Conversion of Municipal Solid Waste into Hydrochar Using Hydrothermal Carbonization

Waseem Raja [1], *Jignesh Brahmbhatt* [2]

[1] M. Tech Environmental Engineering Student, [2] Assistant Professor
[1,2] Department of Civil Engineering
[1,2] BVM Engineering College, Anand, Gujarat, India.

Abstract: Waste to energy concepts are modern techniques to address the growing menace of waste as well as meet energy demands of various small and medium sized ventures in the form of heat and fuels. Hydrothermal Carbonization is a thermal conversion process in which a feedstock is subjected to high temperature > 180 C in water and pressure corresponding to the temperature and generation of vapors. It is combined dehydration and decarboxylation of a substrate to raise its carbon content with the aim of achieving a higher calorific value. In simpler words, it is defined as artificial coalification of biomass in a short span of time. In the following study, Municipal Solid Waste has been taken as a feedstock and subjected to various temperature ranges and time durations. The changes in various physical, chemical and morphological characteristics are studied to quantify and classify the char produced with the prescribed standards of natural coal. The HTC is a promising technique which yielded positive results during different experimental conditions as the Carbon concentration rose to 70% in char from 34% in the feedstock. The calorific value also jumped from 8.97MJ/kg to 29.07 MJ/kg in 6 hours at 220 C. The detailed experimental setup and conditions are greatly discussed in the study below.

***Index Terms* – Solid Fuel, Green Energy, Waste to Energy, Reuse, Sustainable Development.**

I. INTRODUCTION

Waste (or wastes) are substance or objects, which are disposed or are intended to be disposed or are required to be disposed of by the provisions of national law (UNEP). These are unwanted or unusable materials. India is a country with a population of 1.3 billion and huge infrastructure. Being a developing nation there is a huge consumption of raw material which is the first step in the generation of waste. Besides that, agriculture, municipal solid waste, industries are some of the main contributors to waste in India. India generates a whopping 60 million tons of waste every year and is estimated to rise by 4% every year (Agrawal). Out of such a large amount of waste only 60% is collected and its 15% is processed, implying a large amount of waste remains unaddressed resulting in tremendous load on landfills and environment, giving rise to various pollutions and health hazards. Types of wastes include:

- Municipal solid waste
- Hazardous waste
- Biomedical waste
- Special hazardous waste
- Explosive wastes.

MSW, commonly known as “trash or garbage” is a waste type consisting of everyday items that are discarded by the public in every place. Solid waste from all over the cities and at sacred places like temples, commercial areas, hotels restaurants etc. are of mixed composition. Improper disposal of solid waste pollutes all the vital components of the living environment as air, land and water and due to that some health issues are also generated. The problem is more acute in developing countries than among the developed country. The major problems attributed directly or indirectly to Municipal Solid Waste are:

- Solid wastes result in air pollution, water pollution and soil pollution.
- Solid wastes also cause many diseases as these wastes are breeding place for many vectors.
- Substances like polythene bags block drain pipes thereby paralysing the whole drainage system.

The major challenges with Indian MSW are its low calorific value, fibrous nature, high moisture content, bulky volume and natural degradation as far as giving proper treatment is concerned (Hari Bhakta Sharma). The most common treatments given to MSW in India are: Open burning, Sanitary Landfills, Incineration, Pyrolysis, Composting & Ploughing in fields. Every treatment has its own advantages and disadvantages. Open burning causes a lot of pollution, composting requires a huge amount of time and for pyrolysis, incineration, torrefaction etc., the high moisture content in MSW is not suitable and hence pre-treatment is required.

II. HYDROTHERMAL CARBONIZATION

Hydrothermal carbonization (HTC) as the name suggests involves water and heat to carbonize the feedstock. In this process combined dehydration and decarboxylation of a substrate happens to raise its carbon content with the aim of achieving a higher calorific value. HTC is a thermal conversion process that can be used to convert municipal waste streams into sterilized, value-added hydrochar. It is also defined as a chemical process which emulates the natural coalification of biomass in manmade conditions (Ramke). But in difference to the natural process which requires some hundred (peat) to some million (black coal) year the HTC only needs few hours for the transmutation of biomass. It is achieved by applying elevated temperatures >180 to biomass in a suspension with water under saturated pressure for several hours (Sermyagina).

HTC has been mostly applied and studied on a limited number of feedstocks such as wood, with an emphasis on nanostructure generation. There has been little work exploring the carbonization of complex waste streams or of utilizing HTC as a sustainable waste management technique. The HTC process involves the following mechanism:

- Hydrolysis
- Dehydration
- Decarboxylation
- Condensation polymerization
- Aromatization.

During the dehydration the OH group is removed from the feedstock which makes it hydrophobic and hence the end product holds lesser moisture as compared to raw material (Bach Q). It is very novel technique and very less work has been performed on it in India with reference to MSWM. Unlike pyrolysis and incineration, moisture is not a problem for it and hence no pre-treatment is required (Benavente). The end product is a thick slurry and water. The water can be directly used in agriculture and the slurry can be dried to pellets to directly use as a solid fuel. Apart from being used as fuel and fertilizer, the char obtained can be also used to treat wastewater.

III. Material for Feedstock

The HTC has been tried on various feedstocks ranging from wood, sewage, backyard waste to slaughter house residue. For our study we have chosen biodegradable municipal solid waste. The study area being Vadodara, representative segregated biodegradable municipal solid waste from various points in the city is collected and brought to the laboratory. The waste is shredded and ground to a paste in order to fasten and facilitate the reaction using a domestic mixer grinder. The material mostly comprises of dried leaves, vegetable and fruits, kitchen and restaurants left overs and sugarcane leftovers etc. The material even has a small quantity of debris. Most of the material is partially or fully wet except the dried leaves and paper material like cardboards etc.

Fig. 1 MSW Collected, Cut and ground into Paste

The feedstock is analysed for basic physical and chemical properties in the laboratory to find out the initial characteristics of the waste. The original feedstock is named as sample B. Various tests performed to find out the initial chrematistics of the waste are written as under:

Table 1 Physical and chemical properties of Feedstock

Sr. no	Waste Sample	Moisture Content %	pH	Conductivity	C %	H %	N %	Calorific Value (MJ/kg)
01	B	49	8.16	2.0	34.31	6.27	0.98	8.97

IV. HTC Reaction

The HTC reactions for the prepared feedstock are carried out in a locally made HTC reactor. The reactor is made from SS316 material and its capacity is 4L. The reactor is designed to sustain a pressure of 100 bar and can reach a temperature up to 450 C. The heat is provided with the help of a ceramic band heater which is capable of heating the reactor at 5 Celsius per minute.

Fig. 2 HTC Reactor manufactured at VVN GIDC

The water can be filled till the half of the capacity only as the density will tremendously decrease and volume will increase with the increase of temperature. The weight of the feedstock is kept 20% of the volume of water i.e., 400 gm (wet weight) for all the reactions. The tests are carried out on a set combination of temperature and time. The reaction time denotes the time for which the decided temperature is maintained continuously. The following combinations of time and temperature are decided and hence HTC is carried out for the same.

Table 2 Various time and temperature combinations

Sr. No.	Reaction time (hours)	Temperature (Celsius)	Sample identification number
1	1.5	180	S1
2	3	180	S2
3	4.5	180	S3
4	6	180	S4
5	1.5	200	S5
6	3	200	S6
7	4.5	200	S7
8	6	200	S8
9	1.5	220	S9
10	3	220	S10
11	4.5	220	S11
12	6	220	S12

The HTC reactor is set for the first set of trials at 180 C. The pressure at this temperature under closed conditions saturates around 14 Bar. Reactions are carried out at 180 C for 4 different time periods as decided earlier and every time period is named as Trial. Trial 1 is carried out for sample S1 at 180 C temperature and a reaction time of 1.5 hours. The temperature is maintained at 180 C for 1.5 hours and a cooling period of 24 hours is given. The reactor is opened after 24 h and the slurry is collected in a plastic tub and later filtered through a cloth to collect the solid mass. The solid mass is later dried in a hot air oven at 105 C for 24 h. Similarly, the consecutive trials are carried out for S2 to S4. After completing the HTC reactions and drying the samples are analysed for the same parameters as of Sample B and the results obtained are thus as under:

Table 3 Results of Various Parameters for Trial 1 to 4

Sr. no	Waste Sample	Char Yield (%)	pH	Conductivity	C %	H %	N %	Calorific Value
01	S1	77.55	8.02	2.05	39.3	6.01	0.93	15.32
02	S2	75.2	7.96	2.09	42.07	5.98	0.9	18.68
03	S3	72.99	7.91	2.12	44.73	5.94	0.95	19.26
04	S4	71.42	7.86	2.19	45.02	5.93	0.91	21.58

Yield = [Dry weight of char obtained / (Wet weight of feed stock – moisture content of feed stock)] × 100

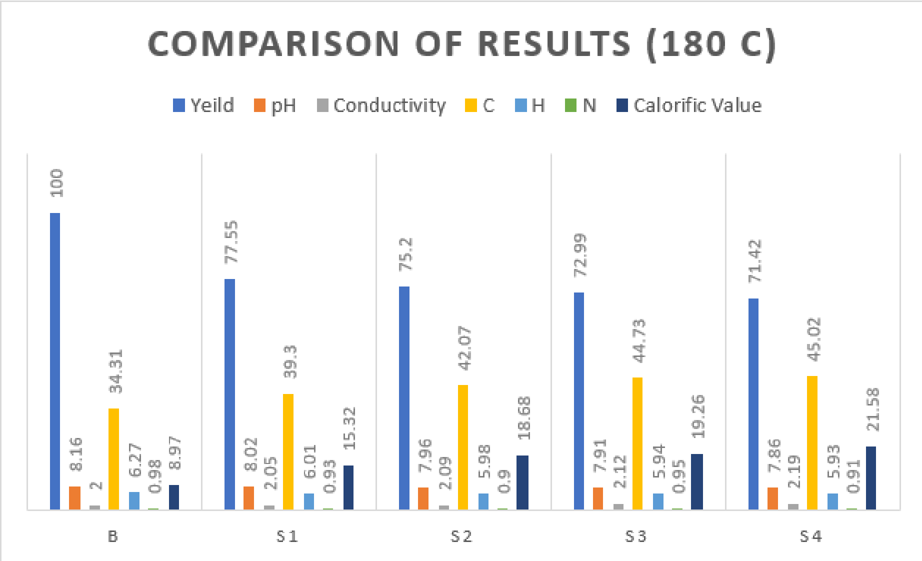

Fig. 3 Graph showing Comparison of results of various parameters at 180 C

Fig. 4 Char obtained from S1, S2, S3, S4

For 200 C temperature conditions, S5 to S8 are subjected to HTC reaction and the similar process is followed as for S1 to S4. The HTC char thus obtained is analysed for the same parameters and the results are as under:

Table 4 Results of Various Parameters for Trial 5 to 8

Sr. no	Waste Sample	Char Yield (%)	pH	Conductivity	C %	H %	N %	Calorific Value
01	S5	74.2	7.73	2.10	43.14	5.89	0.90	17.87
02	S6	69.8	7.6	2.18	49.02	5.66	0.81	22.77
03	S7	66.18	7.97	2.23	52.40	5.19	0.67	24.52
04	S8	61.4	7.42	2.30	54.57	5.03	0.53	26.76

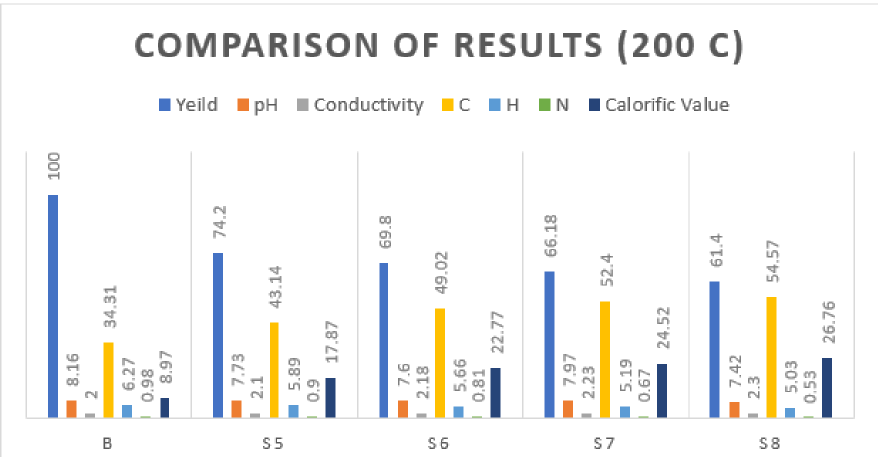

Fig. 5 Graph showing Comparison of results of various parameters at 200 C

Fig. 6 Char obtained from S5, S6, S7, S8

For 220 C temperature conditions, S9 to S12 are subjected to HTC reaction and the similar process is followed. The HTC char thus obtained is analysed for the same parameters and the results are as under:

Table 5 Results of Various Parameters for Trial 9 to 12

Sr. no	Waste Sample	Char Yield (%)	pH	Conductivity	C %	H %	N %	Calorific Value
01	S9	70.20	7.47	2.13	50.33	5.40	0.87	22.10
02	S10	63.9	7.31	2.19	60.54	5.37	0.75	24.84
03	S11	57.5	7.25	2.26	64.98	5.21	0.59	26.43
04	S12	52.7	6.98	2.35	70.06	5.15	0.41	29.07

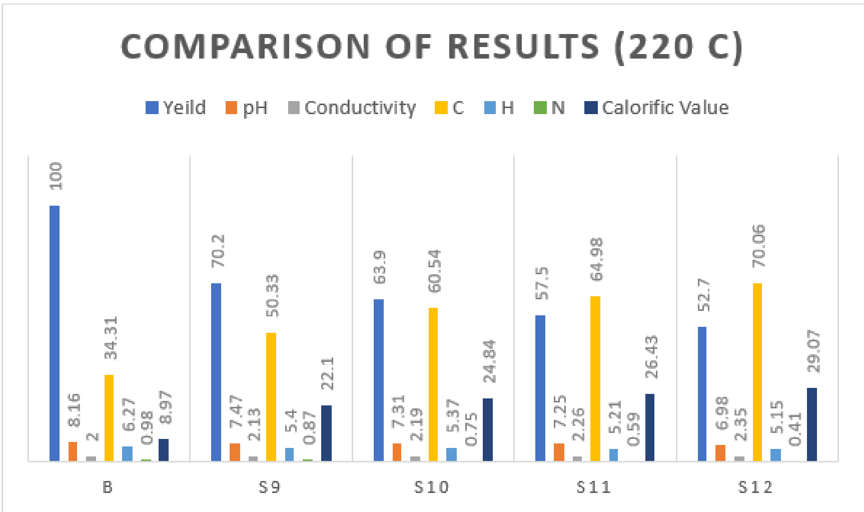

Fig. 7 Graph showing Comparison of results of various parameters at 220 C

Fig. 8 Char obtained from S9, S10, S11, S12

V. Discussion

Every trial has shown one or another change in the various parameters of the char. The general observation has been that carbon concentration has increased in the solid mass and the Hydrogen and nitrogen concentrations have gone down. Our major concern has been to explore the potential of converting the municipal solid waste into a solid fuel, the pH and conductivity has been more or less around the neutral therefore the main aspects like CHN concentration and the calorific values will be discussed extensively. Standard Carbon content and calorific values of various types of coals are as under as a reference to compare.

Table 6 Standard Carbon content and calorific values of various types of coals

Sr.no	Type of Coal	Carbon %	Calorific Value (MJ/kg)
01	Peat	>60	14.7
02	Lignite	65	23
03	Subbituminous	80	33.5
04	High-volatile bituminous	86	35.6
05	Medium-volatile bituminous	90	36
06	Low-volatile bituminous	91	36.4
07	Semianthracite	92	36
08	Anthracite	95	35.2

As per the early trends, the carbon percentage rose to 39.9% in S1 during trial 1 from 34.31% in sample B. It indicates that carbonization indeed started at 180 C but could not yield any desirable results in terms of carbon concentration and calorific value for a reaction time of 1.5 hour. In the subsequent test, Trial 2 for sample S2 at 180 C for 3 hours, the carbon percentage reached a 42.07% and the calorific value crossed a little above 18 MJ/kg. The coal can be used for domestic heating but due to carbon concentration below 50% it will not be a cleaner solution. The general trend has been, with the increase in time the carbon concentration has increased along with the calorific value of the feedstock and hence in trial 4 with S2 at 180 C and 6 hours of reaction time the Carbon percentage achieved is 45.02% and the calorific value rose to 21.58 MJ/kg. After increasing the temperature in the subsequent trials for S5 to S8 the yield decreased greatly but the quality of char increased very well, the yield dropped as 74.2, 69.8, 66.18, 61.4 percent respectively but the Carbon percentage increased up to 54.57% in the trial 8 for S8. The char produced in these trials can be used in domestic heating as well as in the boilers in the briquette form. The third set of trials which involved a temperature of 220 C and pressure at >18 bar saw some desirable and appealing results. Though the yield of the char greatly decreased in the pattern as 70.2, 63.9, 57.5, 52.7 percentages in the S9 to S12 samples respectively but the carbon concentration grew to 50.33, 60.54, 64.98, 70.02 percent from 34.31% in sample B, which is comparable to sub bituminous coal. The calorific value is also observed to grow very well in these trials, the calorific value of S9, S10, S11, S12 is 22.1, 24.84, 26.43, 29.07 MJ/kg respectively. When compared to the standards, the quality of the char produced lies between lignite and sub bituminous coal. The char produced is darker in colour, lighter in weight and much more porous. The Char produced in S12 is compared to the B (written as S1 for testing purpose only) with the help of scanning electron microscope (SEM) images to identify the main changes in the structure of the char. The SEM images of the sample B comprise of a mix of spherical and rod-shaped structures which are densely packed together. The main morphological change observed in the SEM images of sample S12 is that they have become smooth, less dense, which implies that the porosity has increased. One more noticeable change observed in S12 is that the spherical structures have reduced and major mass is rod shaped and smoother than the sample B. The images at different distances are as under.

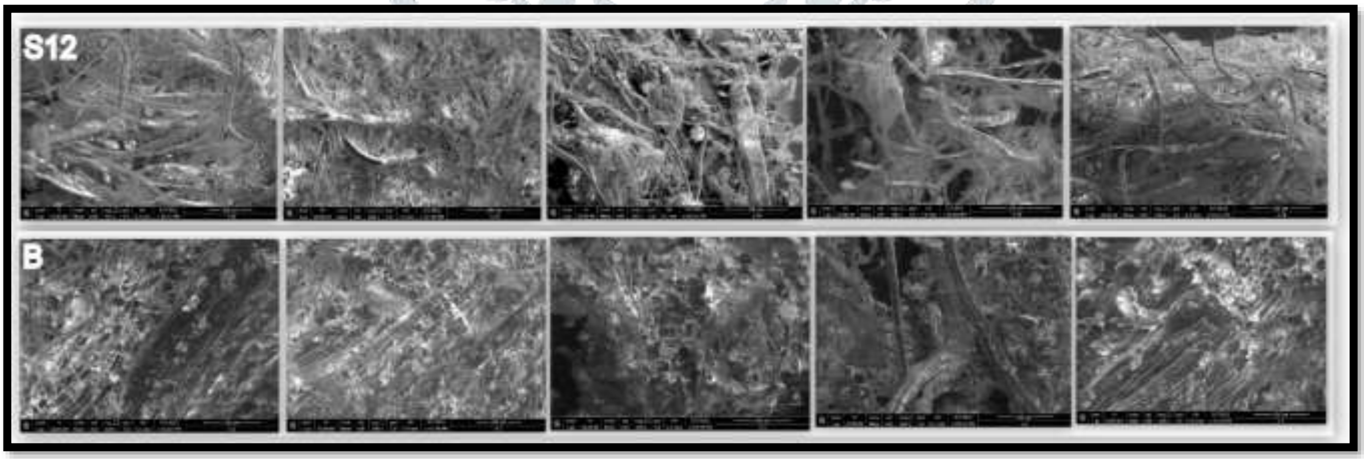

Fig. 9 SEM images of S12 and B

VI. Conclusion

Waste to energy technologies is an emerging trend in the way of sustainable development. It provides safe and environment friendly disposal of municipal solid waste along with products which can be used as fuels, agricultural products, wastewater treatment technologies, soil amendments. It helps to create electricity and heat along with resolves the problem of solid waste management.

The above study reveals that hydrothermal carbonization of municipal solid waste provides a unique opportunity to convert the waste into a value-added char. The testing part makes it clear that the quality of char differs considerably at various temperatures and reaction periods. Surface morphology using SEM micrographs revealed significant increase in rupture of the original structure with an increase in HTC reaction condition. It is also visible that the HTC improved grindability, making it similar to that of coal at higher reaction condition (S6 to S9). Improvement of the grindability is attributed to the weakening of lignocellulosic component of biomass during HTC. Hydrochar prepared by S1 to S5 have better flowability and is suited for fluidized bed combustion however, hydrochar prepared by S6 to S9 have inferior flowability therefore is better suited for making briquettes and fuel pellets.

Every sample treated with HTC has shown positive changes in CHN and Calorific value tests as compared to the precursor, original municipal solid waste sample. Higher temperature and reaction time affects the yield of the char but the overall quality of the char stands improved. Most of the samples resemble peat and lignite type of coal and the sample S11 & S12 nearly show the properties of sub bituminous coal. Peat is used for domestic heating purposes as an alternative to firewood and forms a fuel suitable for boiler firing in either briquetted or pulverized form. Peat is also used for household cooking in some places and has been used to produce small amounts of electricity. Lignite is mostly used to generate electricity. However, small amounts are used in agriculture. Subbituminous coals are a type of coal whose properties range from those of lignite to those of bituminous coal and are used primarily as fuel for steam-electric power generation. The data presented in this study helps us to draw a conclusion that hydrochar with its improved properties such as calorific value, CHN concentration, grindability in comparison to is precursor (Municipal Solid Waste) can be used to substitute coal thus establishing it as a valuable renewable source of energy.

VII. References

(i) Agrawal, Akhilesh Kumar. Avlokita. "Recent trends in solid waste management status, challenges, and potential for the future Indian cities – A review. ." Elsevier, Current Research in Environmental Sustainability (2020).

(ii) Bach Q, Skreiberg. "Upgrading Biomass Fuels via Wet Torrefaction: A Review." Renewable and Sustainable Energy (2016): 665-677.

(iii) Benavente, V., Calabuig, E., Fullana,. "Upgrading of moist agro-industrial wastes by hydrothermal carbonization." Journal of Analytical and Applied Pyrolysis (2015): 89-98.

(iv) Hari Bhakta Sharma, Sagarika Panigrahi, Brajesh K. Dubey. "Hydrothermal carbonization of yard waste for solid bio-fuel production: Study on combustion kinetic, energy properties, grindability and flowability of hydrochar. ." Elsevier. Waste Management (2019): 108-119.

(v) Ramke, Blohse, D., Lehmann, H.-J., Fettig. "Hydrothermal Carbonization of Organic Waste in Sardinia Twelfth International Waste Management and Landfill Symposium." CISA Publisher (2009).

(vi) Sermyagina, E., Saari, J., Kaikko, J. and Vakkilainen, E. "Hydrothermal Carbonization of Coniferous Biomass: Effect of Process Parameters on Mass and Energy." Journal of Analytical and Applied Pyrolysis (2015): 78-83.

(vii) Hoekman, S. K., Broch, A., Felix, L., & Farthing, W. Hydrothermal carbonization (HTC) of loblolly pine using a continuous, reactive twin-screw extruder. Energy Conversion and Management, 134, 247–259. doi:10.1016/j.enconman.2016.12.035. 2017.

(viii) Irena Pavlovic, Zeljko Knez, and Mojca Skerget. Hydrothermal Reactions of Agricultural and Food Processing Wastes in Sub- and Supercritical Water: A Review of Fundamentals, Mechanisms, and State of Research. Journal of Agricultural and Food Chemistry. Sep 2018.

(ix) K. Vijayaraghavan. Recent advancements in biochar preparation, feedstocks, modification, characterization and future applications. Environmental Technology. Reviews. P. 47-64, DOI: 10.1080/21622515.2019.1631393. June 2019

(x) Nicole D. Berge, Kyoung S. Ro, Jingdong Mao, Joseph R. V. Flora, Mark A. Chappell, and Sunyoung Bae. Hydrothermal Carbonization of Municipal Waste Streams. American Chemical Society. 2011.

(xi) Raghu Kc. Hydrothermal Carbonization of Deciduous Biomass (Alnus incana) and Palletization Prospects. Environmental Science and Pollution Research (2020) 27:24369–24379. April 2020.

(xii) Gwenella Saverettiar, Dan Li, Amit Gross, Goen Ho. Hydrothermal Carbonization of Cattle Paunch Waste: Process Conditions and Product Characteristics. Journal of Environmental Chemical Engineering, Elsevier. 2020.