Plastic and Waste Fuel Viability for GreenSteam

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Introduction(Boiler/Furnace)

This report covers the research/work done on the steam Boiler/Furnace section of the GreenSteem project under Professor Simon Penny as of the end of Spring 2020. The focus of this quarter has been on the “burning (of) a diverse range of combustible solid waste - including domestic waste, agricultural waste, industrial/medical waste and plastic waste”, with an emphasis on the feasibility of cleanly disposing of various plastic wastes. Preliminary research was done into the plausible types of boiler design best suited for a low tech environment.

Refuse Derived Fuels for use in GreenSteam Plant

Recovery of energy from municipal solid waste solves the major problem we are currently facing in managing the large amounts of waste we produce annually(over 300 million tons of plastic every year). Of this large amount of plastic, approximately 50% of it is for single use and a whopping 8 million tons of plastic are dumped in our oceans annually. Recovery of energy through combustion would help us deal with the management of such large volumes of waste while producing energy to sustain low-power systems. Improper combustion of waste can lead to contaminants spewing into our environment. Landfilling of plastic waste means that the energy content of the waste is not recovered while incineration of it if done under uncontrolled conditions results in the conversion of the carbon content of the waste into carbon dioxide which is released into our atmosphere.

1. Non-Chemically Treated Plastic/Waste

The burning of non-treated plastic and other combustible waste is very enticing from a pure power perspective, but the byproducts, and their subsequent cleaning, prove to create a currently open ended problem.

1.1 PlastoFuel

Fuel nuggets created from compacted PP, PS, LDPE, and HDPE agricultural plastics with maximizing the effective energy density(by volume) of the plastic fuel. The project utilized a hydraulic compactor to condense and slightly melt and jacket the fuel. The process is fairly efficient, for every kWh expended shredding/compacting the fuel, roughly 37 kWh was generated through 22 test runs for energy ratios[4]. The compaction process is resistant to some level of debris being input into the compaction process. The fuel was tested for use in a furnace/boiler to be co-fired with coal or other solid fuel. Unfortunately there are little to no details on the emissions(furans, dioxins, etc.) as a summary of the paper only states that the “high combustion temperatures used (in the experiment) reduce the amount of harmful emissions"[4]. Additional projects and companies stated to have been created during the life of the project also seem to be on an indefinite hiatus.

Advantages: High energy density, resilient to impurity, deals with various kinds of plastics
Disadvantages: No data on emissions, unsure if emissions are even being mitigated
Conclusion: Later stages of the PlastoFuel project seem to have been scrapped or on indefinite hiatus. Not promising for the scope of the GreenSteam Project.

2. Pyrolytic Gasification

Gasification of plastic waste has attracted interest due to its ability to generate Hydrogen; however, it is a process that also results in a wide range of Hydrocarbons. To obtain a higher Hydrogen yield from plastics a 2-stage pyrolysis-gasification process can be implemented. This 2-stage process results in the pyrolysis of plastic waste (polyethylene, polypropylene, PVC, etc.) which is then followed by steam gasification of the pyrolyzed gases in the presence of Nickel-Magnesium-Aluminium catalysts. This process also tackles the challenge of the state in which a great amount of the plastic is recovered from the oceans (often found in very small sizes making it difficult to identify what type of plastic); this pyrolysis-gasification process does not require separation of plastics. The role that the catalyst plays in this process is crucial to the entire process, with the presence of a Nickel-Magnesium-Aluminium catalyst the temperature of the pyrolysis process is lowered by lowering the reaction activation temperature which yields a higher conversion. Furthermore, catalytic pyrolysis has been shown to lead to desired pyrolysis liquid products that have the potential to be fed back into the furnace/boiler element of a GreenSteam plant. As is the case with the use of catalysts in other catalyst-driven reactions, it's performance deteriorates in this process and must be taken into account to maximize performance.

2.1 Investigation of catalyst

The Ni-Mg-Al catalyst is to be produced using the method reported by Garcia et al. [1], a variety of different Ni-Mg-Al molar ratios are investigated including 1:1:4, 1:1:2 and 1:1:1. Using polypropylene (PP) as the raw material and a mass of PP-catalyst ratio of 2:1 is used. Two different pyrolysis-gasification reactions are run, (1) is at 500 ℃ and the other (2) at 800 ℃ with nitrogen as the carrier gas in both instances. The gaseous products from both reactions were then condensed and collected for examination. The following products were discovered in the condensed product: C_1 to C_4 hydrocarbons, H_2 , CO, O_2 , N_2 and CO_2. The results of this study suggest that the addition of Mg to the Ni-Mg-Al catalyst results in no improvement of the ability of the catalyst to generate hydrogen.

Advantages: reduction of carbon footprint by minimizing carbon monoxide and carbon dioxide emissions, Pyrolysis of plastic produces a high CV fuel that could be easily marketed to produce electricity and heat

Disadvantages: The main disadvantage of pyrolysis is that the product steam is more complex than for many alternative treatments

3. Formation of Dioxins

The formation of dioxins can happen through 2 mechanisms [2] (Mukherjee 2015 , Debnath et al.), one of which is through homogeneous reactions occurring at temperatures in the range of 773-1073 K. The mechanism through which this occurs is the rearrangement reaction of Chlorinated precursors in the gaseous phase which leads to homogeneous PCDD/Fs (polychlorinated dibenzodioxins) or high temperature PCDD/Fs. The second mechanism through which dioxins/furans can be produced is through the heterogeneous reactions in post-combustion zones in temperature ranges between 473-673K.

3.1 Treatment of Furans and Dioxins

As mentioned above, incineration is a great way to reduce the amount of generated waste. One such way of improving efficiency/ reducing harmful toxins of the process is through the addition of a catalyst or simply through the treatment of the flue gas. The following table shows technologies that can be used to irradiate dioxins from flue gas. [2] (Mukherjee 2015 , Debnath et al.).

References	Process	Mechanism behind the process	Benefit	Drawbacks
McKay (1984) Weber et al. (2002) Hatanaka et al. (2004) Fujimori et al. (2010) Froese & Hutzinger (1996) Hung et al. (2014) Korell et al. (2009) Chang et al. (2009) Lu et al. (2013) Boos et al. (1992)	Good combustion practice coupled with end of pipe treatment using scrubber and bag filter	Changes in the operating parameters or combustion practice which includes preparation of Feed stock and feed control , Maximization of combustion efficiency, Management of waste heat boiler conditions, Management of APCD, Control and monitoring of system variables, Emergency and fail-safe system.	Efficient process in reducing the emission of dioxin compounds even up to 99% (0.01ng TEQ/Nm3),cost efficient, simplicity in engineering	Even with GCP and End of pipe treatment emission of dioxins can't be controlled if feedstock will contain large amount of chlorine, so care should be taken in selecting feedstock and feedstock preparation. Even this technology can effectively remove PCDD/Fs but due to memory effect the discharge of dioxins can get increase.
Dvorak et al.(2010) Jones & Ross (1997) Liu et al. (2015) Vermeulen et al. (2014) Ruokojarvi et al. (1998) Ruokojarvi et al. (2004) Wu et al. (2012)	Selective catalytic oxidation using NH3-SCR catalysts (V2O5–WO3/TiO2), NH_3, and Urea	Reheated flue gas is added in the catalytic reactor where high temperature facilitates the oxidation of dioxins over the catalyst	Efficient process and when accompanied with good combustion practice and can generate better result with more than 90 % efficiency.	Feeding of catalyst should be monitored periodically to avoid excessive feeding that might affects the reduction process. Moreover it involves high investment cost and operating cost that limits its use in full scale plants.
Xie et al. (2012) Yan et al. (2006) Hunsinger et al. (2007) Griffin (1986) Gullett et al. (1992) Ryan et al. (2006) Pekarek et al. (2006) Ke S et al. (2010) Liu et al. (2015) Samaras et al. (2000) Tuppurainen et al. (1999).	Injection of sulphur compounds coupled with recycling it.	Sulphur containing compounds reduce the ability of catalytic metals to inhibit the formation of PCDD/Fs. It can convert metal catalysts in to sulphates (by oxidising) or sulphides (by reducing). There are many sulphur compounds that can be recycled for further use.	Efficient process specially when combined with pyrite and becomes more cost effective when the inhibitor is recycled.	Sulphur containing compounds convert metal catalysts by poisoning the surface of metal catalysts either by reducing or oxidising.
Luna et al. (2000) Lin et al. (2015)	Injection of nitrogen compound (Thiourea)	Undergo complex reaction with metal catalysts to form strongly bonded organo-metallic nitride complex.	Doesn't poison the catalytic surface rather deactivate the active sites of catalysts	Not detected

4. Furnace and Boiler Design

The GreenSteam project requires a Furnace/Boiler setup that is feasible to maintain while having fairly lengthy periods in between maintenance cycles. The pressure limitations/ceilings of the initial pre built valve solutions (60 bar give or take, needs some expanding)have been used as boundary conditions in the estimation of the needs of a GreenSteam ‘plant’.

4.1 Fire Tube Boiler

Fire Tube boilers are typically more easily operated and maintained, while additionally being the cheapest of boiler options, they have some unfortunate viability ending caveats. The theoretical max pressure of even very well made fire tube setups, caps out around 20 bar, with lower steam quality than other options.

Advantages: Cheaper/Easier to maintain, well understood
Disadvantages: Maximum pressure attainable is low

4.2 Water Tube Boiler

Water tube boilers are more complex and harder to maintain over their lifespans when compared to firetube boilers, but are able to achieve much higher pressures/qualities of steam. They are also able to be scaled efficiently and the amount of industrial literature on the topic of Water Tube boilers is extensiveRepairs and cleanings must be made from within the boiler chamber.
Advantages: High max pressure
Disadvantages: More costly, harder to repair/clean

4.3 Boiler Conclusions

Both boiler solutions leave something to be desired for the scope of the GreenSteam project. Currently, a water tube boiler is the only current conventional solution that has the required output for GreenSteam. Moving forward, a more modular solution that rests between the concepts of Water and Fire tube boilers, with an emphasis on ease of maintenance, will be expanded upon.

5. Initial Conclusion/Discussion/Challenges

There currently does not seem to be an adequate way to combust raw plastic waste as fuel and adequately deal with the unsavory byproducts that are released. While overall levels of furans and dioxins can be deemed acceptable within Refuse Derived Fuel combustion[3], they are merely masked by the mass of less energy dense parts of the fuel mix.

Pyrolysis does have some fairly promising results in turning end of life plastics into usable hydrocarbons with heavily reduced emissions. While the form of the hydrocarbons produced best suits use in internal combustion engines, there is the possibility of use in a sort of still engine, and at the very least the plastic waste is converted into a more useful form. The complexity and cost of a deployable pyrolysis plant powered by a GreenSteam engine, at least at first glance, seems to be prohibitive.

Additionally, throughout the course of research into these topics, many problems arose in finding detailed information on the makeup and treatment of emission from both combustion and pyrolysis of wastes. Even with the implementation of good combustion practices it is very difficult to eliminate the production of dioxins if our feed contains chlorine. Furthermore, the amount of catalyst must also be controlled to maximize efficiency.

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Next Steps:

Future research focus will move away from solely end of life plastics, and towards non-plastic agricultural waste and paper products.

Numerical modeling of the requirements of a boiler/furnace setup will continue to be updated as more information and data becomes available.

Initial drafting and research of the physical design of a boiler/furnace will be prioritized.

Works Cited and Consulted:

References

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https://plasticoceans.org/the-facts/

Pyrolysis and Catalysts:

[1] https://www.sciencedirect.com/science/article/abs/pii/S0926337309000952
[2] https://www.sciencedirect.com/science/article/pii/S1878029616301268
https://advances.sciencemag.org/content/2/6/e1501591

Furans and Dioxins:

https://www.sciencedirect.com/science/article/pii/S1878029616301268

Municipal Waste/Refuse Derived Fuel:
https://www.mdpi.com/2071-1050/9/9/1638/htm
https://p2infohouse.org/ref/11/10059.pdf

Conventional Boiler Design:
https://www.sciencedirect.com/topics/engineering/fire-tube
https://www.labour.gov.hk/eng/public/bpvd/AGuideforFireTubeBoiler.pdfhttp://www.stanleylouis.com/firetube-boilers-vs-watertube-boilers-which-is-right-for-you/

Plasto Fuel:
[4]https://extension.psu.edu/waste-plastics-as-fuel