Steam-Enhanced Gasification of Municipal Solid Waste (MSW)/Refuse Derived Fuel (RDF)

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Abstract. Steam-enhanced gasification of MSW/RDF is an innovative sustainable waste management technique to generate rich syngas for the generation of either electricity or hydrogen. Renewable energy generation through gasification is clean as well as affordable. It has the potential to facilitate the development of sustainable cities and communities. Auto-thermal, chemical looping gasification, plasma gasification, etc. are types of gasification classified based on variation of the environment of gasification. A demonstration plant, based on steam-enhanced gasification of MSW/RDF effectively gasifies 15 TPD MSW/RDF to produce syngas. Innovative solutions such as for syngas cleaning and refiring of tar collected in the gasifier contribute sustainable waste treatment for energy production. The innovative heat recovery mechanism for in-process applications improves the thermal efficiency of the system. It is analysed that separation of hydrogen from syngas is more efficient and economical as compared to generation of hydrogen through electrolysis using the electricity generated. Enriching an oxidising agent such as air with oxygen will further enhance the hydrogen generation capacity. Hydrogen generated through the thermochemical route, whereas hydrogen separated from syngas using separation technologies, is considered green hydrogen.

Keywords: Gasification, MSW/RDF, Waste to Energy, Hydrogen

1 Introduction

By 2030, energy demand in India is projected to rise by 35%. The energy imports bill of India, the third largest energy consumer globally, has already reached $185 billion in 2022 [1]. Moreover, energy consumption is the main contributor of 33.1 Gt CO_2 emission from energy production based on fossil fuels in 2018 [2].

Municipal solid waste (MSW) contains organic materials such as food waste, decayed vegetables, paper, cardboard, rotten fruits, slaughterhouse waste, etc. and inorganic materials such as electronic waste (e-waste), metals, batteries, construction and demolition debris, textiles, rubber, glass, plastics, ceramics, etc. [3-5]. Conventionally, wastes are dumped into non-engineered landfills or incinerated in the open, either way impacts the environment adversely [2]. For instance, 1805 PJ of energy lost through incinerators and 1409 PJ through landfills for waste disposal in the EU in 2012 [2, 6]. It necessitates the development of technologies and systems for

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sustainable waste management in urgency to tackle the global challenge of projected 6 million tonnes/day waste generation by 2025 [3, 7]. Subsequently, Waste to Energy (WtE), an important global concept to develop a sustainable waste management system, could be a source of affordable and clean energy, leading to the development of sustainable cities and communities, in turn generating wealth from waste. Thus, waste-to-energy technologies could be an instrument to achieve some of the United Nations' sustainable development goals [3, 8].

Either electricity or hydrogen can be generated after gasification of MSW/RDF (refuse derived fuel) and controlled treatment of syngas generated. In line with India's net-zero target, it is required to produce 5 MMTPA of green hydrogen by 2030 [1, 9]. For bolstering green hydrogen generation in India, the World Economic Forum, along with Bain & Company, delineated the strategies in their report titled "Green Hydrogen: Enabling Measures Roadmap for Adoption in India," claiming greenhouse emission reduction by 50 million metric tons [1]. With the expected humongous increase in demand for hydrogen for greening the steel industry and heavy-duty transportation sector, the National Institution for Transforming India (NITI Aayog) projected a quadruple increase in demand for green hydrogen, amounting to 29 million tonnes by 2050 [10]. When produced using renewable energy sources, hydrogen, being a clean fuel, has the potential to contribute to the decarbonisation of the thermal power plants and other industries in the energy sector [3, 11]. Globally, at present 96% of total hydrogen is generated using fossil fuels, which includes 30% from heavy oil and naphtha, 48% from natural gas, and 18% from coal. Hydrogen produced from these processes is not green, as these processes are associated with the emission of about 560 million tonnes CO_2 annually, which accounts for 1.7% of energy-related CO_2 generation globally [3, 12].

A demonstration plant of an MSW/RDF based steam-enhanced gasification plant has been set in Greater Noida by research wing of a power generating public sector enterprise. It was envisioned that hydrogen production would come from the syngas produced in the MSW/RDF gasifier. Moreover, the power block for the generation of electricity using syngas was planned for meeting the part requirement of renewable electricity for the green hydrogen microgrid that will also contribute to making research centre, a net-zero campus. In addition to air, the use of a mixture of air-steam gasification medium may enhance the percentage of hydrogen in the syngas.

2 Material & Methods

2.1 Waste

Suitable wastes for the generation of energy are mainly biomass wood wastes such as paper industry waste, municipal solid waste, packaging and plastics, sewage sludge, RDF, timber industrial wastes, etc. [3, 13, 14]. In general, MSW is comprised of several kinds of wastes, such as recyclable material, biodegradable waste, combustible materials, inert and electronic waste, hazardous toxic wastes, etc. [3]. The average higher heating value of MSW as found in the European Union is around 10 GJ/Mg. As per the Central Electricity Regulatory Commission, "municipal solid waste' implies residential and commercial wastes generated in a notified or municipal area in either solid or semi-solid form. Further, as per this definition, industrial hazardous wastes are not included in municipal solid waste, but treated biomedical wastes are taken. The components of MSW, such as plastic, pulp, wood, organic waste, and other chlorinated materials, are considered combustible parts of MSW. As per the SWM Rules, 2016, the combustible part of MSW in the form of fluff or pellets, which is produced by processes including drying, shredding, dehydrating, and compacting solid waste is called RDF.

As shown in Fig. 1, the residual dry combustible fraction of the municipal solid wastes, such as textiles, rags, paper, jute, multi-layered packaging, leather, rubber, thermocol, non-recyclable plastic, other compound packaging, cell phones, melamine, coconut shells, etc., are different components of RDF taken one or all together. The station heat rate for power projects that use RDF and municipal solid waste (MSW) shall be 4200 kcal/kWh. The energy content of RDF depends upon its composition, which may vary as their origins vary [15-17]. It further depends on methodologies of sorting, separating, and processing waste material. Table 1 compares the energy content of MSW with respect to other potential biomasses. Here, daf is expanded as dry ash basis and db as dry basis.

For meeting the requirement of gasification, MSW is pretreated to achieve desired physical and chemical properties [18]. The pretreatment processes consisted of both mechanical (Fig. 2) and biological techniques, and they were executed in several stages: sorting, separating, size reduction, briquetting, etc.

2.2 Gasification

The thermochemical processes for waste to energy such as gasification, auto-thermal gasification, chemical looping gasification, plasma gasification method, etc. have several advantages, such as seventy to eighty percentage reduction of mass and an eighty to ninety percent reduction of volume of municipal solid wastes fed as feedstock. Further, bottom ash and slag produced as solid residue in thermochemical processes may be reused in construction-related activities like filler for concrete, road construction, asphalt or low-cost tiles, embankments, etc. [19].

The gasification process involves heating carbonaceous feed at a high temperature range such as 500 °C to 1200 °C keeping 0.1 MPa atmospheric pressure, and maintaining an oxygen-deficient environment. In such environment, partial combustion of the combustible component of municipal solid waste occurs, generating syngas rich in hydrogen and carbon monoxide [20]. With air as oxidant, a gasifier operating at atmospheric process produces a low-energy gas mix consisting of about 10% CO_2, 20% CO, 15% H_2 and 2% CH_4 (by volume) with an energy content in the approximate range of 5.2 to 6.0 MJ/m^3 [20]. The energy content of syngas enhances with oxygen as oxidant in the range of 12.9 to 13.8 MJ/m^3 [20]. Further, a stringent pre-treatment process is required for processing feedstock, making it a more energy intensive process [21].

2.3 Production of Syngas from MSW-RDF

A demonstration plant for producing syngas through steam-enhanced gasification of MSW/RDF with a capacity of utilizing 15 TPD MSW/RDF has been set up to generate energy (Fig. 3). The gasifier is designed to feed 565 kg/h of MSW/RDF to produce 1400 Nm^3/h syngas at gasifier output. The produced syngas is cleaned and conditioned and used as a fuel in an internal combustion (IC) engine to generate electricity. With designed feed rate, 130 kg/h ash is also produced as solid residue. About 200 L/h water is fed to water jacket which converts into steam through gasifier heat. This steam along with air are blown to gasifier as oxidiser.

Fig.1. Photograph of MSW-RDF received at site.

Fig.2. Photograph of shredded MSW.

Table 1. Characteristics of MSW and other biomass feedstocks [17]

Biomass/ Parameters	MSW	Grasses	Sugarcane Bagasse	Primary Sewage	Wood
C (%, daf)	27-55	46-51	45.3	43-53.3	50-55
H (%, daf)	3-9	6-7	6.1	6.5-7.2	5-6
N (%, daf)	0.4-1.8	0.4-1.0	0.2	3.8-5.3	0.1-0.2
O (%, daf)	22-44	41-46	46.8	32-46.6	39-44
S (%, daf)	0.04-.18	<0.02-.08	-	2.1	0-0.1
Volatile matter (% db)	41-71	75-83	NR	60-80	70-90
Ash (% db)	12-50	1.4-6.7	NR	16-25	0.1-8
Moisture content (% fresh wt.)	15-40	Not Reported (NR)	NR	90-96	5-20 (dried wood)
HHV (MJ/Kg)	2-14	18.3-20.6	16.7	18-29	19-22
Particle size (mm)	Average: 180-200	Not Applicable (N/A)	0.56-0.85	<5 (82% wt. <0.1)	NA

2.4 Process Description

The process of gasification of MSW/RDF and generation of electricity can be divided into six different sections: 1. Preparatory, 2. Gasification, 3. Gas Cleaning, 4. Engine, 5. Utility, and 6. Auxiliary sections.

Preparatory Section. Pre-treatment of MSW is defined as all intermediate process steps for modifying physical or chemical properties of an MSW/RDF as desired [18]. The intermediate process steps include sorting, separation, mechanical size reduction, and biological treatment [18]. The loose RDF with a size of around 200-250 mm is screened to remove oversize materials, stones, rocks, and heavy materials and passes over a magnetic plate to remove ferrous metals. Then, it is lifted using a Bobcat and loaded on a conveyor for shredding to resize it up to 30-50 mm using a 2 TPH capacity shredder. The shredded material is stored in a storage area of 80 square metres by using a storage conveyor (Fig. 2). Two briquetting machines with one tonne per hour (TPH) production capacity each are utilized for making approximately 100 mm long briquettes with 90 mm diameter after compressing the resized RDF hydraulically. Briquettes are stored manually in a storage area of 75 square metres. Each briquetting machine has its standalone cooling tower and water circulating pumps for internal cooling of its lubricating oil.

Gasification Section. Solid fuel (RDF briquettes) is converted to gaseous fuel (syngas) with the help of a gasifying medium that is a mixture of air and steam. The RDF gasifier is an updraft fixed-bed gasification system designed to process RDF briquettes at a feed rate of 15 tonnes per day (TPD).

Fig. 3. Photograph of the RDF gasification-based net 400 kWe X 24 hrs power generation plant.

As per the design of the updraft-type gasifier, the gasifying medium (air and steam mixture) is forced to pass through the fuel bed in the gasifier from the bottom, and the generated syngas exits out from the top. There are four distinct processes: (i) Combustion, (ii) reduction/gasification, (iii) pyrolysis, and (iv) drying of MSW/RDF occur in different zones of the gasifier with syngas as a final desirable product.

Water, carbon dioxide, and pyrolysis products occur in the combustion zone. Also, pyrolysis products are uncombusted but partially cracked. When these products of the combustion zone pass through the heated charcoal bed, the reduction reactions take place. Fuel pyrolysis is an intricate process. The composition of syngas varies according to temperature, pressure, residence time, and heat losses occurring in the gasifier. Based on experiments, a general trend can be expected based on variation in temperature and other control factors. At first, only water is driven off from RDF up to the temperature of 200 °C. Then, phenolic compounds with left out water are given off between 200°C to 280 °C. Large quantities of tar are produced during actual pyrolysis taking place between 280 °C to 500 °C. During this temperature range of 500 °C to 700 °C, a small quantity of syngas is produced. Thus, the updraft gasifier is prone to produce tar compounds significantly. As the fuel has a moisture content of up to 10%, this moisture gets evaporated in the drying zone to make the fuel dry. The gasifier shell has two jackets, one above the other (Fig. 4). One (topside) for air preheating and another (bottom side) for steam generation. These jackets mainly prevent overheating of the gasifier shell and recycle the heat back to the gasifier in the form of preheated air and steam. The blower supplies adequate air to generate the desired quantity of gas. The air blower changes speed by sensing gasifier outlet pressure with the help of a variable frequency drive (VFD) to maintain the required air quantity in the gasifier. Air is passed through the top side jacket of the gasifier to preheat air before injecting it into the gasifier. The steam generated in the bottom side jacket of the gasifier is mixed with preheated air in the steam injector, and the mixture is introduced in the gasifier. The water level of the steam jacket is maintained by pumping make-up water.

Gas cleaning Section. Hot syngas exiting from the gasifier is cooled with the first gas cooler from 210°C to 85°C. As temperature goes down, the higher volatile compounds (if any) are condensed based on their condensation temperature. The temperature of syngas is maintained around 85°C by controlling the flow of cooling water. The gas then passes through the electrostatic precipitator (ESP), where tar and fine solids are separated. gas from the ESP is passed through the second gas cooler, where it gets cooled to around 45°C and the majority of volatiles and water vapour are removed. Subsequently, cooled syngas is passed through the scrubber.

The process of gasification has been shown in Fig. 5. Here, in the direct contact type, the scrubber, the entire syngas, is scrubbed with water and cleaned up to its maximum limit, and it is ensured that there should not be any unwanted particles and/or phenolic compounds in the gas. Then, the gas is passed through the gas chilling section in the chilled water cooler, where indirect cooling occurs and moisture as well as low-temperature volatiles, if any, get separated.

2.5 Innovative Features

- The gasifier shell has two jackets, one above the other, one for air preheating (topside) and the other for steam generation (bottom side). The main purpose for the arrangement of both jackets is to prevent overheating of the gasifier shell and recycle the heat back to the gasifier in the form of preheated air and steam.
- The required quantity of air by the gasifier to generate the desired quantity of gas is supplied by an air blower, which changes speed by sensing gasifier outlet pressure with the help of a variable frequency drive (VFD) to maintain the required air quantity in the gasifier. Air is passed through the top side jacket of the gasifier to preheat the air before injecting it into the gasifier. The steam generated in the bottom side jacket of the gasifier is mixed with preheated air in the steam injector and then introduced into the gasifier. The water level of the steam jacket is maintained with a pump.
- Water vapour, tar, phenolic compounds, etc., which are generated in the gasifier during the gasification process, need to be separated using the gas cleaning section. The separated liquids called tar and phenolic water (a mixture of water and phenolic compounds) are the liquid pollutants of this process, and both compounds have some calorific value. Therefore, tar and phenolic water are recycled back to the gasifier for re-firing. This recycling helps to utilize available heat value and to reduce effluent, making zero liquid discharge (ZLD) process. All equipment in the cleaning section has a separate bottom outlet for separation of condensed tar and/or phenolic water. This tar and phenolic water are transferred to respective underground tanks for further separation and reuse.

Fig.4. Photograph of the MSW/RDF Gasifier

- Collected tar from the cleaning section is passed through a heater to preheat. The preheated tar is injected into the combustion zone of the gasifier with the help of a gear pump. Phenolic water collected in the cleaning section is evaporated in a separate evaporator with the help of gasifier jacket steam. The generated phenolic water vapours are mixed with the preheated air in the steam injector. The air and phenolic water vapour mixture (as a gasifying medium) is injected to the gasifier.
- The gas cooler has two sections. The gas is cooled to 20°C in a gas cooler, which is used as a pre-cooler for scrubber outlet gas. The scrubber outlet gas is cooled by 20°C. This precooling helps to reduce the load on the chiller.

2.6 Waste to Energy

After gasification, electricity is generated by using any of the two possible routes. First, hydrogen is separated from syngas, and then electricity is generated using PEM-based fuel cells. Additionally, electricity is produced by combusting balanced carbon monoxide with the minimum required percentage of hydrogen in a gas engine. Moreover, separation of hydrogen and then electricity generation has also the advantage of gasifying MSW/RDF at the source and generating electricity at the place of need.

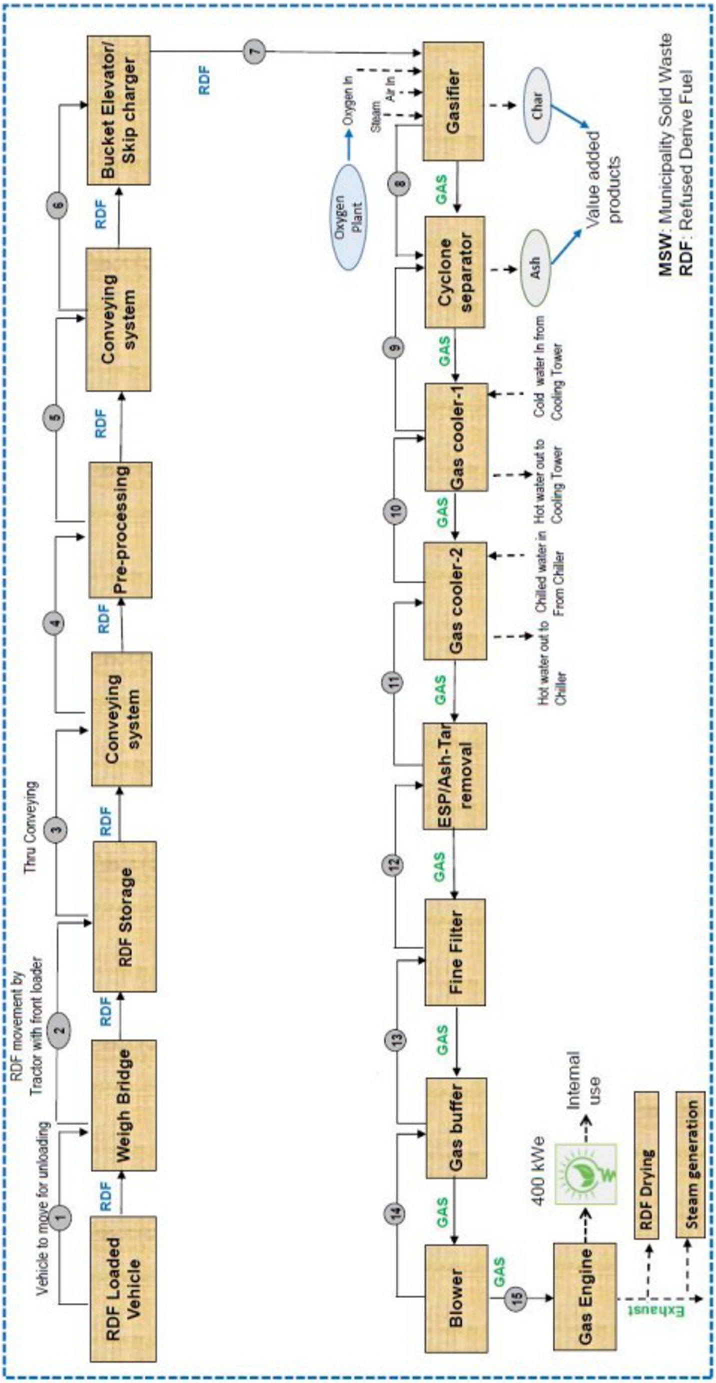

Fig. 5. MSW/RDF based Gasification Process Flow Sheet

Secondly, electricity can be generated directly by combusting total syngas produced in a gas-based internal combustion engine and feeding the power into the grid. Presently, the second path of electricity generation from the gasification of MSW/RDF has been demonstrated.

The power generation section of the demonstration plant consists of a gas engine, an alternator, an engine exhaust, and engine cooling equipment. Clean syngas is transferred into the gas holder with the help of the induced draft (ID) blower. Further, the gas holder acts as a buffer for the supply of gas to the engine. Clean syngas from the holder is combusted in the gas engine to generate the electricity. The ID blower changes speed with the help of VFD by sensing gas holder pressure and varying the gas flow as per requirement. Booster blowers controlled with VFDs supply from the gas holder to the engine in a controlled way, sensing pressure at the engine inlet. Electricity is generated with combustion of syngas in the engine and associated alternator. Two different cooling circuits called high-temperature (HT) cooling and low-temperature (LT) cooling are working independently to fulfil engine-cooling requirements. Part of the generated power is used to operate plant utilities, and the remaining power is exported into the grid.

3 Results and Discussion

3.1 Pre-Treatment of MSW/RDF Feed

The typical composition of briquettes (Fig. 6) consists of 71.64% carbon, 3.51% hydrogen, 2.4% moisture, 0.61% sulphur, 16.54% ash, 0.58% nitrogen, 7.12% oxygen, and 0.10% chlorine with a gross calorific value (GCV) of about 3158 kcal/kg as obtained from laboratory experiment with procedures conforming to IS 1350 Part 1 (proximate analysis), ASTMD 5865 (GCV), ASTMD 5373 (C,H&N), ASTM D 4239 (S) and apparatuses: CHNS Analyser (Vario Macro Cube), automatic bomb calorimeter (Arico Instruments IP-1), Sulfur Analyser (ELTRA CS-580A). For preventing any damages, the briquettes are fed into the gasifier using bucket lift. This ensures in maintaining distinct zones for several processes/reactions for efficient gasification producing quality syngas.

3.2 Operational Evaluation

Operational data of the steam-enhanced MSW/RDF gasification for a random day has been taken for evaluation. As shown in Fig. 7, the syngas generated from gasifier consists of 13.22% H_2, 55.25% N_2, 22.91% CO and 1.493% CH_4 and other gases, which has been evaluated using gas chromatograph (Make: Kshama, Model: 1310RJ). The hourly variation of feed to the gasifier and corresponding power generated, auxiliary power consumed, and net power exported have been shown in Fig. 8. Power has been exported as per demand based on NETRA Microgrid management system. As shown in table 2, 11.11 tonnes of MSW/RDF have been fed to produce 7088 kWh electricity. 1098 kWh electricity out of this generated electricity has been utilized as auxiliary power to run pumps, motors, fans, etc. Based on the energy content in the feedstock and total power generated, 20.56% efficiency has been achieved.

Exhaust Gas Management. To enhance environmental sustainability, exhaust gases from the engine are directed to the auxiliary section for scrubbing before final venting to the atmosphere. As shown in the Fig. 9, the continuous emission monitoring system (Make: Bhoomi, model: B1700-RM-Flexi) monitors pollutants in the exhaust, enabling real-time control to maintain emissions within regulatory limits. It complies the requirement of ISO 17025:2005 standard with certified gas concentration CO2 17.75%, CO-770 ppm, NO-745 ppm and NMHC is 730 PPM.

Energy Recovery in Gas-Gas Heat Exchanger (GGX). During the process, syngas after wet scrubber with temperature 33 °C is cooled using chiller for separation of moisture by condensation and then the cleaned syngas is heated to room temperature 30 °C before blowing into the gas buffer for storage and further applications. For the purpose of energy recovery, as shown in figure, the incoming comparatively hot syngas and outgoing chilled gas are passes through GGX (Fig. 10). The power saved for cooling has been estimated using water droplets from GGX. 5 Kg of water has been collected from GGX. Estimation and consider double effect of cooling and heating, 161 kWh per day.

3.3 Ash Management

Wet Ash Collection. The ash exiting the bottom of the gasifier is wet because it passes through the water seal. As shown in Fig. 11, The wet ash cake is periodically removed by rotating the ash pot. Next, the ash is weighed and loaded into a mobile trolley, which transports it to temporary storage for disposal or use in various applications.

Ash Utilization. According to the preliminary chemical analysis report, the ash can be used as a fertilizer or vermicompost. The bottom ash obtained from the gasification process contains calcium (~218 ppm), potassium (~48 ppm), phosphorous (~4.39%), potash content (~13.90%), and other elements. The test has been carried on by Oatman Overseas Private Ltd. (an ISO: 9001:2015 & ISO:14001 certified laboratory).

Fig. 6. Photograph of the MSW Briquettes.

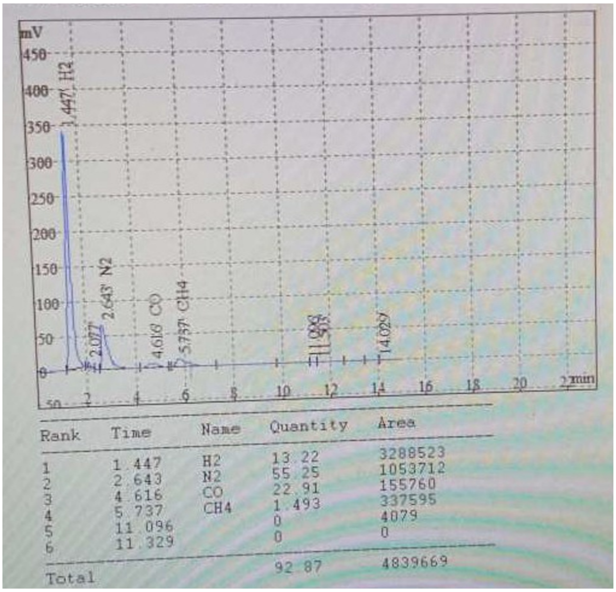

Fig. 7. Syngas Composition

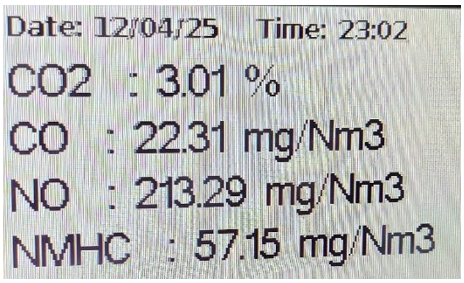

Fig. 8. Photograph of the display screen showing continuous emission monitoring system

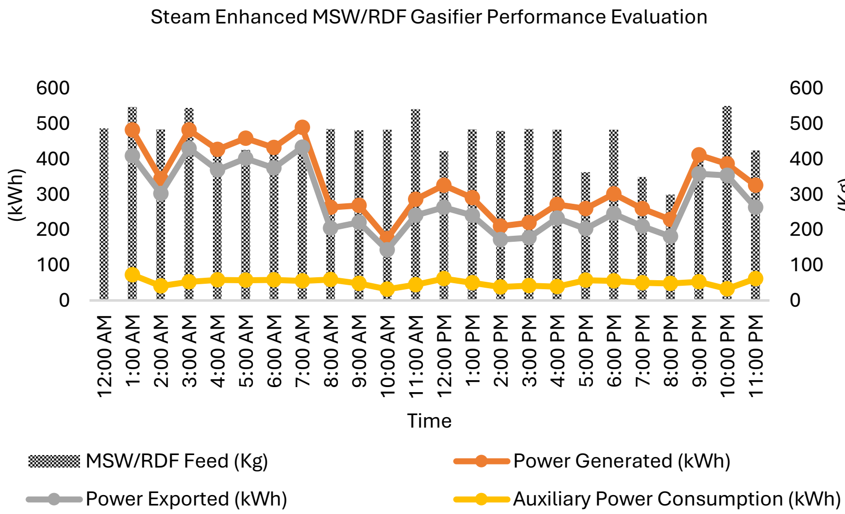

Fig. 9. Performance evaluation of steam enhanced MSW/RDF gasification plant for power generation

Fig. 10. Photograph of the gas-gas heat exchanger with chiller unit.

Table 2. Operational Parameters Evaluation

Plant Performance Indicators	Value
Total Feed in a Day (Kg)	11110
Average Hourly Feed (kg)	462.92
Total number of Bucket used	183
Average per bucket feed (kg/bucket)	60.71
Average Ash % in MSW/RDF	8
Ash% Range in MSW/RDF	7-9
Average Moisture % in MSW/RDF	6
Moisture% Range in MSW/RDF	5-8
Average GCV of MSW/RDF (kcal/kg)	2668.70
Total Energy Input (kcal)	29649257
Total Energy Input (kWh)	34481.76
Power Input (kW)	1436.74
Total Power Produced from gas engine (kWh)	7088
Total Power Exported NETRA grid (kWh)	5990
Auxiliary Power Consumption (kWh)	1098
%Efficiency of Power Conversion	20.56
%Efficiency of the System	17.37
Average AFR	2.27
AFR Range	2-2.5
Water Consumption (L)	7750
Water Consumption per Hour (L/h)	322.92

3.4 Chemical Processes Involved in Gasification

In the current design of the gasification plant, the syngas output has carbon monoxide (CO) between 16% and 18% by volume and hydrogen between 12% and 14% by volume. Further, nitrogen, the major constituent of the syngas, is between 55% and 60% by volume. The calorific value of syngas is determined by the percentage of constituent carbon monoxide, hydrogen, and inert gases in the syngas. composition is identified using online gas analyser (type: Semiconductor sensor, Make: Figaro engineering Inc. for gas sensor and Atmel Corporation for microcontroller).

The gasification process in the gasifier is accomplishes in four stages, which are drying of incoming feedstock, pyrolysis, oxidation (i.e., combustion), and reduction [22]. In the drying stage, moisture from MSW/RDF is evaporated, whereas dried MSW/RDF and water vapour are produced. Dried MSW/RDF undergoes devolatilization reactions during the pyrolysis stage, producing char as solid products, tar as liquid products, and condensable and non-condensable products (CO, CO_2, H_2, CH_4) as gases [23]. During the oxidation stage, partial oxidation reactions take place between oxygen with char, hydrogen, and methane, besides thermal cracking of heavy tar to lighter gases [23].

In the final stage, reduction reactions occur, producing carbon dioxide, hydrogen, and methane. These reactions are critical for the composition of flammable gases (i.e., CO, H_2, CH_4, etc.) and low heating value (LHV) [23]. Reactions occurring in the gasification process are listed in Table. 2. CO_2 formation is required for heat generation and hydrogen generation. The higher the hydrogen percentage, higher is the calorific value of the syngas, but it also generates CO_2 (inert for PG as fuel), which reduces calorific value.

Enrichment of oxygen present in air by 5% shall reduce the presence of inert nitrogen in the syngas, but the hydrogen production does not necessarily increase. In fact, the hydrogen production (in absolute terms) is a function of the heat available for endothermic reaction and the quantity of additional steam injection possible in the gasifier. Table 3 enlists the expected composition of the syngas.

It can be seen from the above data that nitrogen from air forms a maximum of 64% by weight of the syngas. Hydrogen, on the other hand, is 1% by weight, which corresponds to around 15 kg/h for the syngas generation of 1500 kg/h by design. It is possible to isolate this hydrogen through a series of cold separation processes for CO_2, hydrogen, and other gases. A three-column pressure swing adsorption process for low-pressure CO_2 separation has already been demonstrated by setting up a plant.

Combined with this process, molecular sieve-based membrane separation and recovery of hydrogen is possible. The potential for hydrogen recovery at 75% yield is 270 kg/day. Air may be enriched with oxygen to reduce nitrogen concentration. In case of higher concentration (>5%) of oxygen to handle, the basic design parameters & configuration of the existing gasifier reactor need to be changed.

There would be a corresponding change in the weight percentage of hydrogen generated from the syngas through oxygen enrichment as shown in table 4. It is expected that the hydrogen generation can be increased by up to 40% with 10% enrichment of oxygen in air. In other words, for the same 1500 kg/hr syngas generation, hydrogen generation capacity would be 21 kg H_2/hr and potential for hydrogen recovery at 75% yield is 378 kg H_2/day.

Comparison of Hydrogen Generation Options with Electrolysis and Gasification. As shown in table 5, the hydrogen production potential from the syngas generated from the gasifier directly is higher as compared to the hydrogen production potential via electrolysis of water using the same amount of electricity, which can be generated (400 kW) using the syngas generated in the gasifier (1500 kg/day) as a feed in the gas engine. Moreover, the electrolysis process includes capital-intensive equipment such as an engine, electrolyser, etc., whereas pressure swing adsorption (PSA) and molecular sieve can be used for separating hydrogen from syngas, which are comparatively less capital intensive.

Fig. 11. Photograph of the ash collection from gasifier.

Table 3: Reactions occurring during gasification process at 25 °C [22]

Reaction	Reaction type	Reaction	ΔH (kJ/mol)
Carbon reaction			
CR1	Boudouard Reaction	$C + CO_2 \leftrightarrow 2CO$	+172
CR2	Water-gas or steam	$C + H_2O \leftrightarrow CO + H_2$	+131
CR3	Hydrogasification	$C + 2H_2O \leftrightarrow CO_2 + 2H_2$	-7.48
CR4		$C + 0.5O_2 \rightarrow CO$	-111
Oxidation reaction			
OR1		$C + O_2 \rightarrow CO_2$	-394
OR2		$CO + 0.5O_2 \rightarrow CO_2$	-284
OR3		$CH_4 + 2O_2 \leftrightarrow CO_2 + 2\,H_2O$	-803
OR4		$H_2 + 0.5O_2 \leftrightarrow H_2O$	-242
Shift reaction			
SR1	Water Gas Shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41.2
Methanation reaction			
MR1		$2CO + 2H_2 \leftrightarrow CH_4 + CO_2$	-247
MR2		$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	-206
MR3		$CO + 4H_2 \leftrightarrow CH_4 + 2H_2O$	-165
Steam-reforming reaction			
SRR1		$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+206
SRR2		$CH_4 + 0.5O_2 \leftrightarrow CO + 2H_2$	-36

Table 4. Expected composition of syngas and effect of oxygen enrichment [24]

Syngas Composition	Composition with Ambient Air		Composition with O_2 Enrichment (by 5%)	Composition with O_2 Enrichment (by 10%)
	Vol%	Weight %	Vol%	Vol%
CO	16.3%	18.0%	18.8%	21.1%
H_2	13.2%	1.0%	15.2%	17.1%
CH_4	1.1%	0.7%	1.3%	1.4%
CO_2	7.2%	12.5%	8.3%	9.3%
N_2	58.4%	64.3%	52.0%	46.1%
O_2	0.1%	0.1%	0.1%	0.1%
Ar	0.6%	0.9%	0.7%	0.8%
SO_2	0.0%	0.0%	0.0%	0.0%
H_2O	3.0%	2.1%	3.5%	3.9%
VM	0.1%	0.3%	0.1%	0.1%

Table 5: Comparison of hydrogen generation options with electrolysis and gasification [24]

Hydrogen generation options	Capacity
Hydrogen generation potential by electrolysis	192 kg/day
Hydrogen generation potential (Without Oxygen enrichment)	270 kg/day (@75% recovery)
Hydrogen generation potential (With Oxygen enrichment)	378 kg/day (@75% recovery)

4. Conclusion

Gasification technology has been widely exploited for MSW/RDF conversion to syngas as a waste-to-energy technology, a way to sustainable management of municipal solid waste. Technical challenges, because of the uncertainty of the input feed compositions and thermoplastic wastes, make it difficult to control the output of the gasification process. The MSW/RDF-based gasification plant uses steam along with air as a gasifier medium to enhance the hydrogen percentage. Based on the experiment carried out for operating the plant, the following observations have been found:

i. The syngas generated from the gasifier typically consists of 13.22% H2, 55.25% N2, 22.91% CO, 1.493% CH4, and other gases.
ii. Gas exhaust from the gas engine to generate electricity complies with the requirements of the ISO 17025:2005 standard.

iii. Gas-gas heat exchanger (GGX), based on innovative energy recovery, saves 161 kWh per day, meeting the dual purpose of cooling and heating.
iv. The bottom ash obtained from the gasification process contains calcium (~218 ppm), potassium (~48 ppm), phosphorous (~4.39%), potash content (~13.90%), and other elements. The ash can be used as a fertilizer or vermicompost after validation of its nutritious effect on plants in the nursery of the experimental setup.
v. With the average daily feed of 11.11 tonnes of the MSW/RDF briquettes, 7088 kWh of electricity can be generated using the gas engine. Out of this electricity generated, 1098 kWh is utilized as auxiliary consumption, and the balance is exported for meeting the power requirement of the premises/campuses.

Further, the alternate uses of the syngas - either producing electricity using the gas engine and alternator or separating hydrogen using membrane/PSA technologies - have been analysed for identifying the efficient route of hydrogen production. Hydrogen can be separated by utilizing cold separation processes. The percentage of hydrogen also gets enhanced by the air-steam mix as a gasifier medium. Given the same input quantity of MSW/RDF briquettes, potential generation of hydrogen is around 30 to 50% more than equivalent generation via electrical energy and electrolysis routes. It further saves pure water consumption that is required to be split in electrolysis.

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