Renewable Energy Assisted High Temperature Heating System for Plastic to Fuel Conversion Unit

K. R. Bharath*‡, Sarada Balaram**

* Department of Electrical and Electronics Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, India

** Department of Electrical and Electronics Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, India

(bharathkr@am.amrita.edu, saradabalaram@am.students.amrita.edu)

‡ Bharath K R, Dept. of EEE, Amrita School of Engineering, Amritapuri, Kollam, Kerala, India, 690525

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Abstract- Exponential rise in the use of automobile, electronic, electrical and Fast Moving Consumer Goods (FMCG) combines the presence of various grades of plastic materials along with them. This trend resulted in depleting the natural ecosystem of mother earth, as these plastic materials are dumped as landfills or reach water bodies, which in turn destroys the natural ecosystem, thereby backfiring a negative result to humans. Pyrolysis is a technique that can be used for converting such plastic materials into inflammable fuels. But this mechanism is an energy-intensive method, which makes this technique of fuel generation out of reach from the commercial space. In order to tackle this issue, high heat demanded for the pyrolysis process is harnessed from renewable sources, thereby limiting the need of an external entity for sourcing the initial heat demand. This paper proposes a method that can be used for utilizing electrical energy from renewable resources to provide a kick start for the pyrolysis process which in turn converts plastic to inflammable fuel. Experiments were conducted from which it was evident that the heat energy developed from the proposed heating system can successfully support the plastic to fuel conversion using solar photovoltaic units with the help of proposed algorithm. The system efficacy can be enhanced to much higher levels by feedbacking the end fuel to reheat the system for the future conversion processes.

Keywords Pyrolysis; MPPT; Green Energy; Plastic to fuel.

1. Introduction

Plastics, in its several deformations, have supported our life span in different ways as it is affordable in comparison with other alternatives available in the market. This easily available commodity and its variations are capable to satisfy the common demands of the people at a cheaper rate. So, without considering its negative impacts on human life and the environment, people started expending these products exponentially as a result of which its production has also raised drastically [1]. A single plastic bag takes around a millennium for its complete decomposition. So, in the long run, these wastes build up huge heaps in the landscape which can persist even after the inexistence of its end-user. Littered plastics are even responsible for the death of many creatures as they get suffocated while consuming these wastes. The improper treatment of plastic is the foremost reason for environmental degradation. To get rid of these non-biodegradable wastes, generally, people incinerate plastic in the open air which releases toxic fumes into the environment, and hence the air pollution level will rise excessively [2].

The demand for fuel productions has an immense hike in its trend and its cost of the fuel is scaling up day by day. Accelerating urbanization and industrialization is also a cause for the necessity of these fuels in a higher amount. Hence the approach towards the plastic to fuel conversion techniques is upsurging in many industries as the fuel demands are high and traditional recycling techniques of plastics are inefficient [3]. This also helps in the reduction of landfills, resulting in the production of fuel from these awful materials by scientific treatments. This enhances the sustainable development and eradicates disastrous impacts in the biosphere.

Pyrolysis is an optimal method for the chemical treatment of organic materials and a few inorganic materials where in this case thermal degradation of plastics waste occurs in the presence of an anaerobic condition to produce liquefied fuel, usually carried out in temperature range of 300 to 800°C, which may vary according to the material to be converted. Here, the thermal decomposition depends on the thermal stability and leads to the formation of new molecules by the disintegration of the chemical bonds with the help of the heating element. The liquid form of the fuel is obtained after a stream of pyrolysis gas is passed to the condensation unit of the system. The main target of this process is to yield high-value energy products that would satisfy the standards of non-renewable fossil fuels available from nature [4], [5]. This process can be classified in terms of its speed of action as slow, flash, and fast pyrolysis methods. Various factors that influence this process are the particle size and its physical nature, residence time of material in the chamber, temperature requirement for the process to be done, and the composition of the material to be treated [6],[7].

Since the pyrolysis process is carried out at high-temperature ranges, it can be also called an energy-intensive mechanism because an excessive amount of energy is vital for the process to be sustained. Renewable energy resources can be employed in these places since the process can succour without a burden. It is well known that the sun produces enough heat and light to accomplish all the terrestrial needs without any indolence. Solar energy can be interpreted as an inexhaustible source and its versatile nature is the eminent reason for its growth and demand in the past 15 years. When the panel harness the solar energy, electrons are knocked out and this flow of electrons results in the production of electricity. The photovoltaic effect does not involve any intermediate process and is pollution and noise-free [8]. Here, the push-pull inverters act as a subordinate system which supports the transformation of the output DC voltage from the panel to the required AC levels. It gives constant output voltage and helps to modulate input voltage according to the applications [9]. The efficiency of the PV panel mainly depends on the output power which will mainly vary according to the atmospheric conditions like temperature variations, solar irradiations, etc. These effects can be reduced by utilizing one of the convenient Maximum Power Point Tracking (MPPT) methods to harvest the maximum amount of power from the PV module. The selection of MPPT methods depends on factors such as its complexity, cost for implementation, how fast the system converges to the output, number of sensors required, hardware implementation, and finally its overall effectiveness [10],[11]. The fractional open circuit method (FOCV) is the most common method among the MPPT methods because of its inherent simplicity and also regulates tracking efficiency.

2. State of the Art

One of the key factors for environmental distortion is improper techniques adopted for the disposal of plastics. The traditional methods of plastic disposal include incineration, biodegradation, etc which account for more drawbacks rather than supplying benefits. Recycling of plastics produces toxic fumes that could harm the living beings near the plant. Also, it leads to the emission of carbon vapours which add upon global warming [12]. Incineration systems are quite expensive and chances for the emissions of a variety of pollutants which include heavy metals, dioxins, and furans are high and even ashes left behind the process are quite dangerous. If such a system is adopted for waste treatments, several precautions must be taken prior to control these pollutions. Another method is the biodegradation process where microorganisms such as bacteria, fungi, and actinomycetes decompose both natural and synthetic plastic waste but the classification of oxo-biodegradable plastic releases metals into the surroundings which are also detrimental.

Downsides of landfilling processes such as groundwater pollution, producing leachate, and emitting landfill gases mark it as unfavourable among the above categories. Considering the process of pyrolysis as a replacement for other methods is an excellent way of approach for the plastic treatment. It is simple, inexpensive and pre-treatment of the material can be carried out with easiness. The main highlight of this method is the production of valuable fuels like petroleum, diesel, kerosene, etc from the unusable waste products. The solid remaining can be used as a tarring material and this method is safe as there are no harmful emissions of toxic gases [13].

Pyrolysis requires an intense amount of energy for a long period of time and in the conventional methods, this application of heat is furnished by firing the chamber using charcoal, wood, and other essentials [14]. Introducing green energy technology is an adaptable way to save our environment and conserve non-renewable natural resources. Solar energy is always useful even for small scale and isolated production of electricity hence reduces energy imports and always confer sustainable development. Implementation of MPPT algorithm provides good regulation in output voltage under various working conditions, which is also an added advantage [15].

3. System Description

The system under consideration includes a heating system that can build up the initial temperature inside the heating chamber to a level where the plastic material subjects to pyrolysis inside the closed chamber and kick start the process.

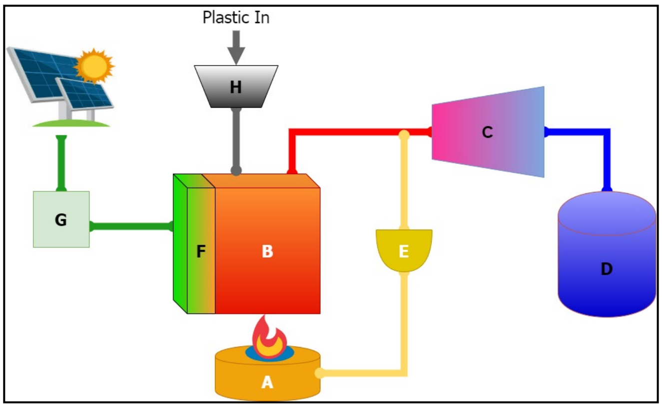

Fig. 1. Block diagram of the system under consideration

3.1. System component description

Figure 1 depicts the block diagram of the entire system. It consists of a closed chamber (Area B in figure 1) which intakes plastic material, where the pyrolysis process gets activated. A condenser path (Area C in figure 1) that brings down the temperature of the gas passing through it and finally changes the state of the material in the tube to liquid. The storage unit (Area D in figure 1) can fill the condensed fuel, where the fuel can be sent to a fractional distillation column to separate fuels of required octane or cetane value. Component E in figure 1 is a control valve, which can control the gaseous fuel emitted as the output of the pyrolysis process to reignite and heat the chamber in order to continue the pyrolysis process.

Component A in figure 1 is the entity which accepts the inflammable gas and converts it to controlled flames which then heats the chamber. Component H is the pathway to insert plastic material into the chamber before starting the pyrolysis process. The electrical heating system proposed, to start the pyrolysis process is depicted as component F in figure 1. Component G in figure 1 is the power converter unit which converts the energy sourced from the renewable sources to the kind voltage signal suitable for the electrical heating element.

3.2. System working

In the beginning, the plastic material of necessary quantity is stored in the closed chamber (component B in figure 1). Electrical energy harnessed from renewable sources such as solar power, wind power, etc. is provided to component G in figure 1. The heating element increases the temperature inside the vacuum chamber, which then subjects plastic material for pyrolysis. Slowly, gaseous fuel passes through the condensation chamber, gets liquefied, and is stored in the container D. Once necessary pressure is built up in the transition path, component E, which controls the gas inflow to the heating unit component A. So, the process works in a closed loop with positive feedback till the entire plastic material in the vacuum chamber is converted in inflammable liquid fuel and is stored in the storage chamber (component D).

4. Temperature control system

Depending on the grade of plastic material used pyrolysis process requires a temperature range of 200ºC to 900ºC in the absence of oxygen to convert the material to inflammable oil. A temperature control system is needed depending on the grade of plastic used to enable this process.

The temperature inside the chamber is brought to an appropriate level, by harnessing energy from renewable energy resources and by taking feedback of inflammable gas produced to flame and heat the chamber. Figure 2 represents the temperature control state diagram of the renewable sourced electrical system. Input parameters to the control system include input voltage and current of the power converter and the actual temperature inside the chamber. Maximum power point tracking is used to harness maximum available energy at any given instant from a renewable source.

The temperature control system uses a combination of hysteresis or bang control and P-I based fixed reference control to achieve the required temperature inside the chamber. As long as the temperature inside the chamber is lesser than T_{low}, the system works in maximum power point tracking mode, where entire energy tapped from the renewable source is used for heating the chamber. As the process continues, the temperature inside the chamber increases with the help of electric heating, and it reaches T_{ref}, crosses this point and reaches the T_{up} level. Once the temperature hits this point, electric control system rolls back MPPT based control and switches to P-I based temperature control in order to maintain the required temperature inside the chamber. If the conversion process inside the chamber demands higher energy, the temperature of the chamber falls with a ramping rate much more than the PI controller can handle. This results in temperature to fall below T_{low} band. During this situation, the electrical control system again switches back to MPPT based control where maximum available power from the source is utilized for heating the chamber. As the process continues, plastic material inside the chamber gets converted into gas and passes through condenser unit 'C' (as per figure 1), where it gets liquefied and settles as liquid in the collecting chamber 'D'. In order to the entire heating process, a part of the inflammable gas produced may be taken out to heat the chamber with the help of heating unit 'A' as per figure 1.

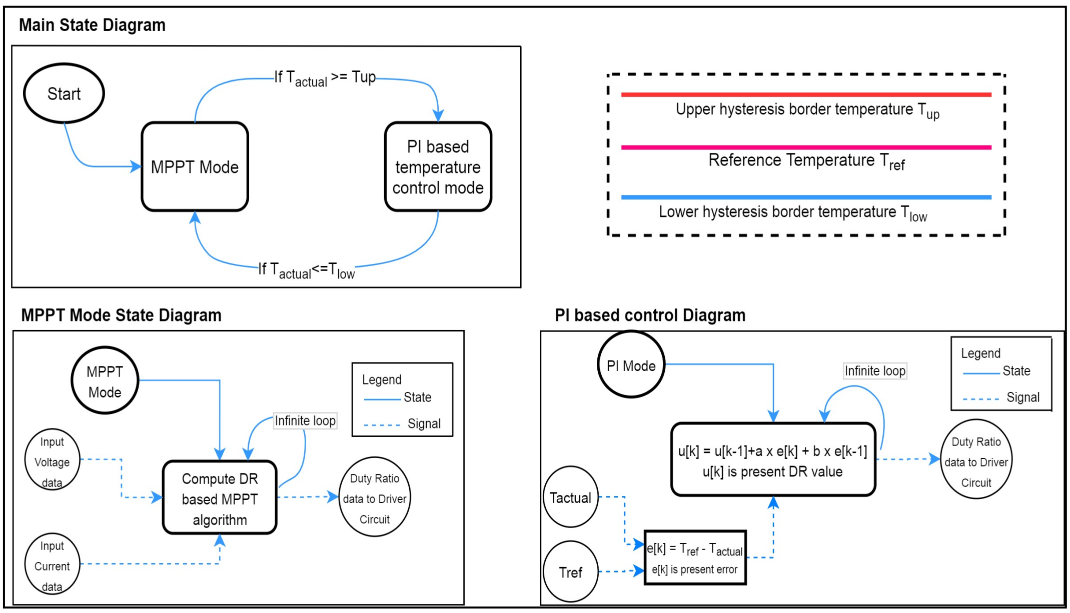

Fig. 2. State flow diagram for the temperature control

To maintain the temperature inside the chamber, a P-I based control system can be adopted to control the heating process of the chamber, by controlling the gas inlet unit 'E' (as per figure). Both the heating process can be used in conjunction with each other to maintain the required temperature inside the chamber, thereby converting the plastic material inside to inflammable fuel.

5. Preliminary electrical section study and experimental results

5.1. Electrical heating methods

The electric heating unit is one of the important parts of this system since the plastic to fuel transformation is only feasible by breaking the long-chain bonds in polymers at a certain temperature level which can be performed via heating. The energy tapped by the solar photovoltaic (SPV) system is available in a suitable form at the output terminals of the power converter which can be used for heating the system.

Electric heating methods can be broadly classified into two types. The first category is power frequency heating where the normal power supply of 50Hz is employed. Resistance heating and electric arc heating are the two most popular classifications in this category. In direct resistance heating, the resistance offered by the body will offer I^2R losses when current is passed through the body to be heated whereas, in indirect resistance heating, the losses in high resistance filament wire is transferred either by convection or radiation which makes the body hot. The former has higher efficiency since heat is produced within the body whereas the latter provides uniform and automatic control of temperature. The intense heat production by means of the arc struck between two electrodes, which is commonly known as arc heating and any of its deviations such as direct or indirect arc furnace can also be used for heating.

The second category is high-frequency heating which requires a high-frequency voltage supply for its action. The selection of frequency depends on the work and method of heating to be employed. Induction and dielectric heating fall under this category [16]. Direct induction heating is a resultant of electro-magnetic action where induced current passes through the body to be heated, hence its resistance produces the heat. In the indirect induction heating method, the body gets heated due to the eddy current set by the alternating magnetic fields produced by the coil which surrounds the material. The ability to use in vacuum and other special environments and also the higher heat penetration rate employing proper frequency are the main highlights of this technique. Dielectric heating is applicable for non-metallic substances and insulators where the production of heat increases with increasing frequency and provides uniform heating at a faster pace.

5.2. Maximum Power Point Tracking

The maximum power point tracking concept is very significant in the field of photovoltaic systems for employing the effective utilization of green energy tapped using solar photovoltaic systems. The operating point of SPV systems has a larger dependence on the load connected to its end terminals and to obtain the maximum available power from the module, the system is desired to operate at the peak point of the P-V curve, which is generally defined as the maximum power point [17],[18]. This is possible either by varying the voltage or current to the corresponding value at MPP but variations in the external factors like irradiance or temperature deviate this point and hence tracking becomes necessary. This process of maintaining the operating point at the maximum power transfer point is known as maximum power point tracking [19].

5.3. Maximum Power Point Tracking Algorithms

MPPT algorithm automatically finds the panel operating voltage that provides maximum power output. There are several algorithms to track the MPPT effectively and these techniques are broadly classified as direct and indirect tracking methods. In indirect tracking methods such as Fractional Open Circuit Voltage (FOCV) method and Fractional Short Circuit Current (FSCC) method, simple assumptions and periodic estimations of MPPT are taken more easily. FOCV technique exploits a good estimation of V_{mpp} using a constant k with the open-circuit voltage available from the panel, makes it simpler, robust, and provides easier implementation when compared with other complicated techniques. We can even use pilot cells to avoid the losses while switching to the open circuit condition for estimating V_{oc} [20]. FSCC technique is also similar to the FOCV method, but instead of open-circuit voltage, short circuit current is taken into consideration. Short-circuiting from time to time increases power loss and heat dissipation which makes it incompetent to use [21].

Perturb and Observe method of MPPT is an example of direct tracking where the maximum power point is converged after several perturbations. The P-V characteristics are considered and the operating point is forced to oscillate near maximum power point by comparing the previous power reading, P_{k-1} with the present one, P_k. If $P_{k-1} < P_k$, the power is increased by increasing the operating voltage and if the reverse happens, then power is decreased by decreasing the operating voltage to tackle V_{mpp}. But changes in the weather conditions or irradiance can severely affect the speed of convergence or even makes a fault in its working [22], [23].

Another method of direct tracking is the incremental conductance method where the algorithm compares the incremental change in conductance with the instantaneous conductance and decides whether the operating point requires a left or right shift to reach the maximum power point and hence the voltage is increased or decreased accordingly. This tracker requires both voltage and current values and makes it strenuous to be implemented [24].

5.4. Fractional Open Circuit Voltage Technique

The Fractional Open Circuit Voltage method of MPPT is implemented by following the linear relationship between open-circuit voltage, V_{oc}, and the voltage corresponding to the maximum power point, V_{mpp} of the panel. The voltage factor, k is considered as 0.75, and V_{mpp} is assumed to be 'k' times the V_{oc}. This method is easier to execute and gives constant power delivery but alterations in environmental factors such as the amount of sunlight, temperature variations, and even shadows disturb the open-circuit voltage and hence disrupting the entire system. This set back can be overcome by taking regular samples of V_{oc} by suspending the energy consumption from the panel for a transient period so that the FOCV tracker can work with maximal regulation. Another main highlight of this technique is the usage of only one sensor that is for measuring voltage and this makes it different from other techniques where more sensing parts come into action. By considering all of its advantages, FOCV method was chosen for conducting the experiment which is explained in further sections.

Figure 3 represents the flowchart of the fractional open circuit voltage based MPPT algorithm interfaced with the timer overflow concept. In the event of timer overflow interrupt, energy consumption is halted for a while and open-circuit voltage is computed and stored as V_{oc}. Then, V_{mpp} is calculated inside the microcontroller, assuming that the maximum power is obtained nearly at k times the open-circuit voltage, where k is an experimentally computed factor and assumed to be 0.75 for simplicity. The controller either increases or decreases the terminal voltage of the panel and make it settle near to V_{mpp} by proper switching of an interfacing power converter. Thus, the variations in V_{oc} due to the environmental parameters can be compensated [25].

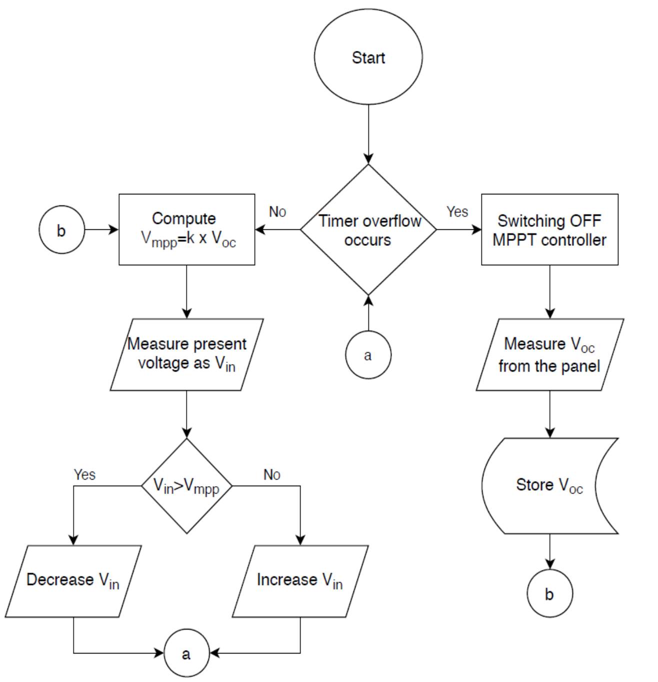

Fig. 3. FOCV based MPPT algorithm

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5.5. Preliminary Test Result

To analyse and understand the performance of the maximum power point tracking section, an experimental set-up as shown in figure 4 is arranged with the assistance of a solar panel of 500W and MPPT circuit as its subsidiary to retrieve the maximum available power from the panel. The extracted power is given to a push-pull inverter which converts DC supply from the panel into AC supply, and also boosts the resulting AC to the main voltage level using a single-phase transformer. When the transformer is ON, due to its high inductance and hence the inductive effect, it tries to draw current resulting in the formation of a heavy back emf. So, for overriding this back emf and to avoid such spikes, capacitor banks are also connected across the input supply. The resultant supply from the inverter is fed to the heating element having a peak voltage, power rating of $230V_{rms}$, 500W.

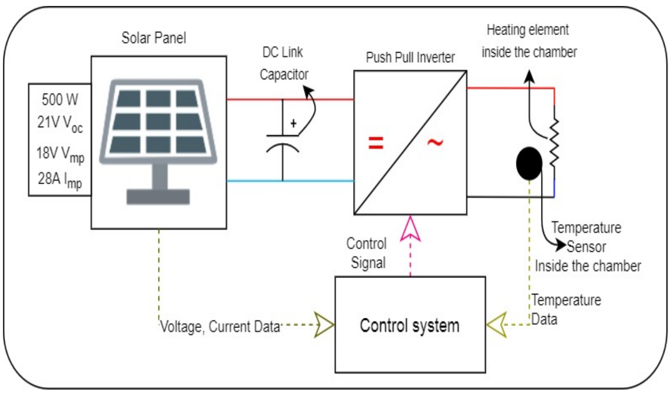

Fig. 4. Working model blocks of plastic to fuel conversion system

In order to comprehend the deviations in irradiance and temperature that leads to progressive alternations in the panel's characteristics, the above-mentioned experiment is operated around 40 minutes where samples are examined in every 5 minutes. Figure 5 shows the plot between the output power from the panel and its corresponding time instances. P_{actual} and P_{out} indicate the ideal maximum power available at the time of execution and the original power extracted from the panel using the proposed MPPT algorithm respectively. P_{out} is calculated by estimating the output voltage and current through the load of the system. By comparing P_{actual} and P_{out}, it is observed that the maximum power point was tracked and the maximum power was transferred to the system with much higher efficiency.

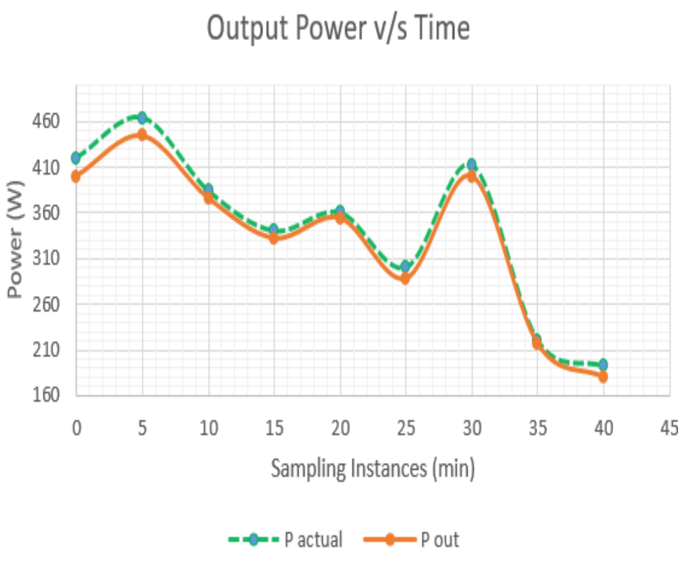

Fig. 5. Graph showing the results of output power w.r.t time

It is also possible to determine the heat energy developed as a result of the MPP tracking technique at the resistive load end by estimating the average power dissipated at that particular time interval. This is depicted in figure 6, where average heat energy delivered due to the effect of resistive heating is used for setting the temperature required to quick-start and maintain the pyrolysis process that assists the plastic deformation.

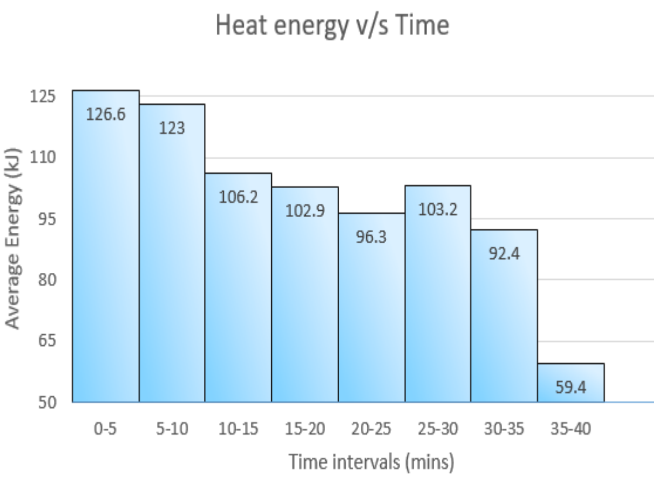

Fig. 6. Graph showing the result of heat energy w.r.t time

The stainless-steel conical chamber shown in figure 7 is deposited with the shredded polyethylene wastes and an initial mass of approximately 1000g can be taken for the analysis. The temperature levels at each sampling instances after the heat injection can be studied from the heat equation, H = mCΔT, where m represents the mass of the substance, ΔT represents the change in temperature and C is the specific heat capacity, which is in the range of 1.9 kJ/kg°C in the case of polyethylene products. The nature of reduction of mass, m will be exponentially decaying w.r.t time, so that as the operating time increases, there will be a faster rate of conversion of mass.

Fig. 7. Stainless steel chamber used for conducting the experiment

Every matter should attain a particular temperature beyond which only the phase change occurs. In the analysis, if the temperature after each interval is greater than this temperature limit, it is assumed that mass starts decaying by 5g after every sampling interval. At some point of time, the temperature gets completely saturated and the heat energy injected is considered as the latent heat for the matter transformation. Hence, even though the mass of the substance gets reduced, the temperature does not vary until the phase conversion gets completed. As the focus of this experiment is on the electrical as well as thermal analysis, the linear variations of temperature w.r.t time corresponding to the heat energy developed using MPP tracking assistance is also observed and this is shown in figure 8. It infers that the material conversion has started at the pace as the temperature moves towards the saturating phase and also requires an additional amount of energy for the complete transformation to take place.

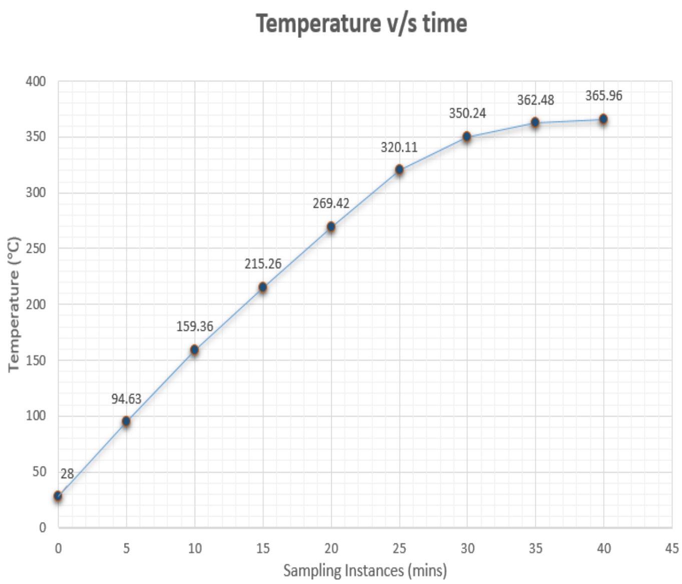

Fig. 8. Analysis of temperature inside the chamber w.r.t time

6. Conclusion

This work has introduced an energy conversion mechanism accompanied by a control strategy using which plastic to fuel conversion process can be initiated and sustained effectively. The results followed by the experimentations makes it clear that the control techniques developed based on the control flow method, applied to the developed circuit helps in ramping up the temperature inside the vacuum chamber that mutates the shredded plastic material to its end product as fuel. As per the method, the system manages the intake power from the SPV unit alone during the initializing phase for the plastic to fuel conversion. The efficiency and conversion speed of the process can be further improved by heating the vacuum chamber by providing heating unit in the feedback path from the fuel developed from the conversion process.

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