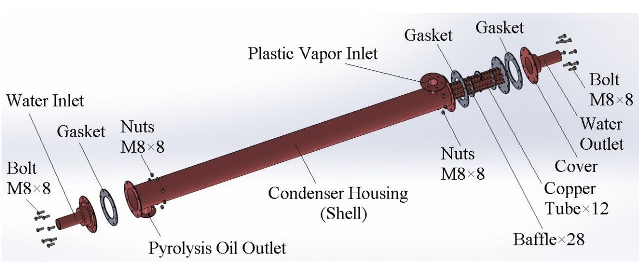

Figure 2: Condenser

Condenser shell, baffles and cover plate were made from mild steel [9]. The copper tubes were arranged in the tube sheet and then brazed to form tube bundle. Gaskets and high temperature silicone were used to seal cover plate and shell of the condenser. Various specifications of the condenser are enlisted in table 2.

Table 2: Specifications of Condenser [9]

Specifications	Value
Condenser type	Shell and Tube
Flow type	Counter flow
Shell side	Plastic Vapor
Copper tube side	Water
Copper tube size	Outer diameter = 12.7 mm
	Inner diameter = 10.92 mm
Tube length per pass	1.5 m
No. of passes	1
No. of copper tubes	12
No. of baffles	28
Baffle Spacing	52 mm

3.3 Assembly

The reactor and the condenser were connected via cast iron water tube of 2.5″ diameter. A locally available LPG stove was used as the heating source. Reactor was placed on the stove and a simple furnace made of bricks and mud was constructed on it. The final assembly of the plant is shown in figure 3.

Figure 3: Waste Plastic Pyrolysis Plant

4. Testing and Analysis

Two water boiling tests were conducted to calculate the efficiency of LPG stove. A known mass of water was boiled in pyrolysis reactor by supplying LPG fuel of known heating value. The ratio of theoretical heat absorbed by water to boil plus pyrolysis reactor itself and heat produced by burning total fuel actually consumed to boil water gave the efficiency of stove. The average efficiency of stove was found to be 51.3%.

Overall heat transfer coefficient of condenser was calculated using the data obtained from the experiment which was 25.326 $W/(m^2 \cdot K)$. The theoretical overall heat transfer coefficient calculated during design was 115.731 $W/(m^2 \cdot K)$. This difference might have been caused due to more fouling factors than expected, variation in water flow rate than design value, rust present in condenser, dissolved water in pyrolysis oil, wastes in the plastics used, etc.

Three experiments of converting waste LDPE into fuel were conducted. The plastics were obtained from a local plastic scrap dealer. First test yielded 6.1 liters of oil and 2.488 kg of char in the expense of 3.096 kg of LPG fuel in the total operation time of 5 hours and 28 minutes. Similarly, second test yielded 7 liters of oil and 2.016 kg char in 4 hours 44 minutes of the plant run. The third test yielded 6.8 liters of oil and 2.2 kg char in 5 hours 10 minutes. The oil collected is shown in figure 4. The actual performance of pyrolysis plant is given in table 5 in appendix.

It was found that the heating rate has significant effect in the oil production rate. Almost 900 ml of surplus oil was collected in the second experiment than that of the first one. Heating rate was drastically increased in the second experiment. Moreover, it was also found that without proper agitation mechanism, the plastics are more prone to be charred. Thus, it is inevitable to incorporate a proper agitator to ensure uniform heating of all the plastics.

4.1 Properties of Pyrolysis Oil obtained

Two samples of pyrolysis oil were tested at the central laboratory of Nepal Oil Corporation at Sinamangal, Kathmandu. The test results are enlisted in table 3.

Table 3: Properties of Pyrolysis Oil

Characteristics	Test Method	Sample 1	Sample 2
Density (@ 15°C, kg/m^3)	ASTM D1298	764.2	782.5
Kinematic Viscosity (@ 40°C, cSt)	ASTM D445	0.992	1.507

4.2 Burning Test of Pyrolysis Oil

A simple burning test was performed as soon as a sample of pyrolysis oil was obtained. 50 ml of sample was taken and simple *tuki*, as shown in figure 5, was made. It continued to burn for 1 hour and 16 minutes.

Figure 4: Pyrolysis Oil

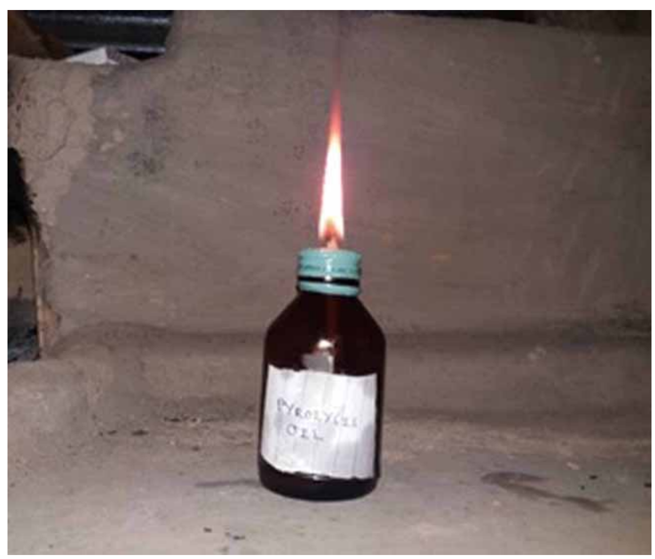

Figure 5: Tuki

5. Conclusions

The following conclusions can be deduced from the project.

- The existing technology and materials can be

utilized to construct waste plastic pyrolysis plant in Nepal.
- It is inevitable to incorporate a proper agitation mechanism in the pyrolysis reactor to ensure uniform heating of plastics. Otherwise, the plastics present at bottom can get charred while the plastics at above may remain unpyrolyzed.
- Appropriate heating rate has to be maintained in order to obtain a good yield of pyrolysis oil. A decreased heating rate does not give good yield of oil.
- On average, 2.236 kg of char and 6.63 liters of pyrolysis oil have been obtained from the pyrolysis of 10 Kg of waste LDPE in the cost of 3.169 kg of LPG gas.

6. Recommendations

- Further research on possibility of pyrolysis of other types of plastic like PET, HDPE, etc using locally available technology and materials can be done.
- Stainless steel should be used in place of mild steel in order to avoid rusting and for higher heat conductivity.
- Recirculation of excess gas to the furnace region can be done in order to conserve the fuel. Excess gases are the gases which the condenser is unable to condense but they are still flammable. Hence, they can be utilized as heating source.
- CFD simulation can be done for more accurate analysis.
- Use of stirring mechanism in pyrolysis reactor can increase the yield of pyrolysis oil.
- The properties of plastic pyrolysis oil like density, viscosity, etc can be improved by blending the oil with diesel. Hence, further study about diesel blended plastic pyrolysis oil can be done.

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Appendix

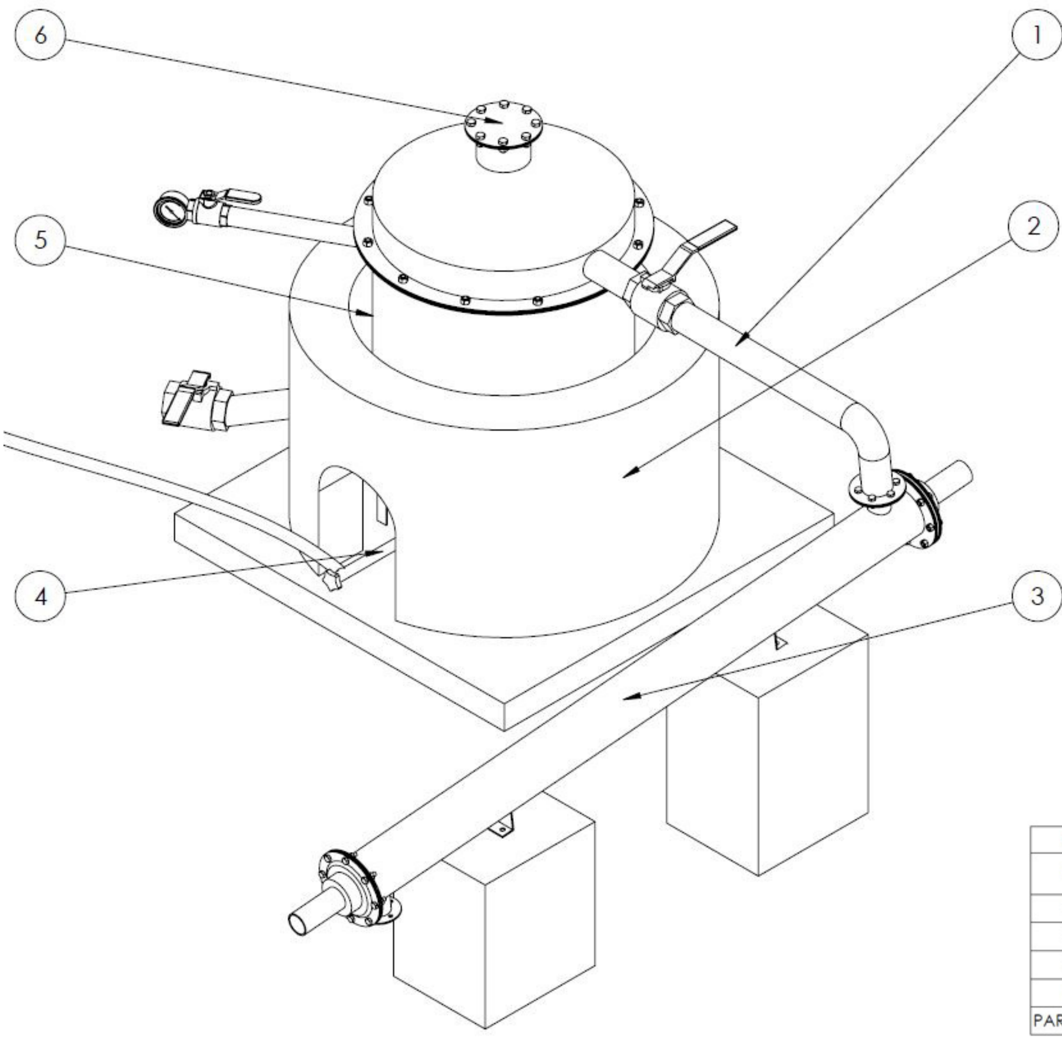
Table 4: Analysis of Design

Inputs	Calculations	Outputs
Internal Design Pressure, $P = 103425\ N/m^2$ Internal Radius, $r = 0.247\ m$ Allowable Stress, $S = 70\ MPa$ @ $850°F$ [10] Weld Joint Efficiency, $E = 70\ \%$ for butt joints [10]	**Design of Reactor** Thickness of Reactor Shell, $t = \frac{P\times r}{S\times E - 0.6\times P}$ [11]	$t = 0.522\ mm$. Considering the safety factor, the calculated thickness of reactor shell has been increased to 3 mm. Hence, $t = 3\ mm$
Heating value of LPG per kg, $Q_{Hv} = 46100\ kJ/kg$ Specific heat capacity of LDPE, $C_p = 2100\ J/(kg\cdot K)$ Specific heat capacity of water, $C_w = 4187\ J/(kg\cdot K)$ Average value of heat of fusion of LDPE, $L_f = 29\ cal/g$ [12] Heat required for pyrolysis plus vaporization of 1 kg liquid PE $= 1047.62\ kJ$ [13] LPG Stove Efficiency $= 51.3\ \%$ Latent heat of vaporization of LDPE $= 180.46\ kJ/kg$ [13] Assumed time for complete pyrolysis $= 3\ hr$ $D_o = 12.7\ mm$, $D_i = 10.92\ mm$, $L = 1.5\ m$, $k_{tube} = 400\ W/(m\cdot K)$ Viscosity of water, $\mu_w = 855\times 10^{-6}\ (N\cdot s)/m^2$ Thermal conductivity of water, $k_w = 0.613\ W/(m\cdot K)$ Assumed temperatures: Ambient temperature, $T_a = 25°C$ Vapor inlet, $T_{oi} = 450°C$ Oil outlet, $T_{oo} = 50°C$ Water inlet, $T_{wi} = 25°C$ Water outlet, $T_{wo} = 45°C$	**Design of Condenser** [8, 9] Heat taken by 10 kg solid plastics till it starts melting at $110°C$, $Q_1 = m\times C_p\times \Delta T = 1785\ kJ$ Heat required to completely melt 10 kg plastics at $110°C$, $Q_2 = m\times L_f = 1213.65\ kJ$ Heat taken by 10 kg liquid plastics till it reaches $450°C$, $Q_3 = m\times C_p\times \Delta T = 7140\ kJ$ Heat required for pyrolysis, $Q_4 = 10\times 1047.62 = 10476.2\ kJ$ Total heat required, $Q = 20614.85\ kJ$ Take 21000 kJ Heat transfer rate required $= \frac{\text{Total heat required}}{\text{Time taken}} = 7000\ kJ/hr$ Plastic vapor production rate $= \frac{\text{Heat transfer rate}}{\text{Latent heat of vaporization}} = 38.7898\ kg/hr$ Mass flow rate of oil vapor, $\dot{m}_o = 38.7898\ kg/hr = 10.775\times 10^{-3}\ kg/s$ Heat load in condenser, $q = (\dot{m}_o C_p \Delta t)_{oil} = 10.775\times 10^{-3}\times 2100\times (450-50) = 9050.953\ J/s$ For safe design, $q = 10\ kJ/s$ Mass flow rate of water, $\dot{m}_w = \frac{q}{C_w(T_{wo}-T_{wi})} = 429.902\ kg/hr$ Calculation of Logarithmic Mean Temperature Difference (LMTD) [8] $\Delta T_1 = T_{oi} - T_{wo} = 405°C$ $\Delta T_2 = T_{oo} - T_{wi} = 25°C$ $LMTD = \frac{\Delta T_2 - \Delta T_1}{ln(\Delta T_2/\Delta T_1)} = 136.445°C$ Correction Factor, $F = 0.882$ Corrected LMTD, $\Delta T_m = F\times LMTD = 120.344°C$	Condenser is designed for vapor flow rate of $38.7898\ kg/hr$

	Design overall heat transfer coefficient, $U_D = 269.717\ W/(m^2 \cdot K)$ [8] Heat transfer area, $A = \frac{q}{U_D \times \Delta T_m} = 0.308\ m^2$ Number of tubes, $n_t = \frac{A}{\pi \times D_0 \times L} = \frac{0.308}{\pi \times 12.7 \times 10^{-3} \times 1.5} = 5.146$ Choose $n_t = 8$ and check if $U_D \geq U_{req}$ $A = n_t(\pi \times D_0 \times L) = 8 \times (\pi \times 12.7 \times 10^{-3} \times 1.5) = 0.479\ m^2$ $U_{req} = \frac{q}{A \times \Delta T_m} = 173.476\ W/(m^2 \cdot K)$ Determine U_D using Nusselt's Theory [8] Mass flow rate through each tube = $\dot{m}_{pertube} = 0.015\ kg/s$ Reynolds number = $\frac{4\dot{m}_{pertube}}{\pi \times D_i \times \mu_w}$ [8] $Re = 2045.562$, $Re < 2300$, flow is laminar $N_u = 3.66$ [14], $N_u = \frac{h_i \times D_i}{k_w}$ Convective heat transfer coefficient inside tube, $h_i = 205.456\ W/(m^2 \cdot K)$ Condensing-side heat transfer coefficient, $h_0 = 1.52[\frac{k_l^3 \rho_l^2 g}{4\mu_l \tau}]^{1/3}$ where $\tau = \frac{\dot{m}_o}{L(n_t)^{2/3}}$ [8] $\tau = 1.796 \times 10^{-3}\ kg/(m \cdot s)$ $h_0 = 3887.425\ W/(m^2 \cdot K)$ Clean overall coefficient, $U_C = [\frac{D_0}{h_i D_i} + \frac{D_0 \ln(\frac{D_o}{D_i})}{2k_{tube}} + \frac{1}{h_0}]^{-1}$ [15] $U_C = 168.92\ W/(m^2 \cdot K)$ $R_{D_0} = 0.0009\ (m^2 \cdot °C)/W$ [15] $R_{D_i} = 0.0004\ (m^2 \cdot °C)/W$ [15] Total fouling allowance, $R_D = \frac{R_{D_i} D_0}{D_i} + R_{D_0} = 0.00137\ (m^2 \cdot °C)/W$ Design overall coefficient, $U_D = (\frac{1}{U_C} + R_D)^{-1}$ $U_D = 137.175\ W/(m^2 \cdot K)$ $U_D < U_{req}$ Similarly, 2^{nd} iteration: n_t = 10, $U_D < U_{req}$ Similarly, 3^{rd} iteration: n_t = 12, $U_D > U_{req}$ Condenser is thermally suitable for n_t = 12	Number of copper tubes to be used in condenser = 12

Table 5: Actual Performance of Pyrolysis Plant

Particulars	Test 1	Test 2	Test 3
Mass of plastics used (kg)	10	10	10
Total oil production	6.1 liters (4.697 kg)	7 liters (5.39 kg)	6.8 liters (5.236 kg)
Total char production (kg)	2.488	2.016	2.2
Total water obtained (liters)	0.880	0.850	0.550
Fuel consumption LPG (kg)	3.096	3.286	3.125
Estimated amount of gas formed (kg)	1.935	1.744	2.014
Time of operation	5 hrs 28 mins	4 hrs 44 mins	5 hrs 10 mins



PART NO.	PART NAME	QTY.
6	Pyrolysis Reactor Cap	1
5	Pyrolysis Reactor Assembly	1
4	LPG Gas Stove	1
3	Condenser Assembly	1
2	Furnace	1
1	Delivery Pipe	1

Figure 6: 3D Model of Waste Plastic Pyrolysis Plant