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Development of a Small-Scale Municipal Solid Waste-to-Energy Conversion System for localized Energy Solutions in Ethiopia

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ABSTRACT

Ethiopia is striving to enhance waste management and energy access but lacks a clear understanding of utilizing waste for energy generation. This underscores the necessity of developing power generation technologies that utilize locally sourced materials. While numerous studies have highlighted the production of municipal solid waste in various Ethiopian cities, there is a lack of localized case studies focusing on specific regions and the composition of waste about small-scale power generation systems that use municipal solid waste as fuel. This study seeks to characterize selected municipal solid waste as a fuel source, as well as to design and develop a small-scale power generation system using locally available materials to utilize municipal solid waste as a fuel source. The Engineering Equation software tool was utilized for system modelling and design. The EA1112 Flash CHNS/O analyzer measured the ultimate analysis of waste samples, while a K-type thermocouple was used to measure combustion temperature. The modelling indicated that the prototype could process 32.5 kg/hr of dry municipal solid waste, with an overall efficiency of 35.2%, generating a theoretical power of 300W. However, in the experiment, the system produced 18.7W by combusting 125 kg/hr of municipal solid waste, resulting in the production of 68.4 kg/hr of steam. The study highlights the need for further efficiency improvements in the combustion system and the thermal-to-mechanical energy converter unit, such as the turbine system. The study shows a feasible way to create a small power generation system using local materials and expertise, which can address energy shortages and waste management problems. This study particularly attempted to fill the spatial research gap of municipal solid waste-based small-scale power generation plants in Ethiopia. Local businesses and industries should consider adopting this technology to overcome these challenges.

Keywords: *Waste to Energy, Municipal Solid Wastes, Ethiopia, Combustion Process, Power Generation, Steam Turbine*

1. Introduction

The amount of waste being produced globally is growing from time to time, driven by the production of goods from raw materials, product packaging, and waste by-products from factories (Muhammad et al., 2013). Wastes can be classified in to industrial, agricultural, animal, forestry residues and municipal according to their sources where they originate (Ogunjuyigbe et al., 2017). Before the integrated waste management system emerged in 1874 in the UK followed by Germany to recover useful energy from wastes, the treatment mechanism was open landfill disposal and incineration (Paper, n.d.,2019). A study by Imran Khan et al. [2022] predicts a 40% increase in waste generation for developing countries and a 19% increase for developed countries by 2050. This highlights the potential for municipal solid waste to be used as a fuel source for generating electricity at small to large-scale levels.

The viewpoint on management, disposal and utilization of waste varies from nation to nation according to the technology development and level of awareness (Gebreslassie et al., 2020; Muhammad et al., 2013; Zhang et al., 2018). According to the type of waste, different types of technologies can be applied to exploit the potential energy of organic matter in the waste into usable energy (Ogunjuyigbe et al., 2017). Waste-to-energy technologies are the conversion routes of organic matter in the wastes to useful by-products by using the two broad domestic paths (i.e. thermochemical and biochemical) conversions (Akpe et al., 2016; Committee, 2014; Gavrilescu, 2014; Levaggi et al., 2020). From the thermochemical energy conversion pathways, incineration is convenient, easiest, cheapest and the most domestic technology for non-biodegradable with a high percentage of organic matter and low moisture content (less than 50%) municipal solid wastes (Okafor et al., 2022).

By 2025, Africa's municipal solid waste generation capacity is estimated to generate 122.2TWh of electric energy. This presents a significant opportunity to reduce energy demand on the continent and prevent environmental pollution through collaborative efforts (Farouk et al., 2022). Ethiopia, as one of the largest African countries, is currently facing triple challenges of increasing population, waste generation and energy access. These challenges tend to push the need for innovative technology development to convert municipal solid waste to energy so to meet the energy demand, develop a circular economy approach to minimize waste.

Various cities in Ethiopia produce significant amounts of solid waste, but researches have primarily focused on waste management and theoretical estimation of power generation capacity rather than on developing small-scale technologies that can utilize municipal solid waste as a fuel source. Cities like Bahirdar, Awassa, and Harrar have theoretical net electric power of 0.5 to 1MW, while Mekelle, Diredawa, and Jimma can generate 1 to 1.5MW. Addis Ababa has the potential to produce 20 to 24.5MW by adjusting the waste combustion rate from 230.04 to 970.92 tons per day (Ing Bogale, 2017). However, recent estimates indicate that power generation potential from waste in Mekelle could reach up to 8.7MW (Gebreslassie et al., 2020). In the studies conducted on Ethiopian cities, there has been no practical implementation or testing of utilizing waste for energy generation, unlike in developed countries where waste-to-energy technology, like incineration plants, is common. For instance, France has 126 plants, Germany 121, and Italy 40 (Asiva Noor Rachmayani, 2015).

Ethiopia recently launched its first waste-to-energy system at the Repi waste site in Addis Ababa. The system aims to address waste management challenges by processing 1400 tons/day of waste to produce approximately 25MW of power, despite falling short of initial expectations as it is not functional due to several reasons (Abebe, 2018). This alternative power system can be implemented across all cities in Ethiopia by setting up small plants based on waste capacity and estimated power output. Small-scale municipal power technologies are gaining traction worldwide with varying results. For example, an experimental power generation system was developed using hazardous chemical wastes as a fuel. The system achieved a flame temperature of 12000°C, 8 bar pressure which Operates a small fan; a single 6W lump consuming equivalent 25Kg of wood as fuel (Incinerators, 2023). A total of 12V, 36 bulbs were powered by incinerating 150kg/hr of municipal solid waste for 15 minutes under various testing conditions in the small-scale power generation system (Abubakar & Oumarou, 2021).

Our study is focused on the design and development of small scale waste to energy to operate under specific waste composition. The study underlines the integration of locally available expertise and materials, which could make it scalable and sustainable for other similar areas. This paper was designed to answer these two questions 1) Can we develop a small scale waste to energy conversion prototype using locally available materials and expertise irrespective of the efficiency and flue gas treatments using locally developed materials?

2) Can we exploit a useful heat energy to generate electricity using solid waste streams generated in the study area as waste management strategy in Ethiopia so that to be the base for further development of the technology?

Despite the potential of waste as an energy source, small-scale waste-to-energy systems have not prototyped and implemented in Ethiopia. This paper aims to address this gap by designing a small-scale power generation system using locally available materials that utilize municipal solid waste as fuel. The primary objectives include analyzing the composition and characterization of the waste, designing, setting up, and testing the power generation system, and conducting experiments to generate steam for spinning a turbine. This enhance the knowledge and perception on waste-to-energy utilization in Ethiopia and raise awareness for future implementation of small-scale power generation technologies. Waste generation rate and waste composition varies from nation to nation according to living standard and socio economic levels (Firmansyah et al., 2024). For the case of Ethiopia, especially on the region where this study conducted, plastic and textile solid wastes are the most abundant and common type municipal solid waste streams. In a particular ratio 50% plastic bottle, 25% plastic bag and 25% textile waste compositions by weight have been chosen for this specific study due to their high proportion presence as a waste product in the study area. Furthermore, the experience of collection, segregation and crushing of plastics and textiles makes it easy for us to utilize them for this study.

2. Methods and materials

2.1. Materials and instruments

The basic software applied during this study is Engineering Equation Solver (for thermo physical properties of water and their numerical analysis), Excel Solver for municipal solid wastes analysis, and CATIA-V5 for modelling the prototype. The materials used to develop the prototype are galvanized iron sheet metals, copper pipes and steel bars for the structure of the system. EA1112flash CHNS/O-analyzer is used for elemental analysis (measurement) of the solid waste. A digital mass balance, camera, stopwatch, K-type thermocouple with data and Pico logger and digital tachometer were used during the experimental test.

Figure 1: k-type thermocouple with data and Pico logger

Figure 2: Digital tachometer

Figure 3: EA1112flash CHNS/O-analyzer

Figure 4: Data logger for manually reading

Figure 5: Digital mass balance

2.2. Methods

The methodology for this study involves solid waste products collection and measurement as primary data collection. Related literatures, published documents experimental results, and associated textbooks were used as secondary data source.

2.2.1. Ultimate analysis and heating values

From the measured ultimate analysis of the municipal solid waste, Dulong's expression is applied to determine the calorific value. Using the ultimate analysis and dulong's expression the energy and mass balance equation was used for the furnace control volume to calculate the flame temperature, mass of the flue gases, enthalpy of the hot flue gases, and air quantity needed.

Dulong's suggested that, heating value can be obtained multiplying the heat contents of the elements by their measured weight percentages of the constituents in the fuel as shown in *Table 1* (Ujam et al., 2012).

Table 1: heat content of constituents of fuel (Ujam & Eboh, 2013)

Constituent	hydrogen	carbon	Sulphur
HCV (kcal)	*34500*	*8075*	*2220*

The ultimate analysis of the municipal solid wastes is as shown in Table *2*.

Table 2: ultimate analysis of the MSW

Sample code	*N (%)*	*C (%)*	*H (%)*	*S (%)*	*O (%)*
Comb.1	*Wt%N*	*Wt%C*	*Wt%H*	-	*Wt%O*

From Dulong's analysis:

$$HHV = 8075 * \%C + 2220 * \%S + 34500 * \left(\%H - \frac{\%O}{8}\right) \quad (1)$$

2.2.2. Energy and mass balance

By considering the furnace as a control volume without any heat and work transfer, the energy

Supplied to the furnace is equal to the energy given by the furnace for ideal conditions as presented in Figure *6*.

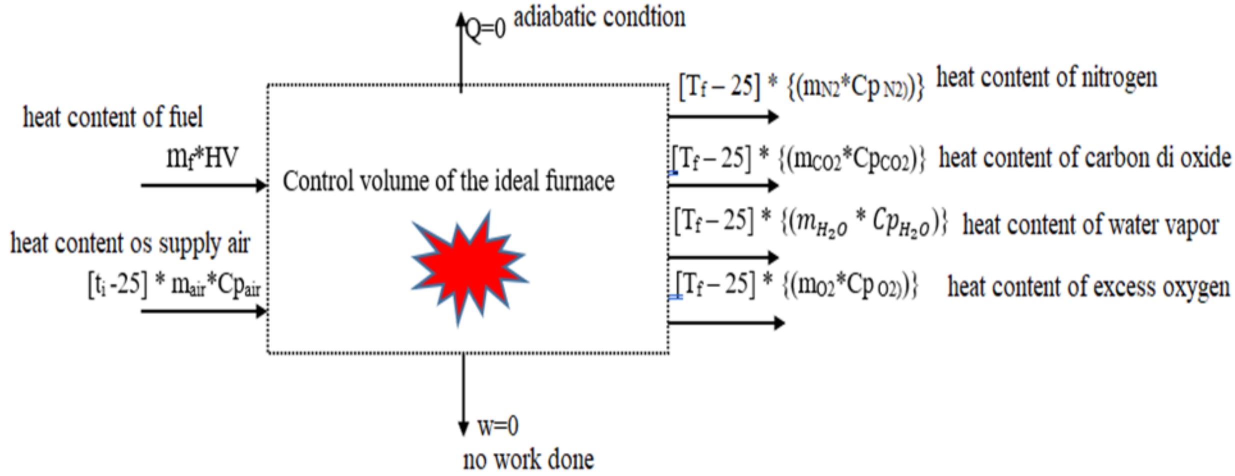


Figure 6: Combustion in control volume of ideal furnace (Omari et al., 2015)

Applying energy and mass balance in the ideal furnace:

$$[m_{fuel} * (HV) + m_{air} * (ti - 25^0c)] = \sum[tf - 25] * (mCO2 * CpCO2) + (mH2O * CpH20) + (mN2 * CpN2) + (mO2 * CpO2) \quad (2)$$

Using Excel solver, putting the term *"*$\left[m_{fuel} * (HV) + m_{air} * (ti - 25^0c)\right] - [[\sum[tf - 25] * (mCO2 * CpCO2) + (mH2O * CpH20) + (mN2 * CpN2) + (mO2 * CpO2)]]$*" to the value of "0"* and as *set objective*, by varying "t_f", flame temperature can be analyzed:

Oxygen required for stoichiometric and excess air for the specific fuel can be obtained by:

$$\left[\frac{wt\%C*32}{12} + \frac{wt\%H*32}{4} - wt\%O_2\right] * 1Kg\ of\ air \quad (3)$$

$$\left[\frac{wt\%C*32}{12} + \frac{wt\%H*32}{4} - wt\%O_2\right] * 1.5Kg\ of\ air \quad (4)$$

In addition, the C_p value of the flu gas products are calculated at the average obtained flame and ambient temperatures.

$$CP_{\text{flue gases}} = a_0 + a_1 t_{av} + a_2 t_{av}{}^2 + a_3\, t_{av}{}^3 = 0.8182 + 9.973E\text{-}49 t_{av} - 7.61047E\text{-}6 t_{av}{}^2 + 2.8E\text{-}10\, t_{av}{}^3 \quad (5)$$

Where, a_0, a_1, a_2 and a_3 are polynomial coefficients for specific heats of flue gases and t_{av} is the average flame and ambient temperatures and CO_2, N_2, H_2O, O_2 are the associated flue gas products.

Enthalpy product of the flue gases are also calculated in the excel solver to obtain the flame temperature and required results applying enthalpy of hot flue gases (Diop et al., 2017).

Enthalpy heat product of the flue gases can be calculated:

$$enthalpy_{flue\ gases} = [tf - 25] * (m_{flue\ gases} * Cp_{flue\ gases}) \qquad (6)$$

2.2.3. Boiler Efficiency and calculation of the required mass of fuel

Efficiency and fuel mass required are calculated using indirect assessment method by adding all the considerable heat losses less than 100% (Terms, n.d.). Considering DAF (Dry and Ash free) analysis, heat losses due to moisture and ash contents of the fuel can be neglected in hypothetical case.

2.2.3.1. Heat loss due to exhaust flue gas

The flue gas products leaving the chimney depend on the elemental constituents which produce flue gas products and moisture content of the fuel (Terhan, 2021). From the combustion analysis of the fuel, the mass of each flue gas products which leaves the chimney carrying heat can be obtained as:

$$\dot{m}CO_2 = wt\%C * \frac{M_{CO_2}}{M_C} = n_{CO_2} \qquad (7)$$

$$\dot{m}H_2O = 4wt\%H * \frac{M_{H_2O}}{M_H} = n_{H_2O} \qquad (8)$$

$$\dot{m}_{N_2} = \mathrm{wt\%N_2} = n_{N_2} \qquad (9)$$

Where: $\dot{m}CO_2$ is the mass of carbon dioxide, $\dot{m}H_2O$ is the mass of water vapor, $\dot{m}_{N_2}$ is the mass of nitrogen, $wt\%C$ is the weight percent of the carbon in the fuel, M_{CO_2} is the molecular weight of carbon dioxide, M_C is the molecular weight of carbon, $wt\%H$ is weight percent of hydrogen in the fuel and $\mathrm{wt\%N_2}$ is the weight percent of nitrogen in the fuel and air supplied.

$$\dot{m}_{flue\ gas} = \sum[\dot{m}CO_2 + \dot{m}H_2O + \dot{m}N_2 + \dot{m}O_{2_{excess}}] \qquad (10)$$

$$C_{p\ flue\ gas} = \sum[C_pCO_2 + C_pH_2O + C_pN_2 + C_pO_{2\_}excess] \qquad (11)$$

From Dalton's law of addition, the temperature of exhaust flue gases can be obtained from the minimum partial pressure of the flue gases at which condensation occurs as shown below.

$$\frac{n_i}{N_{total}} = \frac{P_i}{P_{total}} \quad (12)$$

Where: n_i is partial mole of the mixture

N_{total} Is total mole of the mixture

P_i Partial pressure of the mixture (water)

P_{total} Total pressure of the system

Since the specific fuel used for this study does not consist of sulphur, the minimum pressure from the flue gases is obtained at water vapor, and the minimum reference flue gas temperature can be the water dew point temperature.

$$T_{WDP} = 0.001173 * \left(P_{H_2O}\right)^3 - 0.0942 * \left(P_{H_2O}\right)^2 + 3.423 * \left(P_{H_2O}\right) + 19.7 + 5 = T_{fg} \quad (13)$$

$$Heat\ loss\ due\ to\ dry\ flue\ gas = \frac{\dot{m}_{flue\ gas} * Cp_{fg} * \{T_{fg} - T_{amb}\}}{CV} * 100\% \quad (14)$$

2.2.3.2. Percentage of heat loss due to the formation of water vapor in the fuel:

During combustion, the hydrogen from the fuel starts to react with the supplied air which consists of oxygen to form water vapor and consume a considerable amount of heat energy in the combustion chamber to reduce the heat content of flue gas products (Gebreegziabher et al., 2014).

$$\%Q_{evm} = \frac{9 * \%H * \left[584 + Cp(T_f - T_i)\right]}{CV_{fuel}} * 100\% \quad (15)$$

Where: %H is the weight percent of hydrogen in the fuel and T_f is the flame temperature of the combustion.

2.2.3.3. Heat loss due to moisture present in air

$$\%Q_{moistair} = \frac{AAS * humidity\ factor * C_p * (T_f - T_i)}{CV_{fuel}} * 100\% \quad (16)$$

Where: AAs is the actual air supply and T_f is the flame temperature inside the furnace

2.2.3.4. Heat loss due to side walls

In relatively small boilers, heat losses due to conduction, convection and radiation could amount to 2% of the calorific value of the fuel(Pandey et al., 2016). Accordingly, the aim is to estimate the effective insulation thickness to conserve energy.

$$\frac{2\%*Q}{A} = \frac{\Delta T}{\frac{t_{wall}}{K}+\frac{t_{caolin}}{K}} \quad (17)$$

Therefore, the efficiency of the boiler is given by:

$$\eta_{boiler} = 100 - \{\%Q_{flue\ gas} + \%Q_{water\ vapor} + \%Q_{air\ moisture} + 2\%\} \quad (18)$$

From the efficiency of the boiler, applying energy supply to energy output ratio, the required amount of fuel can be obtained using.

$$\eta_b = \frac{\dot{m}_s*(h_{@11.15bar,200} - h_{water})}{\dot{m}_f*LHV} \quad (19)$$

2.2.4. Theoretical analysis of incinerator size

Incinerator size is the internal volume of the incinerator which can hold the supplied fuel during combustion with the supplied sufficient air to produce enthalpy of the heat of the flue gas products for the given time not including the ash pit (Abubakar & Oumarou, 2021; Diop et al., 2017). To analyze the theoretical size of the incinerator enthalpy of heat of products are the factor parameters. Thus, enthalpy of the flue gases can be estimated as: (Diop et al., 2017).

$$H_{flue\ gas} = V_{CO2}(C_pT_f)_{CO2} + V_{N_2}(C_pT_f)_{N_2} + V_{H_2O}(C_pT_f)_{H_2O} + V_{O_2}(C_pT_f)_{O_2\ exces} \quad (20)$$

Where: V is the volume ratio constituent of the flue gas and (C_pT) is the specific enthalpy (KJ/m^3) of the flue gas at a flame temperature and given ratio of the constituents.

Therefore, the minimum theoretical volume of the combustion chamber can be calculated from the following equation:

$$v_{min} = \frac{m_{fuel}*CV}{V_{CO2}(C_pT_f)_{CO2}+V_{N_2}(C_pT_f)_{N_2}+V_{H_2O}(C_pT_f)_{H_2O}+V_{O_2}(C_pT_f)_{O_2\ exces}} \quad (21)$$

Where:

v_{min} is the minimum theoretical internal volume (m^3)

m_{fuel} is the mass of feedstock (Kg/hr)

CV is the calorific value of the feedstock (KJ/Kg)

T_f flame temperature of the product flue gases

2.2.5. Determination number of pipes

The number of pipes can be calculated as (Akintunde & Adetoro, 2013):

$$N_o pipes = \frac{Energy\ remained}{Enrgy\ recieved/pipe} \quad (22)$$

$$N_o pipes = \frac{\eta_b * \dot{m}_f * CV}{\frac{(\Delta T)}{\frac{1}{h_0}+\frac{r_0}{k}+\frac{r_0}{k}ln\frac{r_0}{r_1}+\frac{1}{h_1}\frac{r_0}{r_1}}} \quad (23)$$

2.2.6. Design of steam turbine

Euler's energy equation is applied to estimate work output of the turbine per unit mass and can be determined using:

$$w = U * (\Delta C_w) \quad (24)$$

From the velocity triangle diagram of steam turbines shown in Figure *7*, whirl velocities, blade angles and blade height and blade efficiencies can be obtained as:

$$C_{w1} = C_1 \cos \alpha_1 \quad (25)$$

The relative velocity is the velocity of the steam with respect to the velocity of the rotating blade and can be obtained as:

$$V_1{}^2 = C_1{}^2 + U_1{}^2 - C_1 * U cos\alpha_1 \quad (26)$$

From the combined velocity diagram of steam turbines, blade angle for symmetrical blades can be obtained by:

$$tan_{\beta 1} = \frac{C_1 * sin\alpha_1}{C_{w1} - U} = tan_{\beta 1} \quad (27)$$

$$\dot{m} = \frac{P}{(C_{w1}+C_{w2}) * \eta_{overall} * U} \quad (28)$$

where: ṁ is the mass flow rate of steam

$\eta_{overall}$ is the overall efficiency of the system and

P is theoretical power developed

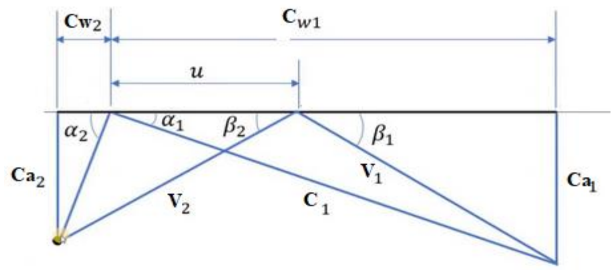
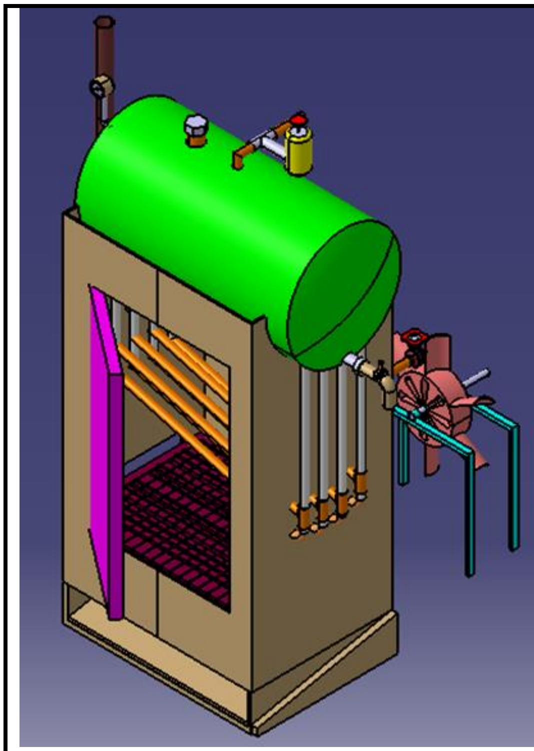


Figure 7: combined velocity triangle of the turbine (Chenduran, n.d. 2021)

2.2.7. Development of the prototype

The prototype is made in Mekelle City. The riser and down comer tubes connected with the boiler drum are welded with the copper pipes by oxyacetylene welding facing directly to the combustion chamber of the furnace. At the top part of the boiler drum, a supper heating copper pipe is connected to collect the separated saturated steam and direct it back to the combustion chamber to get additional heat and leave the combustion chamber at a designed angle of flow. The combustion chamber is manufactured based on the theoretical dimensions obtained. An impulse-type steam turbine is manufactured based on the theoretical modeling specifications obtained. Other machine elements assembled to the system are purchased to match the design. A movable ash collector was putted in the bottom of the incinerator to remove the collected ash during combustion. Fiberglass and kaolin clay are the insulating materials and basically were used to coat surfaces of the combustion chamber, boiler drum and supper heating pipes to minimize the possible heat energy wastage. Figure *8* shows the pictorial drawing of the system to develop the prototype.



s.no.	Part names
1	furnace
2	down comers
3	copper pipe heat exchangers
4	boiler drum
5	water inlet valve
6	pressure relief valve
7	pressure gage
8	drainage valve
9	chimney
10	T-fittings
11	Elbow fittings
12	shaft
13	steam turbine
14	supper heat line
15	flow control valve
16	saturated steam collector
17	fuel and air inlet
18	turbine stands

Figure 8: pictorial drawing of the system using CATIA-V5 and part names

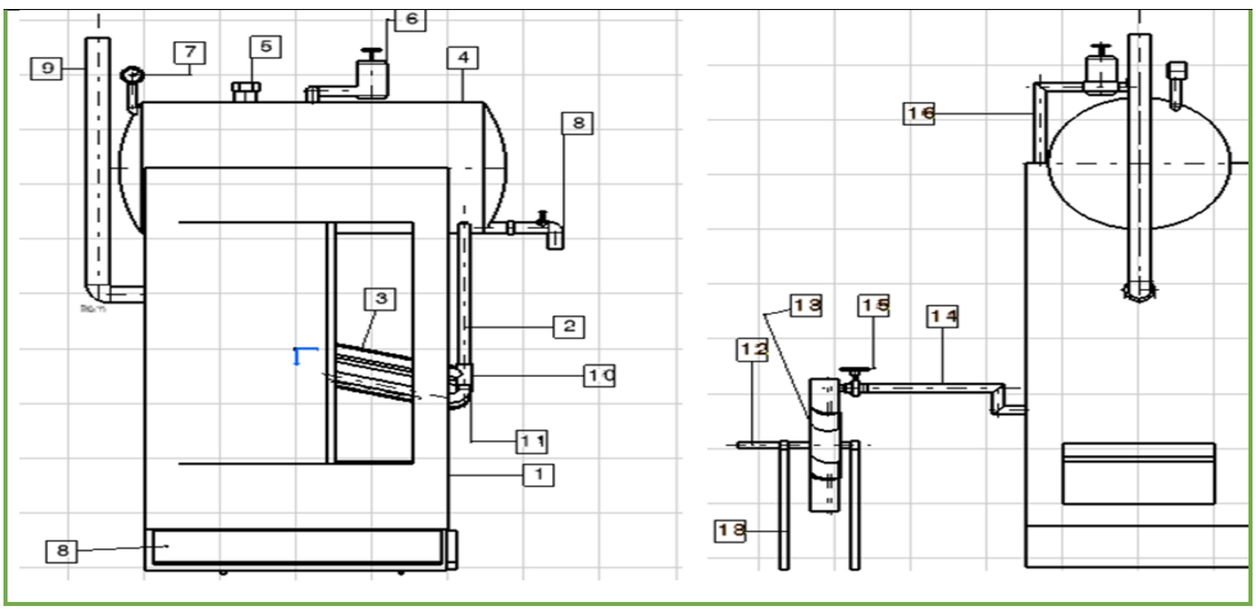


Figure 9: 2D drawing of the system using CATIA-V5

Figure 10: manufacturing of the prototype

2.2.8. Experimental setup and evaluation

Figure *11* illustrates the experimental setup for data collection and observation. Mathematical correlations and justifications were also utilized alongside data measurements from the instruments.

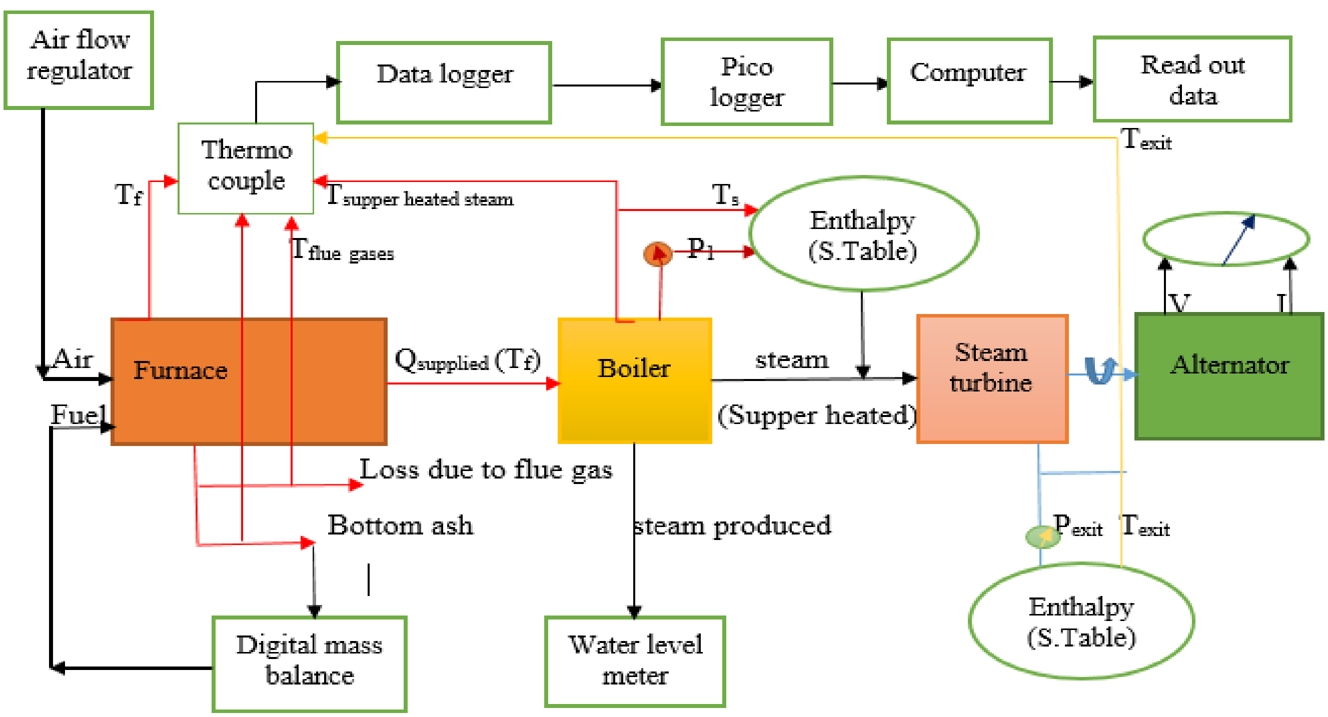


Figure 11: Block diagram of the experimental setup

(a) (b)

Figure 12: preparation for experimental work (a, b)

3. Results and Discussions

3.1. Determination of flame temperature, CO2 emission and air required

Municipal solid waste has generally variable composition, which poses challenges of combustion, biochemical transformation, and thermochemical conversion. Even the variability of plastic waste affects the waste to energy conversion performance. A municipal solid waste with composition of 50% plastic bottle, 25% plastic bag and 25% textile by weight was used as a fuel for this specific study. The specific ratio for the mixture of the solid wastes to be utilized as fuel is based on, calorific value, energy conversion route convenience, waste type, generation rate, moisture content and decomposition potential and availability of recycling plants for the selected solid wastes. The study particularly focuses on harnessing calorific values of plastic solid waste mixed with textile products due to their high heat contents. The specified waste composition ratio was selected as a case specific example based on the availability of waste locally. As the varying properties of municipal solid waste poses combustion and thermal conversion challenges, this sample was not considered as a standard sample. Moreover, the ratio of the mixture is only for a single conversion performance assessment, the authors acknowledge the idealized aspect of the case specific sample as a drawback. The authors also recommended for further effort on obtaining optimized mixture ratio of the municipal solid wastes.

Table *3* shows the elemental constituents of the municipal solid waste utilized as fuel.

Table 3: elemental composition of the MSW

Sample code	N (%)	C (%)	H (%)	S (%)	O (%)
Comb.1	9.6	60.4	8.7	-	21.3

From energy and mass balance in the furnace, it is known that incineration of a given amount of fuel with the corresponding air required in the furnace at flame temperature of combustion chamber yields a mass of hot flue gas products with their corresponding flame temperature. The municipal solid waste utilized as fuel for this specific study is analyzed using Excel solver, which yields 1330^0c flame temperature and important results as discussed in equation (3). In addition, the other results from Excel solver incorporated to the fuel analysis are summarized in Table *4*.

Average heating value of municipal solid wastes is environmentally, technically and economically feasible comparing to low grade coal for electric power generation (Kokalj & Samec, n.d.). The obtained calorific value and corresponding flame temperature of the municipal solid wastes utilized as fuel for this specific study are 20500KJ/kg and 1330^0c respectively. The theoretical and experimental results observed during the study indicated that the specific municipal solid waste used for this study is factual to produce power compared to the low grade coals. According to the findings, municipal solid wastes can be alternative sources of energy by employing locally developed small scale power generation plants in terms of addressing the energy demand of local community and waste management strategy. For the developing nations like Ethiopia, transferring technology from the developed nations is being an essential issue to meet the sustainable development goals. Despite efficiency improvements and the need for additional research, the study's findings promise to construct municipal solid waste fired small scale power plants.

Table 4: summary of the obtained theoretical results from energy and mass balance

Required parameters at stoichiometric conditions	Obtained results
calorific value	20500KJ/Kg
Total mass of flue gasses	3.09Kg/kg of dry fuel

Flame temperature	1330^0c
Mass of carbon di oxide	2.21Kg/kg dry fuel
Mass of air required	9.5Kg/Kg dry fuel

The results in Table *4* showed that, the attained theoretical flame temperature in the furnace is enough to turn water into steam to strike a steam turbine for power generation system. Notwithstanding difficulties, the furnaces flame temperature must be regulated to match the intended operating temperature of the heat transfer pipes inside the combustion chamber.

In connection to that, for real calculations analyzing flame temperature at some percent of excess air is necessary to use more than the theoretical air requirement to assure sufficient oxygen for complete combustion since it is not possible to have an ideally perfect mix of air and fuel in a boiler(Gebreegziabher et al., 2014; Incinerators, 2023). Furthermore, the regulation of flame temperature is implemented to safeguard the copper pipes that transfer heat from departure nucleate boiling (DNB) for the system effective operation.

Table 5: summary of the obtained theoretical results from energy and mass balance

Required things at 50% excess air	Obtained results
calorific value	20500KJ/Kg
Total mass of flue gasses	3.1Kg/Kg fuel
Flame temperature	975^0c
Mass of air required	13.25Kg/Kg dry fuel

3.1.1. Influence of excess air

But then again, the excess air that is not used in the combustion of the fuel leaves the boiler at the stack temperature, thus resulting in a heat loss. It is therefore necessary to keep the excess air at an optimum level in order to hold down the stack loss, but also accomplish near complete combustion of the fuel. For unprocessed municipal solid waste, the optimal excess air required to achieve high combustion efficiency in a water wall furnace is approximately 40 - 50%. Thus, 50% excess air is considered to calculate the flame temperature (Pandey et al., 2016). Figure *13* shows the influence of excess air on the combustion flame temperature analysis.

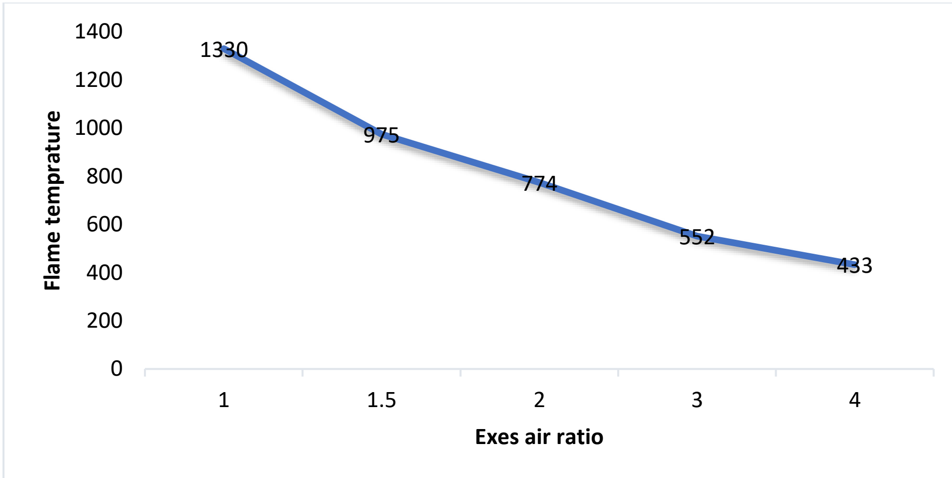


Figure 13: influence of excess air in the flame temperature

3.2. Heat losses on the furnace and estimated required mass of fuel

The furnace is the combustion chamber of the supplied fuel and air to produce heat energy, which is then used to convert the working fluid into super-heated steam. Effective conversion heat energy is a major obstacle in turning fuel's energy content in to usable energy. In general the efficiency of working waste to energy systems is too low which ranges from 20% to 30% (Di Maria et al., 2016). Despite being practically different from the experimental results, this particular study attempts to develop and model an efficient furnace. The theoretical and experimental results indicate that there are a problems of heat losses from sidewall of the combustion chamber, flame temperature variations, which demands parameters for improvement such as; optimized composition, better insulation, air to fuel ratio optimization, and preheating of the working fluid and fuel. However, with time and budget constraints we had; our study basically focused on the system feasibility using the mentioned ratios and system of the prototype. The authors acknowledge and identify the mentioned parameters could farther enhance the performance of the system. Heat loss from the side walls and variation in flame temperature during combustion due to air-fuel mixture was the main efficiency disruptive observed during the experimental work. The steam turbine used for the developed small scale power generation system operates at a significant speed during the test period, producing torque for the production of electricity. Since heat energy cannot be conserved entirely, a considerable amount of heat losses can be quantified by different techniques. The heat losses indicate the system efficiency in connection to the system design, fuel type and environmental conditions of the study area. The major heat losses and results incorporated to the furnace are summarized as shown in *Table 6*.

Table 6: summery of the theoretical performance of the furnace

Possible heat losses	Obtained values
Heat loss due to dry flue gas	13.8%
Heat loss due to vapor formation	6.3%
Heat loss due to moist air	1.2%
Heat loss due to side surfaces	2%
Mass of fuel	32.5Kg/hr
Efficiency of furnace	76.7%
Number of pipes	$9.66 \approx 10$
Theoretical internal volume of the incinerator	0.131m^3

Although it was not measured, environmental factors such as wind speed, temperature and humidity influences the performance of the system (*US Department of Energy*, 2019). Lower ambient temperature is expected to have reduced the system efficiency due to losses. The prototype development and experimental test was conducted at Mekelle during December, where this season is characterized by low humidity (45%-50%), low ambient temperature ranging from 8°C and 22°C, and mild wind speed 10km/hr. Wind speed in Mekelle is mild which could have anticipated to the contribution of heat loss during the experimentation time. This paper underlines the importance of accounting for environmental conditions when conducting studies in various regions as these factors influence system performance.

3.3. Analysis of the steam turbine

There are two broad classifications for quantifying the power output of steam turbines. A change of linear momentum analysis is applied for this research work. For the change of linear momentum, all the velocity components have been calculated. The geometry and size of the steam turbine are analyzed based on the mathematical correlations from the velocity triangle and standard-derived equations as a datum. The analyzed results from the system design and analysis indicate that a mini turbine can be developed and manufactured locally to exploit the heat energy in the steam for electricity production. The required parameters have to be calculated based on the power generation capacity, type and heat energy available in the system to generate the required amount of electric power. Table *7* presents the geometric modeling of the steam turbine and mass of steam required for power generation.

Table 7: summary of the steam turbine analysis

Required sizes	Obtained values
Nozzle angle	15^0
Blade speed ratio	0.48
Velocity of steam entering the blade	293m/s
Relative velocity	160m/s
Inlet whirl velocity	284.9
Inlet axial velocity	68.4
Inlet and outlet blade angle	28^0
Considered blade velocity coefficient	0.85
Outlet whirl velocity	-8m/s
Blade efficiency	83%
Mass of steam required	0.016Kg/s
Blade diameter	0.32m
Blade height	0.06m

4. Experimental setup and evaluation

The experiment was conducted at the Mekelle University campus for consecutive 3 days (starting from December 24, 2023, to December 26, 2023). However, after some adjustments were made during the setup of the prototype and instruments, the real data measurement was taken on the third day. Due to time and resource constraints the experiment was conducted in a short period. However, in this phase of experimental test, power can be generated from specific waste material with a locally produced waste to energy prototype. The measured data taken during experimental time are summarized in *Table 8*.

Table 8: experimental measured and observed data

Parameter	Recorded data	Instrument/concept used
Quantity of Fuel consumed	0.035Kg/s	Digital mass balance
Quantity of steam generated	0.019Kg/s	Measuring the remained hot water from the filled water to the tank
Quantity of remaining water in the boiler tank	4Kg	Tapering the remained water from the tank and measuring the weight by digital mass balance
Average rotation of the shaft	98rpm	Tachometer
Ash temperature	67.25^0c	Infrared thermocouple
Remained water temperature	54.5^0c	Infrared thermocouple
Pressure	5.77bar	Pressure gauge
Temperature of steam leaving the turbine	45^0c	Infrared thermocouple

The graph displayed in Figure *14* shows the different temperature readings at specified places of the prototype to record important data for comparison between the theoretical and experimental results. Even though, there is variation of readings, the required data was taken at a constant temperature reading from the graph, which means there would not be any change as recording time goes. The chimney temperature, superheated line, saturated temperature, side temperature and flame temperature was recorded. From the graph, it was observed that the chimney temperature sharply increased during the first 9 minutes and starts to stabilize after wards. In the first 9 minutes the flue gases go out effectively through the chimney but after that temperature fluctuation is observed, which tells there was variations in combustion conditions. The side temperature normally measures the heat losses and the gradual increase of the loss suggests there is heat loss alongside of the furnace. This implies proper insulation is required.

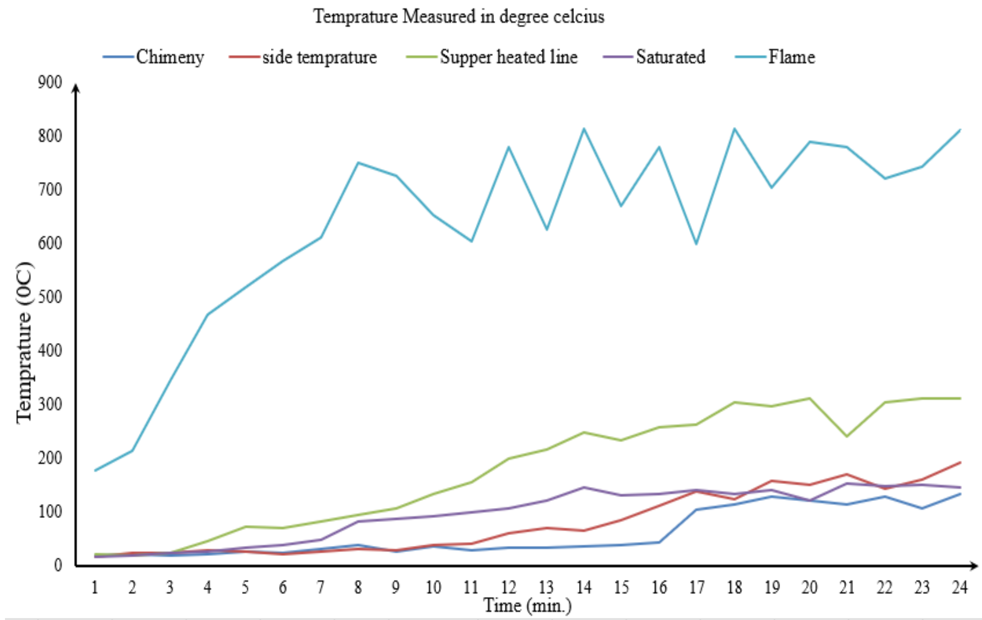


Figure 14: temperature reading of the system

The graphs discussed in Figure *15* and *Figure 16* are the comparisons between the theoretical and experimental work during performance assessment. As shown *Figure 15*, the CO_2 emission at the theoretical analysis was calculated mass of theoretical fuel multiplied by the carbon di oxide emission calculated per kilogram of municipal solid waste. The power was theoretically expected to be 300W by combusting 32.5Kg of the selected and actual power output was measured to be 18.7W which can light 3, 6W lumps. Likewise, the theoretical fuel supplied to the system was expected to generate 50.4Kg steam to spin the turbine, however during experiment the measured steam was 68.4Kg to spin the steam turbine coupled to the shaft. The discrepancies observed between the experimental and theoretical highlights efficiency loss in the energy conversion system. The experimental set up may have experienced incomplete combustion and heat loss from the combustion chamber which leads to lower energy output. Furthermore, heat loss, inefficient heat transfer to the working fluid may have also reduce to get effective thermal energy that enables power generation. It is also observed that though energy generation using the specified fuel ratio was achievable, more steam was required to generate the needed energy, and this could be due to inefficient steam consumption in the turbine. The experimental study was conducted December 2023, under specific environmental conditions of wind conditions, humidity and temperature variations. for example, the wind speed in Mekelle is average which may facilitate the heat loss from the combustion chamber. Though the system was experimented under controlled parameters, real world parameters can affect the system performance.

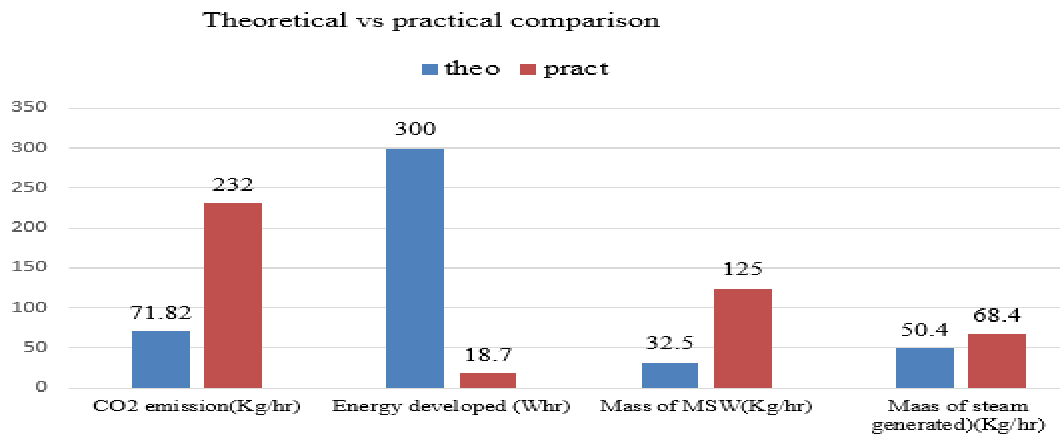


Figure 15: theoretical and experimental results comparison

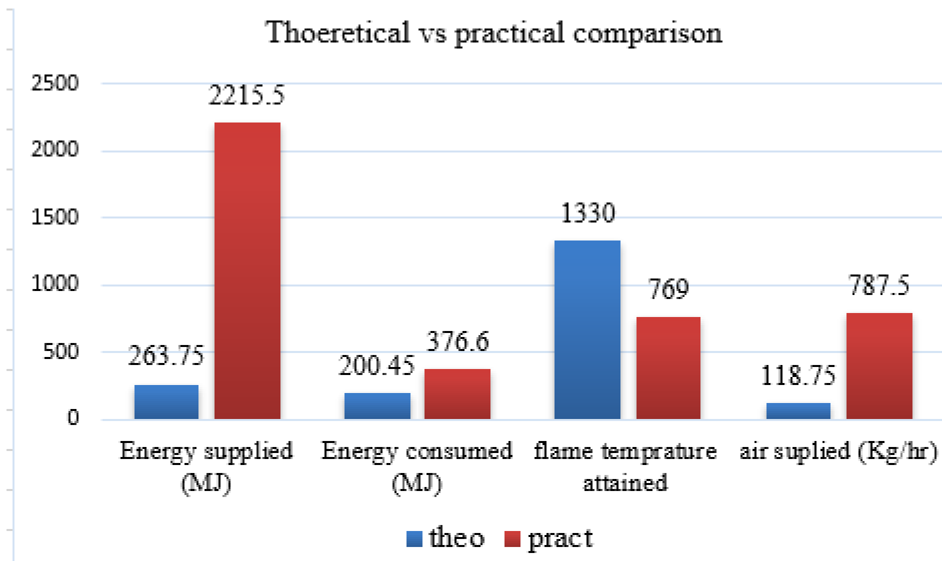


Figure 16: theoretical and experimental results comparison

As discussed in *Figure 16*, the comparison results are based on the theoretical analysis of the system and performance assessment of the prototype to develop the actual output power by consuming the supplied actual fuel to the system. The energy supplied to the system was calculated using mass of the fuel multiplied by the energy content of the municipal solid waste. Flame temperature of the system during the performance assessment was the actual measured temperature and compared to theoretical expected flame temperature analyzed by considering control volume inside the furnace. As shown in *Figure 17*, the power generation system combustion chamber yields adequate power to run the steam turbine and the remained ash collected at the ash pit is turned in to dusty ash, which indicates the combustion inside the chamber was effective.

(a) (b) (c)

Figure 17: (a), (b), (c), flame inside the combustion chamber, while the system is running, the appearance of the bottom ash

5. Conclusion

The study initially analyzes waste composition and calorific value to estimate flue gas flame temperature, CO2 emissions, combustion air requirements, and waste quantity for specific power generation and system size. The waste blend has high and low heating values of 21800KJ/kg and 20500KJ/kg. The adiabatic flame temperatures of flue gases are 1330°C and 975°C with stoichiometric and 50% excess air. Turbine shaft rotation is monitored using a digital tachometer, showing an average speed of 98rpm. During the experiment, the combustion chamber reached a peak flue gas temperature of 7690°C. By investing in small-scale power generation technologies utilizing municipal waste, Ethiopia can tackle waste management issues and improve energy security. Although initial data suggests limitations in our waste-to-energy pilot project, enhancing energy conversion efficiency through research and development efforts can generate substantial energy for steam production.

Recommendations

To address the identified gaps and to provide attractive insights this study proposed the following recommendations.

- Conducting further optimization studies to determine the best composition of solid wastes for power generation, rather than recycling, while assessing cost benefits and environmental impacts.
- Select proper insulation to increase both heat transfer and steam generation efficiency.
- It is also advisable to use advanced modelling tools to align the theoretical and experimental results.
- Improve turbine efficiency for better steam expansion and energy conversion.
- Conducting experimental testing for an extended time to see the actual performance of the system.
- Study the impact of environmental factors that can affect the performance of the technology.
- Enhancing prototype development by focusing on efficient materials for steam turbines and improving the feeding mechanism for fuel-to-air ratio. Installing fuel and air preheaters to ensure dry fuel and air reach the combustion chamber efficiently.
- Small enterprises are advised to collaborate with academic institutions, local governments, and NGOs to access expertise and financial support for developing small-scale waste-to-energy technologies.

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