

Design and Development of an Infrared Heater For Waste Plastic Gasification

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Abstract— This paper outlines the design, manufacture and analysis of a far infrared ceramic heater for plastic gasification purposes. The study includes the theoretical overview of the mathematical modelling of the far infrared ceramic heater. This study gives a novel energy conversion system of waste plastic materials. In this system, waste plastics are converted into gaseous fuel by gasification using infrared gasifier system. The derived gaseous fuels can then be used in fuel cell for purposes of electricity production. In this study two types of waste plastics (high density polyethylene, low density polyethylene) have been used as feedstock for the infrared gasifier. Analysis of the spectral properties of the waste plastics has been performed. Gasification of plastic waste as carbonaceous material, basic reactions during the gasification of plastics and gasification results has been analysed. The ceramic infrared heaters developed in this research are fully functional and all test results obtained are accurate to a very fair degree. The results obtained from the gasification experiment shows that using infrared heaters on gasification is practically sound because of significant advantages of infrared heating compared to the landfill and incineration. The work is intended to develop a low-cost ceramic infrared heater solution to be used in plastic waste gasification.

Keywords — Gasification, Infrared heater, Plastic waste, LabVIEW.

I. INTRODUCTION

The energy demand has been increasing, and the combustion of fossil fuel to cover energy demand is associated with serious environmental problems through the emission of CO₂. The researchers have been researching for clean and reliable energy source that could substitute fossil fuel. Hydrogen gas is clean fuel with no CO₂ emission used in fuel cell for electricity generation. It is valuable gas as clean fuel, it has high energy content, 122kJ/g [1], therefore, demand on hydrogen has increased considerably in recent years. Hydrogen production methods include electrolysis of water, steam reforming of hydrocarbons and auto-thermal process.

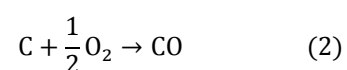
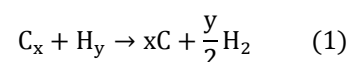
With the modern lifestyle, the consumption of plastics continues to increase every year and therefore the amount of plastic waste has also increased. Traditional ways of plastic waste disposal have been either to bury or burn them in landfill incinerators, respectively. Landfills and incinerations however are associated with serious environmental concerns.

There are different technologies such as gasification and pyrolysis which transform waste plastic to useful fuels or petrochemicals. One of these technologies is infrared radiation heating which is often said to be more efficient and cost effective. The use of infrared radiant heating in the gasification of waste plastic is performed because infrared radiation does not emit harmful fumes and do not require air movement [2]. This project is concerned with the use of infrared energy in the disposal of plastic waste.

II. BACKGROUND REVIEW

Waste plastics are one of the most promising resources for fuel production because of useful gases that it contains. Plastic recycling can be divided into three methods; mechanical recycling, chemical recycling and energy recovery. Chemical recycling which, converts plastic materials into useful chemicals have been recognized as an advanced technology process [3]. In recent years the gasification of plastics has been intensively conducted and some useful results have been seen in different studies [4], [5]. Two types of fuel-coal and polyethylene, were gasified in a 250mm across 3.4m high drop tube furnace, the study conclude that the gasification of coal has produce H₂, CO with concentrations of 15% and 25% respectively. Gasification is a process that converts carbonaceous materials such as plastic, coal and petroleum into carbon monoxide and hydrogen. The gas yield from the gasification process is called syngas. Equation 1 and 2 represent the raw material decomposition and reaction with oxygen during gasification.

A two-stage thermal gasification process for plastics has been studied and developed by Tashiro [6], [7]. Polyethylene (PE), polypropylene (PP) and polystyrene (PS) have been gasified using two stage thermal degradation. Plastics have been transformed to liquid and then to gas during gasification. A gasification process which converted waste plastics to synthetic gases (CO, H₂), at a high temperatures (over 1600K) has also been studied by Takatoshi [8].



III. METHODOLOGY

A. Overview of Methodology

The plastic samples were washed with hot water prior the gasification tests to remove dirt and any possible contaminants on the surface of the samples. Samples were also weighed using measuring scale to measure the mass of each sample before and after gasification. Samples of High density polyethylene (HDPE) and Low density polyethylene (LDPE) from municipal solid waste were collected and cut into $5\text{cm} \times 5\text{cm}$ squares.

The methodology used within this study;

- Mathematical modeling of an infrared ceramic heater
- Wavelength measurements of waste plastics using Fourier Transform Infrared Spectroscopy (FTIR).
The design of a data acquisition system to verify results.
- Using Quadrupole Mass Spectrometer 200 gas analyser for gas analysis.

IV. MODELLING AND DESIGN

The design of a ceramic infrared heater which has a surface temperature lower than 800°C shall be considered. The heater is made of a ceramic body with resistance wire (filament) embedded in it. A fibre blanket placed behind the filament to avoid heat loss from the back of the heater. Ceramic infrared heaters are designed to emit wavelengths in the far infrared range at certain operational temperatures. As voltage is applied, a current and resistive loss in the filament that translates to heat build-up. The higher the temperature the higher the filament resistivity, with a reduction in the amount of current and power consumed. The rise in filament temperature results in heat transfer by means of conduction to the ceramic body and then radiation to the environment. The passage of electric current through the filament when voltage is applied is given by

$$i(t) = \frac{U}{R}(1 - e^{k_1}) + c_2 e^{k_2} k_{1,2} = -\frac{1}{2RC} \left[1 \pm \sqrt{1 - \frac{4CR^2}{L}} \right] \quad (3)$$

Where c_2 is constant.

$$k_1 = R/L$$

$$k_2 = -1/RC + R/L$$

Where U is energy storage.

The mechanism involved in the heat transfer in ceramic heaters is conduction from the filament to the ceramic body. A

Fourier equation can be used to calculate the rate of heating and cooling of the heater:

$$T = T_1 + (T_0 + T_1)e^{-\frac{2Na_0^2}{r_0}} \quad (4)$$

Where ($a = c_p \lambda$).

Where T, T_0, T_1 are the running temperature of the surface of the heater after the time t , the initial temperature of the heater, and the temperature of the medium respectively, a is the diffusivity, equal to the product of the heat capacity of the heater, its density and the thermal conductivity of the insulating sheath, N is the heat transfer coefficient characterizing heat exchange with the medium, r is the depth of penetration of the heat pulse. The heating element reliability and stability are determined by the extent to which the heater remains constant over its service life. The relation in equation (5) describes the rate of degradation.

$$\xi = \xi_0 \exp\left[-\frac{Q}{RT}\right] \quad (5)$$

Where ξ_0 is a constant dependent on the composition and method of production of the material of the conducting phase, the electrical insulator, or the casing, Q is the energy of activation of the aging process, which depends on the ambient conditions and the thermo-mechanical stability of the material of the heater, T is the working temperature of the heater.

A. Energy Balance

Energy balance is when the rate at which energy is transferred from the heater surface to the surface of the target is equal, given mathematically as follows:

$$E_{\text{out}} - E_{\text{in}} = 0 \quad (6)$$

Considering ceramic heaters as having a resistance wires of diameter D and length L initially at thermal equilibrium with the ambient air and its surroundings, this equilibrium condition is only distributed when an electric current I is passed through the wire. An equation that could be used to compute the variation of the wire temperature with time during the passage of the current is developed using the first law of thermodynamics, often used for determining unknown temperatures. Relevant terms involve heat transfer by radiation from the surface of the heater, internal energy generation due to electrical current passage through the wire, and a change in internal energy storage. For determining the rate of change of temperature and applying the first law of thermodynamics to a system of length L of the wire, it follows that:

$$E_g - E_{\text{out}} = E_{\text{st}} \quad (7)$$

Where the energy generation due to the electric resistant heating is given by:

$$E_g = I^2 R_e L \quad (8)$$

Energy outflow due to net radiation leaving the surface is given by:

$$E_{out} = \epsilon \sigma (\pi D L) (T^4 - T_{sur}^4) \quad (9)$$

The change of energy storage due to the temperature change is:

$$E_{st} = \frac{dU}{dt} = \rho c V \frac{dT}{dt} \quad (10)$$

Where ρ and c are the density and specific heat, respectively of the wire material and V is the volume of the wire $V = \left(\frac{\pi D^2}{4}\right) L$

Substituting the rate equations into the energy balance, it follows that:

$$I^2 R_e L - \epsilon \sigma (\pi D L) (T^4 - T_{sur}^4) = \rho c \left(\frac{\pi D^2}{4}\right) L \frac{dT}{dt} \quad (11)$$

Hence the time rate of change of the wire temperature is:

$$\frac{dT}{dt} = \frac{I^2 R_e L - \epsilon \sigma (\pi D) (T^4 - T_{sur}^4)}{\rho c \left(\frac{\pi D^2}{4}\right)} \quad (12)$$

The heat transfer is defined as one dimensional conduction in the reflector which itself is considered as an opaque body. The equation in the reflector is defined as:

$$\frac{\partial T_r}{\partial t} = \frac{K_c}{\rho C_p} \frac{\partial^2 T_r}{\partial x^2} \quad (13)$$

Since there is an insulation blanket, the boundary condition at the back of the heater is:

$$\frac{\partial T_r}{\partial x} = 0 \quad (14)$$

The boundary conditions at the front surface of the heater involve radiation and it is represented as follows:

$$-K_c \frac{\partial T_r}{\partial x} = \epsilon \sigma A (T^4 - T_{sur}^4) \quad (15)$$

V. TESTING AND MEASUREMENTS

Testing of the manufactured heaters has been conducted by connecting the heater leads to the wall socket, which normally gives 220 to 230 volts, and the temperature sensor has been mounted in front of the heater to sense the temperature of the heater surface. The maximum values of temperature recorded were as follows: 187.8 °C and 234.9°C. "Table 1" shows the manufactured heaters specifications including temperatures and calculated wavelength.

The wavelength of the manufactured heaters is calculated using Wien's displacement law. The wavelength of the emitter is inversely proportional to the temperature, and is given by:

$$\lambda_{max} T = 2897 \mu\text{m} \cdot \text{K} \quad (16)$$

Where b is a constant.

Different samples of plastic waste have been tested in terms of absorptivity and transmittivity in order to determine the exact wavelengths at which high density polyethylene, low density polyethylene, teraphthalate perfectly absorb infrared radiation. The results showed that the absorption of the infrared radiation by any sample of plastics strongly depends on the thickness of the sample: the thinner the sample the better and stronger the absorption, while the opposite also held true - the thicker the sample the poorer the absorption.

Transmittance measurements of LDPE and HDPE using FTIR spectroscopy were conducted and the results are shown in "Fig. 1 and 2". A sample wavelength measurement was implemented to determine the infrared absorption wavelength of LDPE and HDPE. Peak absorption values shown in "Table 2" were calculated after conversion from cm^{-1} to μm .

TABLE 1
 MANUFACTURED HEATER SPECIFICATIONS

Parameter	Heater 1	Heater 2
Size (mm)	265×198	216×122
Typical operating temperature	187.8	234.9
Wavelength (μm)	6.2	5.70

TABLE 2
 MEASURED WAVELENGTH VALUES

Sample	Measured Peak Value Absorption Wavelengths (μm)		
LDPE	3.3	6.6	12
HDPE	3.3	4.5	6.6

VI. GASIFICATION OF PLASTICS

The manufactured ceramic infrared heaters were carefully placed inside the gasifier before establishing the electrical connections. The input voltage to the gasifier was 230 volts and the rated current was 4.2A. The gasification tests then conducted on each sample separately.

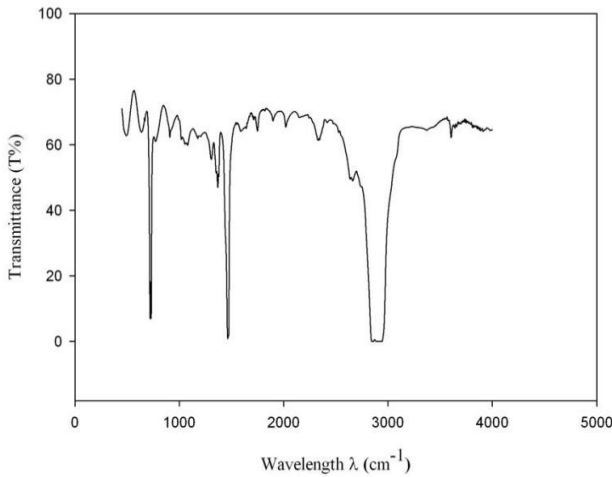


Fig 1: Transmittance spectrograph of LDPE

A. Sample Preparation

The plastic samples were washed with hot water prior to the gasification tests to remove dirt and any possible contaminants that stick on the surface of the samples. Samples were also weighted using measuring scale to determine the mass of each sample before and after gasification, “Table 3” shows the measured mass of samples.

TABLE 3
MASS OF SAMPLES

Sample	Mass (grams)
LDPE	153.9
HDPE	190.05

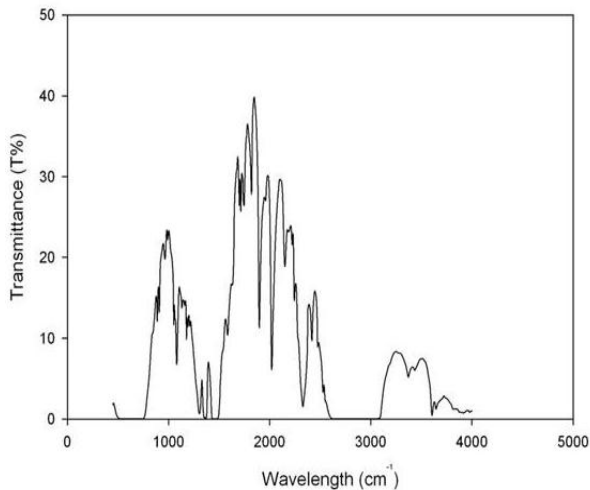


Fig 2: Transmittance spectrograph of HDPE

VII. RESULTS

In order to test and validate the manufactured ceramic infrared heaters for the gasification process and the production of

syngas, gasification experiments were conducted. The infrared gasifier was left for 20 minutes to reach an operating temperature of 457 °C. The gasifier was heated to reach temperature of 457 °C before feeding the samples to the gasifier. After feeding the LDPE sample and during the gasification, the emission of gases started after 10 seconds. Gases continue to yield for 12 minutes before it stops completely, results of gasification tests are shown in “Table 4” below. The temperature measurements inside and outside the gasifier and the temperature of the samples during gasification were performed using a Fluke Ti20 (Thermal imager). The total gas yield of LDPE and HDPE were 96.7wt% and 95 wt% each at a temperature of 457 °C. The formation of carbonaceous residue or coke was 3.3wt%, 5.2wt% for LDPE and HDPE respectively. After taking all the plastic samples, the test run is considered finished and the gasification then concluded.

TABLE 4
GASIFICATION RESULTS

Sample	Mass (a) (Grams)	Duration (Minute)	Mass (b) (Grams)	temperature (°C)	yield Wt %
LDPE	153.9	10	5.06	457	96.7
HDPE	190.5	12	9.95	457	95

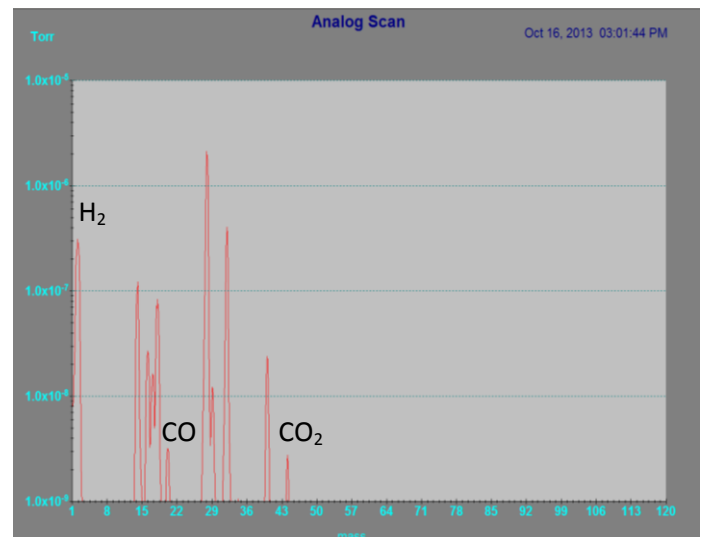


Fig 3: LDPE gas spectrum analysis

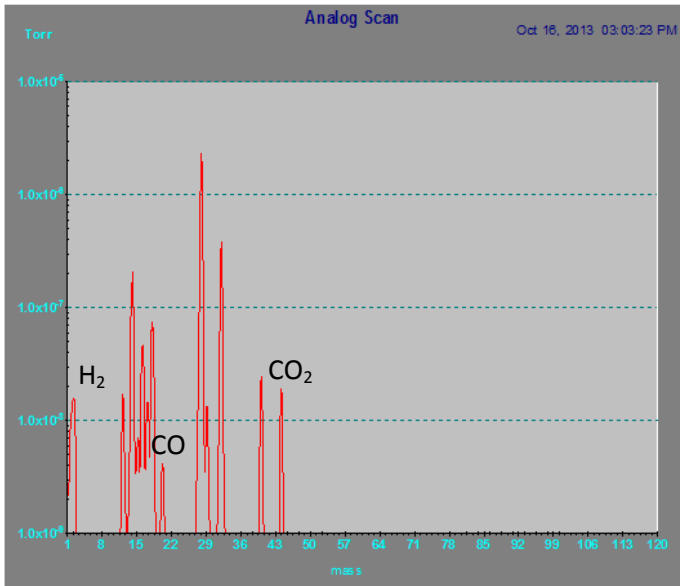


Fig 4: HDPE gas spectrum analysis

VIII. ANALYSIS OF RESULTS

The comparison of the wt% of coke residue and the wt% of the feed reveals the fact that the carbonaceous residue is very low, less than 5%, which makes the use of ceramic infrared heaters efficient. The plastics started react at 457°C, the wavelength emitted by the manufactured infrared heaters was successfully absorbed by the plastic samples. The short period gasification time of the plastic sample during gasification confirms the high thermal efficiency of the infrared gasifier and therefore the validity of infrared technology used in gasification of plastics. Whereas in this experiments the difference of gasification residence time between samples referred to the difference in the samples thickness. Gasification process shows that the amount of the produced gases increased when gasification temperature increased. Gasification results derived from this project were compared to other models (Toshiro, 2009) (Takatoshi, 2001). The comparison has shown that the production of syngas is comparable to models and the designed gasifier has low coke formation less than 5wt%. Gasification time and formation of residue needs further modification in the infrared gasifier compared to the two stage gasification procedures.

IX. GAS ANALYSIS

Quadrupole Mass Spectrometer 200 gas analyser was used to further analyse the resultant gas derived from the gasification of plastic samples. Analog scan mode has been chosen for analysis, it is the spectrum analysis mode common to all gas analysers. X-axis represents the atomic mass range chosen in the mass spectrometer. The Y-axis represents the amplitude of every mass increment measured.

Atmospheric scan inside the gasifier was performed and set as reference for any increase in gas yield. The experiments

concentrated in the production of H₂, CO and CO₂. Gases derived from the gasification of the two plastic samples then carefully injected to the gas analyser. Gas sample analyses have shown increase in hydrogen production for LDPE. Increase in CO₂ was also observed for HDPE. In all samples,

TABLE 5
 GAS ANALYSIS RESULTS

Sample	Gasification temperature (°C)	H ₂ production	CO production	CO ₂ production
LDPE	457	Increased	No change	No change
HDPE	457	No change	No change	Increased

the production of CO stayed unchanged during the analysis. "Figure 1 and 4" shows the gas analysis of chosen samples, where "Table 4" summarises the gas analysis results.

X. CONCLUSION

Gasification results derived from this project were compared to other models, the comparison of the coke residue and the feedstock reveals that carbonaceous residue is very low, which makes the use of ceramic infrared heaters very efficient. The plastics reacted at 457°C because of the good match of the heaters wavelength and the absorption characteristics of the samples. The short gasification times of the plastic samples during gasification confirms the high thermal efficiency of the infrared gasifier and therefore the validity of infrared use in the gasification of plastics. In this experiment the difference in gasification time between samples referred to the difference in samples thickness. Gasification process shows that the amount of the produced gases increased when gasification temperature increased. The comparison has shown that the production of syngas is comparable to models and the designed gasifier has low coke formation less than 5wt%.

REFERENCES

- [1] M. Hamai, M. Kondo, M. Yamaguchi, G. Piao, Y. Itaya and S. Mori. "Gasification of organic waste materials for power generation using fuel cell", In environmentally conscious design and inverse manufacturing, pp. 103-106, IEEE., 2001.
- [2] K. Kathiravan and K. H. Kaur and S. Jun and I. Joseph and D. Ali, "Infrared heating in food processing: An overview", Comprehensive reviews in food science and food safety, Vol. 7, N. 1, pp. 2-13, 2008.
- [3] P. Martin, T. Norbert, J. Eberhard, W. Ernst, "Recycling of plastics in Germany", Resources, Conservation and Recycling Vol. 29, N. 1, pp. 65-90, 2000.
- [4] V. Cornelia, A. B. Mihai, K. Tamer, Y.J ale, D. Hristea, "Feedstock recycling from plastics and thermosets fractions of used computers II Pyrolysis oil upgrading", Fuel, Vol. 86, N. 2, pp. 477-485, March 2007.

- [5] K. Peter, M.A.Barlaz, R. P. Alix, A. Baun, A. Ledin, T. H. Christensen, "Present and Long-Term Composition of MSW Landfill Leachate: A Review", Critical review in environmental science and technology, Vol. 32, N. 4, pp. 297-336, 2002.
- [6] T. Tashiro, Yoshikitanaka, S. Toshiharu, U. Osamu, I. Hironori, "Two stage thermal gasification of plastics", Proceedings of the 1st ISFR, Tohoku University Press, Sendai, pp. 211-214, 1999.
- [7] T. Toshiro, H. Akito, "Gasification of waste plastics by steam reforming in fluidized bed", Journal of Material Cycle and Waste Management, Vol. 11, No. 2 pp. 144-147, 2009.
- [8] T. Shoji, K. Shindoh, Y. Kajibata, A. Sodeyama, "Waste plastics recycling by an entrained flow gasifier", Journal of Material Cycles and Waste Management, Vol.3, No.2, pp. 75-81, 2001.

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