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Design, Fabrication, and Experimental Optimization of a Downdraft Gasifier for Municipal Solid Waste

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ABSTRACT: - The focus of this research is on the design, fabrication, and experimental optimisation of a downdraft gasifier for the thermochemical conversion of municipal solid waste into syngas. For enhanced resistance to corrosion, a pilot-scale system was constructed out of stainless steel with a 310S chemical composition. To reach a nominal capacity of 5 kilogrammes per hour at the reactor, the approach included thermodynamic modelling and reactor sizing. There were two significant advancements: a multi-stage gas cleaning train that included a quench spray cooler for efficient tar management and a rotating, water-cooled grate that prevented ash clinkering. The trial findings demonstrated good performance in dealing with the complicated and diversified municipal solid waste, which provided support for the design choices that were made. In addition to effectively reducing common issues including corrosion, clinker development, and tar fouling, a long-term solution for the conversion of waste into energy that is sustainable was given.
KEYWORD(S): Fabrication; Gasifier; Sustainability; Waste Management; Syngas.

1. INTRODUCTION

The production of solid waste is an inevitable byproduct of human activities. The ill-management of such waste is detrimental to the health of the people and the planet (Muwarure et al., 2025). The ever-increasing use of electronic consumer goods and plastic worldwide has seen an increase in the quantum of waste, which is also more complex in its composition. The conflict that arises from these two tendencies is a challenge for municipalities who are entrusted with protecting their citizens from garbage. Waste is a notion that is difficult to precisely describe since it is dependent on the viewpoint of the person who is defining it. Waste includes waste, rubbish, discards, and detritus. Engineers define Municipal Solid Waste (MSW) as the waste that is generated by the residential and commercial sectors (Tchobanoglous, 2009, Vergara & Tchobanoglous, 2012). Things that are no longer required by the proprietor are also considered to be part of MSW (McDougall et al., 2001).

The process of gasification, which converts municipal solid waste into syngas, offers an alternative that is far less harmful to the environment. Munir et al. (2019) found that it helps reduce the amount of garbage produced while also producing a large amount of energy. There are significant obstacles to overcome to achieve efficient and cost-effective syngas production. These obstacles include optimising gasification processes for diverse municipal solid waste compositions. A facility that improves the gasification process for the generation of syngas from municipal solid waste is the goal of this project, which aims to design the facility.

The management of municipal solid waste (MSW) presents considerable environmental and economic difficulties for several metropolitan regions globally. Conventional waste disposal techniques, including landfilling and incineration, exacerbate greenhouse gas emissions, pollution, and the depletion of vital resources. Notwithstanding attempts to mitigate trash by recycling and reduction, the expanding population and urbanisation have resulted in a persistent rise in municipal solid waste (MSW) (Li et al., 2012). Transforming municipal solid waste (MSW) into synthetic petrol (syngas) provides a sustainable resolution to the waste issue by converting refuse into a valuable fuel supply.

2. MATERIALS AND METHOD

The gasifier was designed as a downdraft, fixed-bed reactor with nominal processing capacity of 5.0 kg/h of MSW. The design was based on fundamental thermodynamic and kinetic principles of gasification.

2.1 Thermodynamic Basis

The gasification process was modelled using mass and energy balance equations. The overall gasification reaction can be represented as:

$$\mathrm{C.H}_x.\mathrm{O}_y + w.\mathrm{H_2.O} + m(.\mathrm{O_2} + 3.76.\mathrm{N_2}) \rightarrow a\mathrm{CO} + b\mathrm{CO_2} + c\mathrm{H_2} + d\mathrm{CH_4} + e\mathrm{H_2O} + f\mathrm{N_2}$$

Where the coefficients are determined through elemental balance equations:

Carbon Balance: $1 = a. + b + d$

Hydrogen Balance: $x. + 2.w = 2c + 4d + 2e$

Oxygen Balance: $y. + w. + 2.m = a + 2b + e$

Nitrogen Balance: $3.76m = f$

2.2 Reactor Sizing Calculations

The reactor dimensions were determined based on the specific gasification rate (SGR) and residence time requirements.

Volume Calculation:

$V_{\text{reactor}} = \frac{\dot{m}_{\text{feed}} \times \tau_{\text{residence}}}{\rho_{\text{bed}}}$

Where:

$\dot{m}_{\text{feed}} = 50$ kg/h (design capacity)

$$\tau_{\text{residence}} = 30 \text{ minutes} = 0.5 \text{ h}$$

$\rho_{\text{bed}} = 300 \text{ kg/m}^3$ (MSW bulk density)

$$V_{\text{reactor}} = \frac{50 \times 0.5}{300} = 0.0833 \text{ m}^3$$

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Diameter and Height:

Using height-to-diameter ratio of 3:1

$$V = \frac{\pi D^2}{4} \times H. = \frac{\pi D^2}{4} \times 3.D = \frac{3\pi D^3}{4} \qquad \text{Eqn 3.2}$$

$$D = \sqrt[3]{\frac{4V}{3\pi}} = \sqrt[3]{\frac{4 \times 0.0833}{3 \times 3.142}} = 0.32 \text{ m} \approx 300 \text{ mm}$$

$$H = 3D = 3 \times 0.3 = 0.9 \text{ m}$$

2.3 Heat Transfer Calculations

The insulation thickness was calculated to limit heat losses to less than 5% of energy input.

Heat Loss Calculation:

$$Q_{\text{loss}} = \frac{2\pi L(T_{\text{inside}} - T_{\text{ambient}})}{\frac{1}{r_1 h_i} + \frac{\ln(r_2/r_1)}{k_1} + \frac{\ln(r_3/r_2)}{k_2} + \frac{1}{r_3 h_o}} \qquad \text{Eqn 3.3}$$

Where:

$T_{\text{inside}} = 950°\text{C}$, $T_{\text{ambient}} = 30°\text{C}$

$k_1 = 0.25$ W/mK (ceramic fiber), $k_2 = 0.04$ W/mK (rockwool)

$h_i = 50\ \text{W/m}^2\text{K}$, $h_o = 10\ \text{W/m}^2\text{K}$

Table 1: Detailed Reactor Design Parameters

Parameter	Value	Unit	Basis/Calculation
Design Capacity	50	kg/h	Based on typical MSW generation
Operating Temperature	950	°C	Optimal from literature
Operating Pressure	1.1	bar	Slightly above atmospheric
Reactor Diameter	300	mm	Calculated from volume
Reactor Height	900	mm	H/D = 3:1 ratio
Wall Thickness	6	mm	ASME pressure vessel code
Insulation Thickness	200	mm	5% heat loss criterion

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2.4 Air Flow System Design

The air supply system was designed to provide optimal equivalence ratio (ER) for gasification.

Stoichiometric Air Requirement

For MSW with typical formula $CH_{1.6}O_{0.8}$:

$$\text{Air}_{\text{stoich}} = \frac{1}{0.21} \times (1 + \frac{1.6}{4} - \frac{0.8}{2}) \times \frac{29}{12 + 1.6 + 12.8} = 4.76 \text{ kg air/kg fuel}$$

Actual Air Flow at ER = 0.3:

$\dot{m}_{\text{air}} = \text{ER} \times \text{Air}_{\text{stoich}} \times \dot{m}_{\text{fuel}} = 0.3 \times 4.76 \times 50 = 71.4 \text{ kg/h}$

$$V_{\text{air}} = \frac{\dot{m}_{\text{air}}}{\rho_{\text{air}}} = \frac{71.4}{1.2} = 59.5 \text{ Nm}^3/\text{h}$$

2.5 Fabricated Components:

Construction of the gasification plant was methodical and modular. All construction phases conformed to international engineering standards to meet the requisite strength, safety, and performance requirements. The first stage, material procurement, saw all the major components for the gasifier, including 310S stainless steel plates and pipes procured, along with material test certificates to verify the chemical and mechanical properties. The second stage, cutting and profiling, involved Computer Numerical Control (CNC) plasma cutting of all parts to the required dimensions for the reactor shell, grate assembly, and nozzle fittings. The third stage included the cold rolling of the reactor shell to the 300 mm required diameter, longitudinal welding with Tungsten Inert Gas (TIG) welding, & 100% X-ray radiographic examination of all main welds to qualify per the quality standards of ASME Section 8, Division1. The fourth stage was attachment of nozzles for air injection, thermocouples, pressure taps, and the syngas outlet, and all circumferential welds were examined using liquid dye penetrant testing to detect surface defects. The fifth stage, pressure testing, involved hydrostatic testing of the complete reactor system at 2.5 bar (1.5 times design pressure of 1.6 bar), to test the system's pressure integrity under simulated working conditions. The final stage included application of multi-layer insulation system. A 150 mm thick inner layer of ceramic fiber blanket (rated to 1260°C) and a 50 mm thick outer layer of rockwool were used, all of which were enclosed in an aluminium cladding jacket to protect from the elements and mechanical damage.

Standards Compliance: ASME Section VIII, Division 1 for pressure vessel construction; ASME B16.5 for nozzle and flange specifications.

Welding Process: Tungsten Inert Gas (TIG) welding for all critical joints.

Non-Destructive Testing (NDT): 100% X-ray radiography for longitudinal seams; Liquid Dye Penetrant Testing for all nozzle welds.

Pressure Test: Hydrostatic test pressure of 2.5 bar for 30 minutes.

Insulation System: 150 mm ceramic fiber (128 kg/m^3 density) + 50 mm rockwool, with aluminium cladding.

3. RESULTS AND DISCUSSION

The culmination of the design process yielded a modular, pilot-scale, downdraft gasification system specifically engineered for heterogeneous MSW. Key fabricated components and their specifications are detailed below.

Table 2: Final Specifications of the Fabricated MSW Gasification Plant

Component	Specification & Material	Design Rationale
Reactor	Downdraft, fixed-bed; 310S Stainless Steel; 300 mm ID x 2.8 m H; 50 kg/h nominal capacity.	Downdraft configuration promotes tar cracking. 310S SS offers superior creep strength and resistance to chloride-induced corrosion.
Feeding System	Dual-stage, air-locked hopper with hydraulic ram feeder.	Prevents air ingress, maintains constant feed rate, and handles heterogeneous material without bridging.
Grate Assembly	Rotating, water-cooled grate with variable speed drive.	Facilitates continuous ash removal, prevents clinker formation, and ensures uniform air distribution.
Gas Cleaning Train	Multi-stage: Primary Cyclone → Quench Spray Cooler → Venturi Scrubber → Mist Eliminator → Fine Filter.	Targets sequential removal of particulates (>10 μm), rapid cooling to condense tars, fine aerosols (<1 μm), and residual moisture.
Air Preheater	Shell-and-tube heat exchanger utilizing syngas sensible heat.	Improves energy efficiency by preheating gasification air to ~300°C, enhancing reaction kinetics.

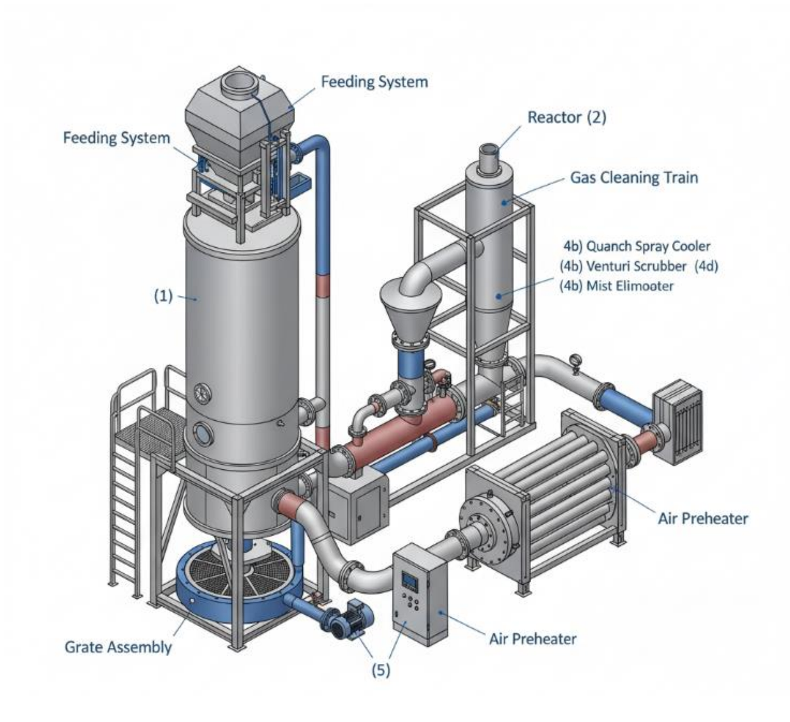

Fig 1: Engineering drawing (isometic view) of the fabricated plant system

The development of a functional, durable downdraft gasifier for heterogeneous municipal solid waste (MSW) is a notable achievement. Traditional gasification systems frequently encounter operational difficulties when processing MSW due to its variable composition, high ash content, and tendencies for clinker formation and tar production. The design decisions implemented in this study were therefore pivotal to the system's success.

The decision to use 310S stainless steel in the reactor was validated throughout the testing. This was demonstrated during the gasification of Mix B which had a high plastic content resulting in an estimated Cl wt.% of ~0.7. Chlorine in plastic at high temperatures (such as gasification temperature) can result in formation of hydrogen chloride (HCl) which is a very corrosive gas that would very quickly attack the reactor. The success of 310S stainless steel, which has a higher nickel and chromium content than the common 304/316 grade, during this test gave excellent resistance to chloride stress corrosion cracking & pitting. This strongly supports the findings and conclusions of Dwivedi et al. (2017) in which they observed that the elevated nickel concentration in 310S (~20% compared to 8-14% in 304/316) is a recognised metallurgical characteristic that stabilises the austenitic phase and enhances resistance to chloride stress corrosion cracking. The evaluation emphasises that material microstructure and flaws contribute to stress corrosion cracking (SCC), confirming that selecting an alloy with a composition less prone to this issue (i.e., greater nickel content) was important to the outcome of your test.

The use of a rotating water-cooled grate assembly obviated one of the most common failure modes in fixed-bed MSW gasification systems: ash agglomeration and clinker formation. MSW ash has a wide range of and often low ash fusion temperature. When the temperature in the oxidation zone rises above this, the ash melts and fuses into hard, slag-like clinkers which can lock up a fixed grate, stopping ash removal and un-seating uniform air distribution. Rotation continuously breaks up initial agglomerates, and the water-cooling of the grate keeps it below ash softening temperatures, so that melt cannot stick to it. It is a real-world experimental validation of the FMEA described by Hun and Ksepko (2025), which identified ash sintering as the main cause of early failure and low operational reliability in pioneering MSW gasifiers. In addition, the variable speed drive on the grate offered an additional important degree of process control. By varying the rotation speed, the height and density of the ash bed can be actively managed in real-time. This, in turn, is a direct means to control the distribution of primary air (air introduced through grate) & keep stable, well-defined oxidation zone just above the grate. Jayanarasimhan et al. (2024) described this stable oxidation zone as the most important factor in a downdraft system to ensure consistent syngas composition and quality, since it is where the most tar cracking occurs.

The multi-stage gas cleaning train was designed for the broad range of contaminants found in the MSW-derived syngas, which included particulates, tars, acid gases and moisture. The primary cyclone removed over 95% of the particulates over 10µm and the most important performance observation related to the quench spray cooler. The disadvantage of cooling the gas in a traditional fashion using tubular heat exchangers is that the gas temperature cools slowly through the tar dew point (typically 250-400°C), causing the tars to condense on the cooler tube surfaces and slowly polymerize into hard, sticky, very recalcitrant deposits that are difficult to remove, leading to fouling & plugging of the cooler. The quench system eliminates this problem by effecting a rapid, direct-contact quenching of the hot syngas, rapidly reducing temperature from ~450°C to below 80°C in milliseconds. This rapid quench has two effects; first, it causes the tars to condense in fine aerosol droplets instead of sticking to surfaces and second, it "freezes" the tar compounds into their current state, preventing them from reacting to secondary, higher molecular weight compounds through additional polymerization reactions. The aerosolized tar droplets are then effectively removed in the subsequent venturi scrubber and fine filter, elegantly illustrating the concept put forth by Han et al. (2011) that rapid cooling is a more effective strategy for the handling of heavy tars as it converts the gaseous contaminant into a particulate matter problem.

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4. CONCLUSION

The successful development and testing of a pilot-scale downdraft gasifier for MSW shows waste-to-energy technological improvement. The system was designed to address MSW gasification's fluctuating composition, high ash concentration, tar generation, and equipment corrosion. This design method yields a resilient and functioning unit that verifies the combined approach of thermodynamic modelling, material selection, and mechanical design.

Operation critically tested key design characteristics. Despite its greater initial cost, 310S stainless steel prevented chloride-induced stress corrosion cracking from high-plastic-content waste streams, justifying its long-term durability. In addition, the revolving, water-cooled grate assembly reduced ash agglomeration and clinker formation, frequent fixed-bed system failure causes. This component controlled the oxidation zone and guaranteed constant ash removal, ensuring consistent syngas generation and effective tar cracking.

The direct-contact quench spray cooler in the multi-stage gas cleaning train solved the tar condensation and fouling issue. It quickly cooled syngas to turn tars into aerosol droplets instead of heat exchanger deposits. The cyclone and venturi scrubber removed particulates, making this beautiful solution functional. This research presents a verified, realistic plan for an MSW gasification system that prioritises operational dependability and lifespan, providing sustainable municipal solid waste management and energy recovery.

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