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Research Article

Harnessing Conventional Fuel Production Using Solar-Actuated Pyrolysis Reactor from Waste Plastics in Developing Countries

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It is estimated that only about 10% of the 9 billion tonnes of plastics being produced is being recycled. Its abandonment after use in the environment has enormously contributed to flooding, loss of aquatic lives and gives an unsatisfying look to the environment. In a means to sanitize the environment, polymer wastes undergo series of recycling processes of which pyrolysis, which is the thermal conversion of plastics into conventional fuel without the presence of oxygen is being done. Although this is very recommending, it requires a lot of energy to achieve which hinders developing countries from actively participating due to their low power generating capacity. Hence, this paper looks at the possibility of performing the pyrolysis reaction of waste plastics in developing countries using the solar energy. The actuation was achieved by a concentrated radiation from the sun and backed up with flue Pyrolysis Gas when required. A process flow configuration which involves the reactor, solar lenses, vacuum pump, solar panel, inline components and the condenser is set up to perform the thermal gasification and condensation of waste plastics in the reactor. Computationally, finite element analysis (FEA) was done to see the thermodynamic effects inside and outside the reactor for effective pyrolysis oil production. Once successfully built, this will act as a model to aid environmental sanitation and creation of jobs in developing countries.

Introduction

Plastic waste has become a large concern in the world which has caused many havocs beyond measures. This is followed with the fact that most countries do not have the capacity to recycle its own plastic wastes. The Gurdian new paper records in july 2018 that the UK's recycling rate hits a stagnating 44% of which others are being dumped in sites along Turkey to Malaysia pathway [1]. In South Africa, the recycling activities has increased reaching almost the standards of the United Kingdom of which 41.8% according to the National plastics recycling survey in 2016. But all these are for emerging societies which have the required facilities and technologies to drive them. In developing countries like Nigeria with a large population base that lacks the required technologies and utilities to drive waste plastic processes could be more disadvantage to their economy, the people and the environment. According to National Geographic, the rise in the Lagos population is estimated to be around 24 million which is estimated to increase at a rate of about 500,000 per year [2]. Records shows that Lagos generates about 600,000 metric tons of plastic wastes per year having more than 16.7% of this figure into the ocean [2]. Other places for waste disposal can be seen in rivers, beaches, streets, drainages, slums and across homes.

Handling these challenges can only be confronted with recycling as a way out but has also been hampered by the technicalities involved in setting up a commercial recycling plant in developing countries. Factors include available power, assess to energy, capital intensiveness, high operating costs, availability of feed materials, technical know-how, governmental constrains and potential hazards all constitutes to the poor recycling rates in developing countries. Another challenge can be seen in the selectibility of plastics types when recycled into pellets. Small plastic wrappers like indomine wrappers, films and bags require a different technology from the conventional recycling programs available [3]. It is advised that the best approach that can accommodate the recycling of different types of plastics at the same time is through the use of pyrolysis. Pyrolysis is a process of thermochemically decomposing carbon-based products without the presence of oxygen to produce fuel or chemical substances [4]. Even though the process shows promising end points, developing countries are still no ready to engage in this technology. Hence, this paper aims to initiate the pyrolysis reaction using solar energy for developing countries and then re-igniting the intermediate product (Pyro-gas) for thermal stabilization in the reactor. The choice of using solar is due to the high solar irradiation experienced across Nigeria ranging from the mean monthly global solar radiation of 22.88MJ/m2/day (6.35KWh/m^2), 18.29MJ/m2/day (5.08 KWh/m^2) and 17.08MJ/m2/day (4.74 KWh/m^2) for high, medium and low zones in Nigeria respectively at an average time period of 12 hours per day [5]. It is believed that with the aid of spot lenses (solar concentrators) which is aimed at reflecting the image of the sun at a focal point (desired area), the intensity would be amplified to cause a large amount of heat transfer due to radiation on the surface of the pyrolysis reactor.

Materials and Methods

The materials to be used in achieving the entire process comprises of both some static and rotating equipment's which are fashioned in a process.

The solar concentrator (spot lens)

The solar concentrator is either a glass or plastic reflecting mirror which reflects the sun's image on a designated surface area. This works

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by concentrating all the rays towards a focal point thereby increasing the solar flux density. The concentration ratio from the lens is given by the ratio of the rate of useful energy available at the absorber/receiver (A_r) to the beam energy incident on the aperture (A_a). It is given by

$$c = \frac{A_a}{A_r} \quad (1)$$

From figure 1, a circular solar concentrator with aperture area A_a and receiver/absorber area A_r, along with sun's view having a radius r at some distance R. For a seamless solar concentrator, the radiated beam from the Sun on the aperture is a ratio of the solar radiation that is emitted by the Sun and that is intercepted by the aperture area Aa. The radiation from the Sun to the aperture can be expressed as:

If a lens with an aperture radius r and a focal length f is being applied, then the image of the casted sunlight applied from infinity will likely appear at some distance f from the lens. The angular separation, α, between the two points of the object will be the same as the angle between the images of two points in the focal point seen from a distance f. Thus, the area of the casted sunlight is given by $\pi\alpha^2 f^2$

where α -the angle between the centre of the object (assumed to be spherical) and the edge. This is assumed to be a small angle of about 1-2°. If the sun, has a radius of R, a temperature of T and is a distance d away, then the flux of radiation reaching the lens is:

$$F = \sigma T^4 (R/d)^2 = \sigma T^4 \alpha^2 \quad (2)$$

where σ is the Stefan–Boltzmann constant.

The total power of the radiation that enters the lens P is the area of the lens times the flux:

$$P = \pi r^2 F = \pi \sigma T^4 \alpha^2 r^2 \quad (3)$$

This power ends up heating the area of the image in the focal plane. The flux of radiation there is:

$$F_{im} = \frac{P}{\pi \alpha^2 f^2} = \alpha T^4 \frac{r^2}{f^2} \quad (4)$$

Suppose $\sigma T_{im}{}^4 = F_{im}$ then that you put a black body in the image plane, then the temperature there would be T_{im} where therefore:

$$T_{im} = \sqrt{\frac{r}{f}} T \quad (5)$$

According to the World Book Encyclopedia, the sun's surface or photosphere is about 340 miles thick and its temperature about 5,500 °C and using the Stefan's Boltzmann constant is 5.67×10^{-8} with a static lens of area of 1m^2 and a focal length 75mm

$$F = \alpha T^4 \left(\frac{R}{d}\right)^2 = \alpha T^4 \alpha^2 \quad (6)$$

Also, when you focus light from the Sun you are actually creating an image of the Sun. If the focal length of the lens is f the radius of the image is given by:

$$r = \frac{r_s}{d} \quad (7)$$

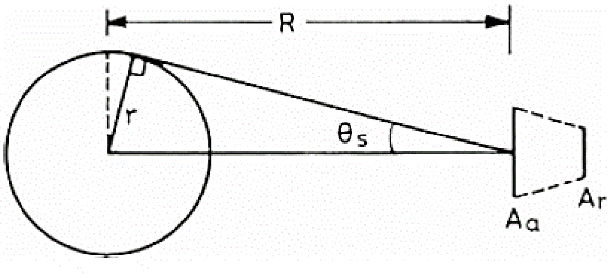

Figure 1: Solar concentrator with aperture receiving energy from sun.

where d_s is the distance to the Sun and r_s is the radius of the Sun. The fraction $r_s/d_s \approx 10^{-3}$ so if you choose a lens with a focal length of 10cm the radius of the image is about 0.1mm (assuming the lens is perfect). The intensity of sunlight is around 1kW/m^2 around the world but varies in Nigeria, the exact value depends on latitude, season, time of day, cloud cover, etc. All the light falling on your lens is being concentrated into the radius image of the Sun, so if the radius of your lens is rl the power per unit area in the image is:

$$I = \left(\frac{r_i}{r}\right)^2 . I_s \quad (8)$$

The Reactor

This is where the pyrolysis reaction takes place using heat transfer models to initiate the thermal decomposition of the waste plastics. This reactor is made out of stainless steel because of its rust-free chacterersitics as well as its high conductivity. The base of the reactor is painted dull black so as to absorb almost all the radiant light from the lens. Through conduction, heat is transferred to the waste plastics which collects heat energy via the latent heat of fusion and vaporization to change the state of the waste plastics to vapor. The energy through radiation per time taken is expressed as:

$$q = \varepsilon\sigma\left(T_h^4 - T_C^4\right) A_c \quad (9)$$

where

T_h = the abosolute temperature of the hot body (K)

T_c = the abosolute temperature of the cold receiving body (K)

A_c = area of the object (m^2)

The heat ttransfer from the base of the reactor to the waste plastics inside the reactor is governed by the expression:

$$Q = -kA\left(dT/dx\right) \quad (10)$$

where,

'Q' = heat flow rate by conduction (W)

'k' = thermal conductivity of body material (W·m^{-1}·K^{-1})

'A' = cross-sectional area normal to direction of heat flow (m^2) and

'dT/dx' = temperature gradient (K·m^{-1}).

Now inside the reactor where the molecules are gaining heat and vaporizing, the difference in densities causes a circular motion exhibited by the convection heat transfer. The expression is as stated in (10)

$$Q = hA\left(T_a - T_b\right) \quad (11)$$

Vacuum Pump

The essences of the vacuum pump is to reduce the pressure inside the reactor so as to enable quicker boiling rate experienced by the melting of the plastics in the transition from soiled to liquid phase. Once pressure is reduced to vacuum, the set temperature where plastics melts and tends to vaporized is forced to reduced. Hence, the vacuum pressure P_v can be stated as:

$$P_v = Pa_i - Pa_o \quad (12)$$

where

Pa_i = absolute pressure inside the vessel

Pa_o =absolute pressure outside the vessel

The vacuum pump is operated at a 12volts source that exerts an amount of pressure per seconds at 8 amperes of current. The hose whose cross-section is circular of which its lateral dimensions are much smaller than the total length. To determine the throughput across the hose is related to the pressure gradient by the expressed:

$$Q_x = \frac{8}{3\pi^{1/2}}\left(\frac{2KT}{m}\right)^{1/2}\frac{A^2}{s}\frac{dP}{dx} \qquad 13$$

Condenser

The condenser uses a direct contact of the pyro-gas with water. This occurs in a bubbling state where the gas is allowed to bubble into the water. At this stage, latent heat is released from the pyro-gas and absorbed into the water body. Hence, for an ideal single-pass condenser having its coolant with a constant density, constant heat capacity, linear enthalpy over the temperature range, perfect cross-sectional heat transfer, and zero longitudinal heat transfer, and whose tubing has constant perimeter, constant thickness, and constant heat conductivity, and whose condensable fluid is perfectly mixed and at constant temperature, the coolant temperature varies along its tube according to:

$$\Theta(x) = \frac{T_H - T_x}{T_H - T_0} = e^{-NTU} = e\frac{-hp_x}{mc} = e^{-\frac{G_x}{mcL}} \qquad 14$$

where:

- x = the distance from the coolant inlet;
- $T(x)$ = the coolant temperature, and $T(0)$ the coolant temperature at its inlet;
- T_H = the hot fluid's temperature;
- NTU = the number of transfer units;
- m = the coolant's mass or mass flow rate;
- c = the coolant's heat capacity at constant pressure per unit mass (or other);
- h = the heat transfer coefficient of the coolant tube;
- P = the perimeter of the coolant tube;
- G = the heat conductance of the coolant tube (often denoted UA);
- L = the length of the coolant tube.

Solar Panel

The solar power is the source of energy which converts light energy into electrical energy. Solar panels technically called photovoltaic (PV) cells convert the rays from the sun into electricity by raising the excitation level of electrons in silicon cells using the photons present in light that originates from sun light. It is from the solar panel that aids in powering the vacuum pump which changes the condition of the reactor.

Other components include the inline comments: valves, gauges, structural components and clips for regulating, measuring, platform casing and firm grip of inter-connecting hoses respectively. The process involves crushed plastics (pellets or crushed with a mechanical crusher) to be inserted into the reactor at a pre-determined weight. A solar panel converts light energy into electricity which is used to power the vacuum pump at a current of 8A. The vacuum pump then reduces the pressure below the atmospheric pressure aiding the boiling rate of the plastic pellets. With a direct focus of lens on the base of the reactor, heat is being transferred through radiation, raising the temperature of the reactor to about 855°C as described by Stephen et al [6]. This raises the temperature of the waste plastics, changing them to vapors and pressurizing the reactor. This pyro-gas is then charged into the reactor to experience a sudden drop in temperature, releasing latent heat and converted into liquid. The condenser liquid (water) gains a sufficient amount of heat and starts raising its temperature up [7-9]. This liquid (pyro-oil) being produced exhibits characteristics of hydrocarbons which has similar behaviors as diesel fuels. The figure can be shown in Figure 2 where all the assembly of components are displayed.

The reactor design is being initialized using the Comutaional fluid dydnamics (CFD) apprach wbich involves designing the reactor 3D model using the Autodesk Inventor software. The model is then exported using the STEP file into Ansys (Fluent) software. The model was meshed using the tetrahedron mesh type with a minimum size of 8.2778e-005 m. A total of 25088 nodes and 129900 elements.

Result and Discussion

Calculating the Solar flux from the lens to the base of the reactor, it is clear that there is an amplification of the solar irradiation approaching the reactor which results to an increase in the temperature of the base reactor. The solar lens of 1m^2 and focal length of 75cm was used to increase the solar irradiation from 2.25 KW/m^2 in areas of Port Harcourt (Nigeria) reaching the reactor to about 380.7KW/m^2 and an estimated temperature of 855.38°C. Table 1.

The interior of the reactor exhibits an internal temperature of 467°C, which is enough to perform the pyrolysis reaction. A back flow of temperature occurs at the outlet due to turbulent fluxes occurring. Figure 3.

The density was checked of the pyro-oil which was about 1154 kg/m^3. This happens to be denser than the conventional fuel oil and also denser than the density of the waste plastics. The higher heating value (HHV) attained in the pyrolysis process was at 23.4MJ/l as compared to fossil fuel estimated around 37 MJ/l. The oil does not readily mix with hydrocarbons due to the large number of oxygenated components existing as part of the pyro-oil. The water content present in the singled-phase oil was 16wt.%. Other properties of pyro-oil were experimentally attained. Table 2.

Conclusion

The products that were obtained from the process were Liquid (pyro-oil), solid (char), and Gas (pyro-gas). This was obtained from a solar-actuated pyrolysis reactor where solar energy was concentrated

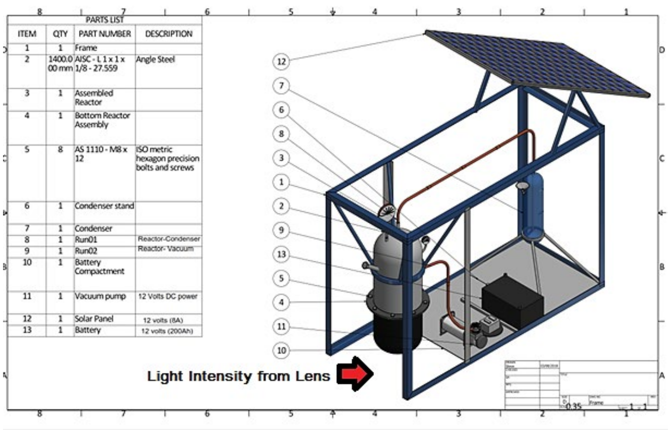

Figure 2: Assembly of the mini- solar-actuated pyrolysis plant.

Table 1: Solar irradiation and temperature amplification via solar concentration.

Is(KW/m2)	2.25
f (mm)	750
r (mm)	0.75
rl (mm)	56.4
I_{im}	380.7
Stefan B	5.76E-08
T_{im}	855.384454

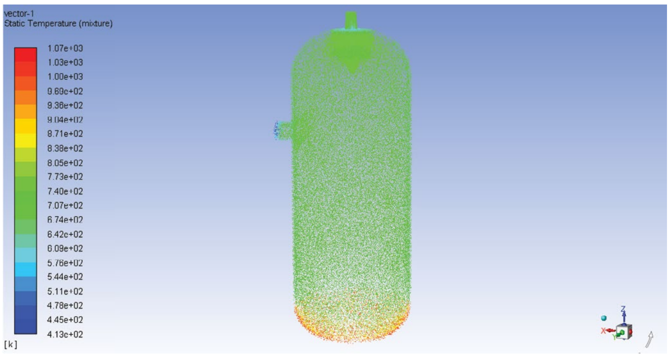

Figure 3: Temperature distribution of the Pyrolysis reactor.

Table 2: Solar irradiation and temperature amplification via solar concentration.

Property	**Unit**	**Value**
C	wt%	46
H	wt%	7
N	wt%	< 0.01
O (Balance)	wt%	47
Water content	wt%	25
Ash content	wt%	0.02
Solids content	wt%	0.04
Density	kg/Ltr	1,2
LHV	MJ/kg	16
LHV	MJ/Ltr	19
pH	-	2.9
Kinematic viscosity (40 °C)	cSt	13

to act as the heating source for the pyrolysis reaction. Computationally (using CFD), it was attained that the inside temperature of the reactor was stipulated at 467°C which is enough to perform pyrolysis. The liquid part of the pyrolysis products contains about 80% per kg of waste plastic processed which also contains a some organo-oxygen compounds. The pyro-oil is of the greatest interest because of its direct application to engines that can power the transportation sector or its diversity when refined in a distillation column. The higher heating value (HHV) obtained of the pyro-oil is 23.4 MJ/kg. The liquid density of pyrolysis oil is 1,154±200 kg/m^3, as compared to 800–1,000 kg/m^3 as obtained in petroleum products for low - high fuel oils.

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