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Research Article

Environmental Assessment Of The Gasification Technology And The Internal Combustion Engine With The Monte Carlo Method.

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Abstract

The approach to clean energy sources has been a severe issue for sustainable development. Power generation from Municipal Solid Waste (MSW) must increase for the growing power demand in the sustainable development. The small-scale gasification is combined with an engine to reform the waste to energy. In this paper, the analysis of operating parameters and emissions is presented. A syngas is used for the engine feedstock for evaluation of the performance and emissions. The output power, gas composition, electrical efficiency, and exhaust emissions are measured. The model is validated, and experiments are accomplished to attain relations and parameters for modeling. Available data show that mass fractions of food, plastic, and paper, vary seasonally and daily. A Monte Carlo method is modeled by MATLAB R2019a. The mean value of net power, fuel consumption, and emission, is obtained using the Monte Carlo method. The mean values from a composition of CO, NO, and CO2 emissions are 12.46%, 11.3%, and 13.69%. The results indicate that the system has 859.5 g/kWh fuel consumption, 10.35 kW generated power, and 0.88727 power factor. The results from this paper present that gasification system combined with the engine can produce sustainable power, high electrical efficiency, and minimum emissions.

Keywords : Monte Carlo method; biomass gasification; power production; emissions.

INTRODUCTION

Gasification of solid wastes process means the total or partial transformation of solid wastes components into gases, and has developed in recent years [1]. Development will stay as environmental regulation, economic forces, and global energy demand for power and heat generation. The gasification and engine technologies for power generation are presented for greater energy efficiency and environmental performance than the conventional power plant. The increasing part of the gaseous emission pollutants will not appear from direct combustion. These pollutants will rather appear from the combustion of a generated syngas throughout the gasification. It is helpful to think about the emissions from syngas combustion and their effect on air pollution.

Production rate, composition, and calorific value are the essential factors of the solid waste in studying the emission. The composition of municipal solid waste influences on the power plant performance. In a technical analysis of each power plant, one of the issues is the comparison of emissions and electricity generation from the power plant. For the emissions estimation, Ahmed M. Salem (2023) [2] introduces the system for a recycling of the exhaust emissions from engines inside the gasification system. A 2D Computational Fluid Dynamics (CFD) model is presented to consider the effects on the gasifier performance.

Elaheh Sadeghibakhtiar et al. (2024) [3] estimate a power of a solar irradiance, wind speed, and hybrid system, to measure the uncertainties with using the Monte Carlo algorithm. In the solar power plants, because of the time dependence fluctuation of solar radiation, produced power changes seasonal and hourly. So, transient models are used to simulate the solar power plants. In the wind power plant, wind velocity doesn't change definitively, and random wind speed data is used to compute the produced electricity.

For waste-to-energy power plants, a fraction of fluctuating

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components of waste is left. A few studies attend the power production systems and the use of the Monte Carlo method to model the pollutant emissions of power plants. For example, Yi Fang et al. (2022) [4] combined the random forest algorithm, gasification kinetic modeling, and the Monte Carlo simulation approach, to show the optimal gasification process parameters. Andrea Colantoni et al. (2021) [5] evaluate the uncertainty in a Net Present Value of investment in the gasifier and the engine. Monte Carlo simulation estimates a probability of the Net Present Value for three sizes of plants. Afreen Siddiqi et al. (2020) [6] simulated urban waste-to-energy recovery assessment for advancing countries with the Monte Carlo method. They incorporate the social benefits and costs of high energy production and low emissions and influences on public health. For emission with Monte Carlo method, Taneya et al. (2024) [7] develop a quantitative uncertainty assessment framework in building material emissions and recommend how these uncertainties could be controlled by the Monte Carlo Simulation (MCS).

The analysis of the energy recovery and emissions model for the fluctuating components of solid wastes with gasification and internal combustion engine in Tehran is presented. This system has a variable fuel composition at each hour, day, and season because of the fluctuations of the input solid waste composition. Because of the uncertainty in the composition of the input feedstock, the Monte Carlo method and the probability density function will be suitable. Attaining the probability distribution for the input solid waste and output syngas is necessary. The output is the probability distribution of the engine emissions.

The primary goals of this project are as follows:

1. to model the small-scale gasification by way of an internal combustion engine system for power production,
2. to obtain the histogram of emissions, power, and fuel consumption
3. to validate the calculated model with the experimental data
4. to study the influence of the uncertainty in the input fuel composition with the probability density function,

So, the innovation and importance of this project are stated in this section. The innovation is the model for analyzing emissions and energy recovery from the fluctuating components of solid wastes by gasification and internal combustion engine technology. Section 2 shows the system description of this modeling. Section 3 presents the assumptions, methods, and equations, for modeling. Section 4 reports the results, while the conclusions are given in Section 5.

The findings are accurately:

- The amount and composition of emissions and power output are evaluated throughout a system.
- The integrated model is certified by an experimental data.
- The impact of the uncertainty in a composition of an input feedstock is studied with a probability density function.
- The Monte Carlo method is used by a different mass fraction of food, paper, plastic, and other components,
- The probabilistic methodology for the power generation, the emission composition, and the power factor of the power plant is estimated.

Nomenclature

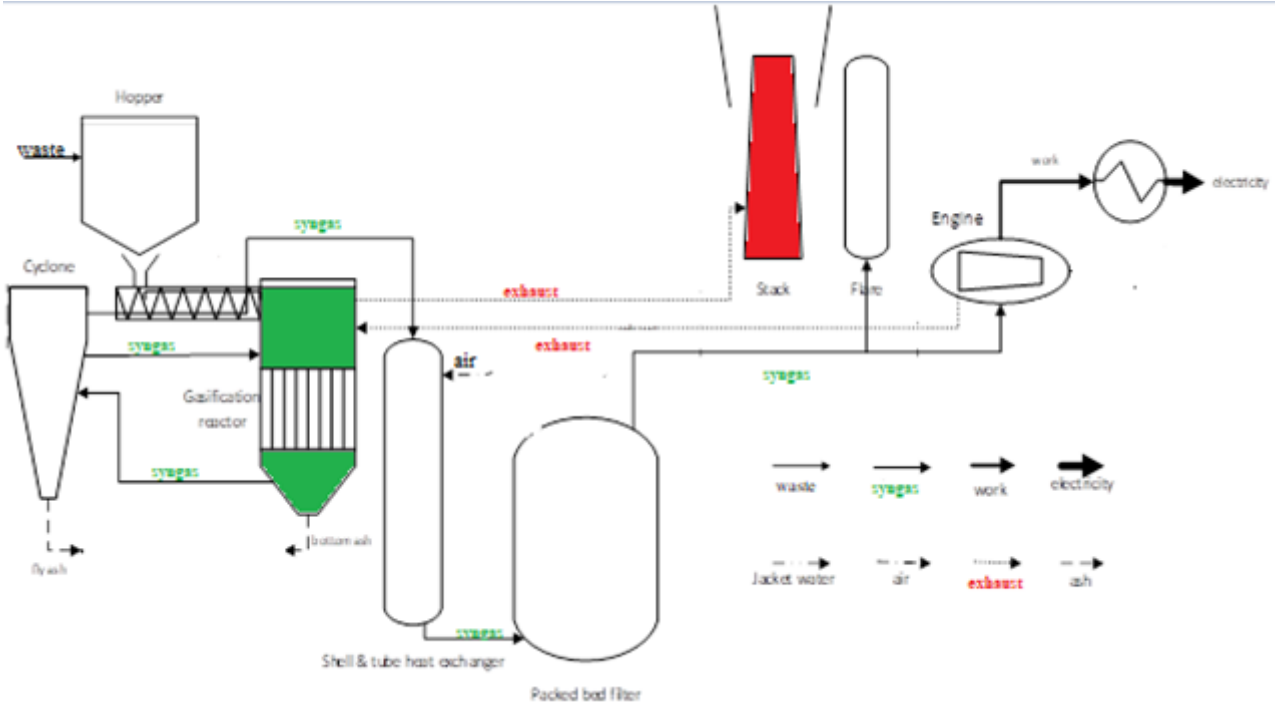
Variable name	Unit	Definition
A1, A2, …	-	input parameters to the Monte Carlo method
a, b, c	-	stoichiometric cooperatives in the chemical formula of biomass
AFR	-	the stoichiometric air-to-fuel ratio
B1, B2, …	-	output parameters to the Monte Carlo method
C	-	mass fraction of carbon
CC	kmolC/kgfuel	carbon content of the fuel
CO	-	molar fraction of carbon monoxide
CO2	-	molar fraction of carbon dioxide
dm/dt	Kg/h	mass flow rate of air–fuel mixture
e	g/kWh	the specific emission
ER	-	equivalence ratio
G^0	kJ/kmol	standard Gibbs function of reaction
g^0	kJ/kmol	standard Gibbs function of formation
H	-	mass fraction of hydrogen
h0	kJ/kmol	Enthalpy of formation
K	-	equilibrium invariable
M	kg/h	mass flow rate
m	mol/mol	molar generation rate of O2 per mole of biomass

MW	kg/mol	molecular mass
N	-	mass fraction of nitrogen
n	mol/mol	molar generation rate per mole of biomass
NO	-	mass fraction of nitrogen monoxide
O	-	mass fraction of oxygen
OH	-	mass fraction of hydrogen monoxide
P	kW	electrical power generation
p	kPa	pressure
per	-	volume percentage of O2 in the air
Q	-	coefficient of air molecular components
q	kW	thermal power
R	kJ/kmol.K	global gas constant
Ri	mol/s	equilibrium rate for reaction i
r	-	coefficients for atom balances in emission analysis
T	K	temperature
V	Nm3/h	volumetric flow rate
w	mol/mol	molar water content per mole of biomass
xi	-	mole fractions of the product species for emission analysis
yi	-	molar fractions of the product species for gasification analysis
Subscripts		
b		burned
bio		biomass feedstock (municipal solid waste)
c		cylinder
com		component of exhaust gas
e		equilibrium
exh		exhaust gas
f		fuel
fm		fully mixed
g		generator
jw		jacket water
p		piston
r		reduction
st		stoichiometric
syn		syngas
t		total
u		unburned
Greek symbol		
α	-	stoichiometric combined for C in the formula of biomass
β	-	stoichiometric combined for H in the formula of biomass
γ	-	stoichiometric combined for O in the formula of biomass
δ	-	stoichiometric combined for N in the formula of biomass
ε	-	coefficient of the feedstock mass
φ	-	coefficient of the feedstock relative to air
η	-	efficiency of conversion
ɵ	-	crank angle
ν	-	stoichiometric coefficient in the reaction

SYSTEM DESCRIPTION

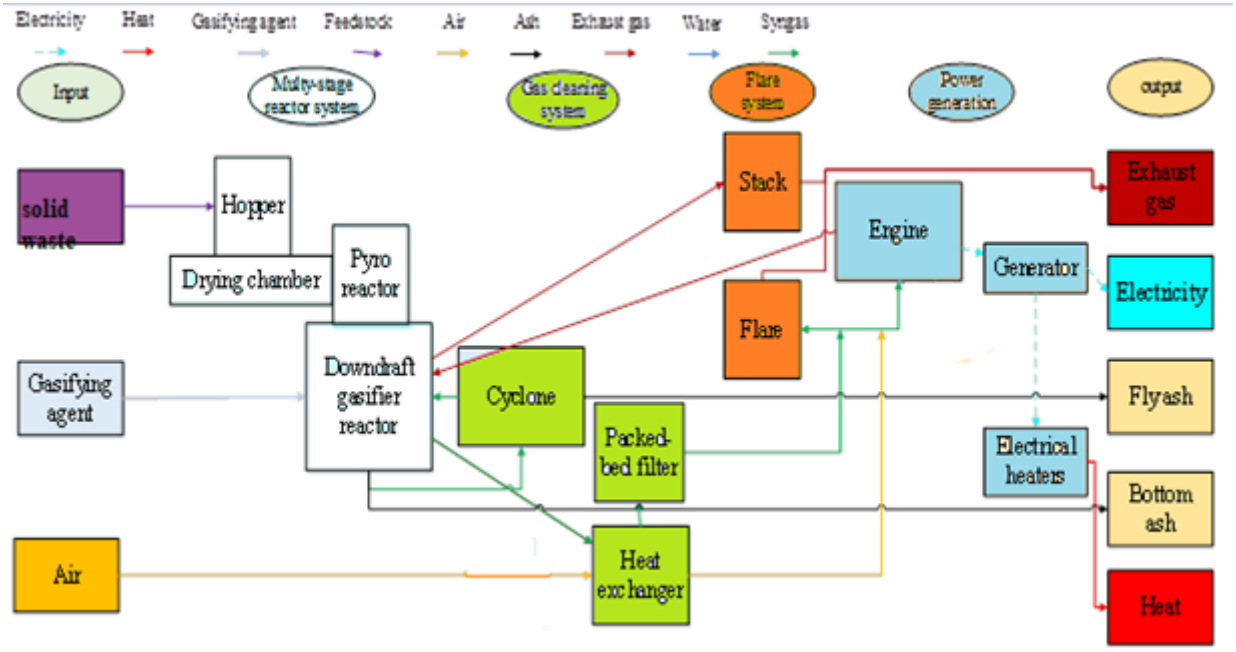
Experimental runs of gasification were achieved by applying the Power Pallet 10 kWe gasifier. This is the integration of a downdraft fixed bed reactor and the electrical power generator. The unit schematic is described in **Figure 1**. The gasifier is made from the feedstock storage hopper. Collection of ash is operated in the apart tank, whereas a generated syngas moves throughout the cyclone. This gas is managed into a hopper to dry and filtrate. Afterwards, this gas immediately injects into the generator. The gasifier constricts under a flame zone to limit the tar content in a syngas.
In the process, the small-scale downdraft gasification is linked to the engine power generation. The system converts municipal solid waste to energy in the appearance of electricity and heat. The schematic of a power plant is presented in **Figure 1** The process schematic This process involves the gasification reactor, internal combustion engine, and stack section for exhaust gas emission.

Figure 1. The process schematic



The solid waste is retained in a hopper and transferred to a reactor. To decrease a waste moisture, the solid waste is transferred during the drying chamber provided by the double-layered heat exchanger [8]. The drained waste is converted to volatile matters, tar gases, and charcoal. Tar is a condensable hydrocarbon formed of single and multiple aromatics compounds [9].
An internal combustion engine combusts the syngas to produce electricity and heat. The exhaust gas waste heat is recaptured with a solid waste in a drying section, and a mixture of air and syngas enters the engine. The exhaust gas generated from an engine is discharged during an exhaust stack.
The gasification and engine process converts approximately 80% of total matter existent in a feedstock to a flue gas [10]. The main parts are water, CO_2, and oxidation products from the waste. A flue gas moves the mixture from another component to the environment. Results of emissions are the acid gaseous compounds SO_2 and HCl. Metal sulphate decomposes at high temperature, and forms SO_2. Another gaseous emission is NO, which can be oxidized and become the acid rain. NOx derives entirely from nitrogen compounds of municipal solid waste [10].
The Reference Energy System (RES) describes the available energy conversion technologies. Energy conversion technology directs to all energy technologies, from resource extraction to transformation, transport, distribution of energy carriers, and end-use technologies. The reference energy system diagram of the studied power plant is presented in **Figure 2** The reference energy system diagram.
For modeling the performance and emissions from the gasification and engine, it is first necessary to have information in the field of gasification technology, the engine modeling, and the emission analysis in the methodology section. Therefore, this section will examine this critical issue.

Figure 2. The reference energy system diagram.



METHODOLOGY

For inventing the performance and emission model to investigate engine pollutants, the exhaustive algorithm is used as part of the model. The general levels involve:

1. Data Collection
- Data collecting about engine specifications such as fuel type, engine volume, etc.
- Information gathering on pollutant levels such as CO2, nitrogen oxides, particulate matter, etc.

2. Data Preprocessing
- Normalizing the information and transforming it to the model format.

3. Model Selection
- Choosing an exhaustive algorithm such as linear regression, neural networks, or other appropriate models.

4. Model Evaluation
- Appreciating the performance of the model with the test data.

5. Prediction of Pollutants
- Using the model to forecast pollutants based on engine inputs.

This paper describes validation and development of the thermodynamic gasification and combustion model to analyze pollutant emission mechanisms. The model has been introduced as the fundamental of the closed cycle of the downdraft gasification and power generation unit [11]. Its goal is the forecast of gasification and engine outputs and emissions, with attention to the mass and energy balancing for the pollutant emission mechanisms from the gasification and combustion phase of Spark Ignition (SI) engines. Computed details for approving a model is utilized with an aftercooled Natural Gas (NG), turbocharged, multi-cylinder, and four-stroke SI engine with syngas fuel [11].

The goal of the source [12] is the finding of the electrical power load effect on an experimental power, fuel consumption, efficiency, NO and CO emissions. A load of power about 40 to 100 kW was assumed and operated by linking the various load. An amount of energy and emissions were computed with experiments and stated in the source [12]. In the source [13], specific emissions of CO and NO, and electrical efficiency with the generated power are compared, too.

As a result, the paper innovation is the modeling of the amount of the emissions with the mass and energy balances for the gasification and engine. Exclusive the power load and emissions from a source [12], and specific emissions of CO and NO from the source [13], are applied for the model validation. Applying the Monte Carlo method, a normal distribution function of food waste, plastic, and paper, entrances a gasification and power generation systems. The systems are modeled with 1000 waste data from Tehran.

So, the histograms of the generated power, fuel consumption, emission compositions of NO, CO, and CO2, and specific emissions of NO and CO, are drawn. A gasification and 1-D internal combustion engine model is elected for the base model. So, the gasifier and an internal combustion engine are modeled. Then the model is validated with the experimental results of the references [12] and [13]. This model is advanced in MATLAB R2019a.

The gasification model

In the paper, by assuming the gasification modeling, the analysis of other researches in this area is studied. Many

researchers have been organized in various countries to elect a suitable system in environmental and economic outlooks.

Mass balance

The municipal solid waste is assumed to be generated of *C, H,* and *O* elements, and a chemical formula is *CHaObNc*. About the gasification products, close to syngas components, by-products tar, and char, are also assumed. As believed by the similarity of chemical forms, char and tar are explained by graphite (C) [14] and benzene (C_6H_6) [15]. So, a global gasification reaction can be displayed as [16]:

$$CHaObNc+wH_2O+m(O_2+3.76N_2) \Rightarrow n_{syn}(y_{H2}H_2+y_{CO}\,CO+y_{CO2}\,CO_2+y_{CH4}\,CH4+y_{H2O}\,H_2O+y_{N2}\,N_2)+n_{tar}\,Tar+n_{char}\,C \quad (1)$$

where *a, b, c,* and *w* parameters are considered from the municipal solid waste estates, which can be assumed as recognized parameters [8].

A molar percent of syngas components is limited by Dalton's law, and, as stated by a global gasification reaction displayed in Eq. (1), a mass balance for *C, H, O,* and *N* elements can be presented in Eqs. (4)–(7):

$$1= n_{syn}(y_{CO}+y_{CO2}+y_{CH4})+6\,n_{tar}+n_{char} \quad (3)$$

$$a+2w= n_{syn}(2\,y_{H2}+4y_{CH4}+2y_{H2O})+6\,n_{tar} \quad (4)$$

$$b+w+2m = n_{syn}(y_{CO}+2y_{CO2})+y_{H2O}) \quad (5)$$

$$c+2\times3.76m = 2y_{N2}\,n_{syn} \quad (6)$$

$$(y_{H2}+y_{CO}+y_{CO2}+y_{CH4}+y_{H2O}+y_{N2})=1 \quad (7)$$

where *yi* shows a mole percent for components of syngas. All these items can be calculated with particular equations, which have been omitted due to the necessity of brevity.

Thermodynamic equilibrium

The thermodynamic equilibrium is presented for all of the chemical reactions. All of the reactions are done at 1 atm pressure and the whole of the gases are assumed ideal. So, for the water–gas shift reaction (Eqs. (15)) and the methane reaction (Eqs. (16)), the following equations are presented:

$$K_1 = \frac{(y_{CO_2})(y_{H_2})}{(y_{CO})(y_{H_2O})} \quad (13)$$

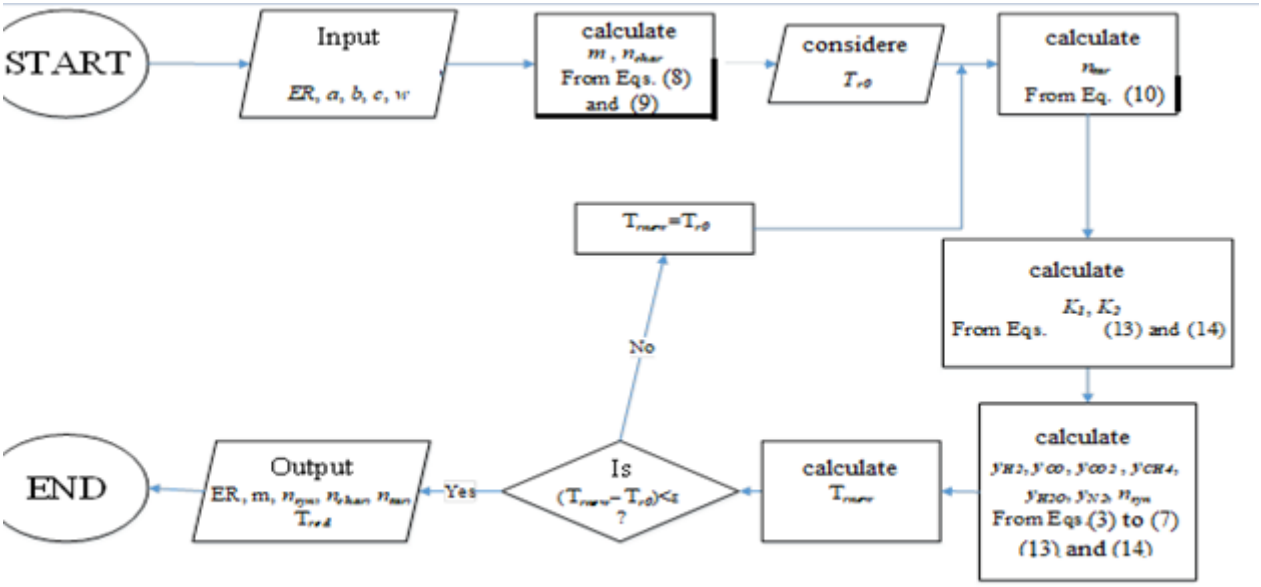
$$K_2 = \frac{(y_{CH_4})}{(y_{H_2})^2} \quad (14)$$

where y_i shows the mole fraction of species *i*.

Energy balance

The enthalpy or energy balance is presented. **Figure 3** The thermo-equilibrium gasification model flowchartpresents the gasification model flowchart. It shows the perfect flowchart for understanding the modeling.

Figure 3. The thermo-equilibrium gasification model flowchart.



After that, computing *m, n_{char}, n_{tar}, K1*, and *K2*, there are seven equations and eight unknowable variables. The Newton-Raphson method is used to verify variables.

The power generation model

The fuel chemical energy is reformed into four components, i.e., the shaft work, the waste heat in the exhaust gas, the waste

heat in jacket water, and the unrecoverable heat loss [16]:

$$q_f = P_{shaft} + q_{exh} + q_{jw} + q_{loss} \quad (18)$$

where q_f is a chemical energy in a fuel input per unit of time and equals to a syngas lower heating value per unit of time, and P_{shaft}, q_{exh}, q_{jw}, and q_{loss} are four items referred to them per unit of time. Eq. (23) involves the total components required for the engine model. All these items can be calculated with particular equations, which have been omitted due to the necessity of brevity. To calculate qf, the heat quantity is calculated with a heat produced when the unit quantity is burned in the bomb calorimeter with oxygen [17].

The emission model

NO formation

Nitrogen oxide (NO) emissions from combustion approach generally from two sources, thermal NO formation and fuel NO formation [18]. As stated by the Zeldovich mechanism, three reactions are assumed:

1. $N + NO \Leftrightarrow N_2 + O \qquad K_{f1} = 1.6 \times 10^{10} \quad (19)$
2. $N + O_2 \Leftrightarrow NO + O \qquad K_{f2} = 6.4 \times 10^{6}\ T \exp\left(-\frac{3150}{T}\right) \quad (20)$
3. $N + OH \Leftrightarrow NO + H \qquad K_{f3} = 4.1 \times 10^{10} \quad (21)$

To assume the change rate of NO, two presumptions are considered. First, a concentration for N is unimportant with contrast by concentrations for another species, so its change rate can be specified capable of zero. Secondly, it is assumed that concentrations of H, O, OH, N_2, and O_2 can be approached from their equilibrium amounts. Applying presumptions, the change rate of NO concentration, indicated as [NO], is presented from:

$$\frac{d[NO]}{dt} = \frac{2R1\left\{1 - \left(\frac{[NO]}{[NO]_e}\right)^2\right\}}{1 + \left(\frac{[NO]}{[NO]_e}\right)\cdot\left(\frac{R1}{R2 + R3}\right)} \quad (22)$$

where R_i is the one-way equilibrium rate for reaction i, described as:

$$R_1 = k_{f1}\,[N]_e\,[NO]_e \quad (23)$$
$$R_2 = k_{f2}\,[N]_e\,[O_2]_e \quad (24)$$
$$R_3 = k_{f3}\,[N]_e\,[OH]_e \quad (25)$$

The NO concentration of each burned gas zone has been concluded by integration of Eq. (21), average NO mole fraction for the whole cylinder content is determined by:

$$[NO]_{fm} = \frac{N_{NO}}{N_{tot}} \quad (26)$$

N_{NO} shows a number of NO kmol in a cylinder of the engine, presented from:

$$N_{NO} = m\left(\sum_{i=1}^{n}[NO]_{b,i}\frac{X_{b,i}}{M_{b,i}} + [NO]_u\frac{1 - X_b}{M_u}\right) \quad (27)$$

where an amount of $[NO]_u$ descends competent into zero, as no nitric oxide survives in the unburned section. N_{tot} shows an entirety number from all components kmol in a cylinder of the engine, calculated by:

$$N_{tot} = \sum_{X=0}^{11} N_X \quad (28)$$

where indication X expands 0 toward 11, by numbers nominating twelve in the overall chemical category integrated for a model, and N_X is presented in every species.

CO formation

Carbon monoxide in syngas combustion products have two primary sources: unburned syngas CO, deriving from ineffectual mixing producing regions with equivalence ratios, and imperfect combustion of hydrocarbon species in the syngas. The amount formed of CO from a combustion procedure is oxidized and converted to CO_2 at a rate that is comparatively slow contrasted with a rate from the formation of CO. Two kinetically handled reactions, are indicated:

$$CO + OH \Leftrightarrow CO_2 + H \quad K_1\left(\frac{m^3}{kmol.s}\right) = 6.76 \times 10^{10} \exp\left(\frac{T}{1102}\right) \quad (29)$$

$$CO_2 + O \Leftrightarrow CO + O_2 \quad K_2\left(\frac{m^3}{kmol.s}\right) = 2.51 \times 10^{12} \exp\left(-\frac{22041}{T}\right) \quad (30)$$

Emission model explanation and thermodynamic properties

The multi-zone model is used throughout the closed section of the engine cycle between compression, combustion, and expansion. It needs the geometric characteristics of the engine, engine speed, Wiebe function parameters, start of combustion, equivalence ratio, duration of combustion, and pressure and temperature in the inlet valve closing occurrence as input data [19].

For every engine load investigated, the syngas fuel supply is achieved from the formula:

$$\left(\frac{dm}{dt}\right)_{fuel} = \frac{\left(\frac{dm}{dt}\right)_{0,mix}}{\lambda \times AFR_{st,fuel} + 1} \quad (31)$$

where $\left(\frac{dm}{dt}\right)_{0,mix}$ is the mass flow rate of the air-fuel mixture interior combustion chamber at the entrance of compression stroke, and fuel $AFR_{st,fuel}$ is the stoichiometric Air to Fuel Ratio that is computed from the recognized composition of every fuel examined.

Combustion products consist of eleven chemical species (H_2O, H_2, OH, H, N_2, NO, N, CO_2, CO, O_2 and O), which are assumed to be in chemical equilibrium. It should be noted that every species is related to some CH_4 given for the syngas. The different thermodynamic qualities from burned and unburned mixtures, required in computations, are calculated as stated by every species mole fraction [19].

Mathematical Model of emission

Subordinate the atmospheric air composition supposition (79% volume Nitrogen and 21% volume Oxygen), the species involving O, H, OH, and NO are significant because of dissociation. Accordingly, the combustion reaction develops and a fuel $C_\alpha H_\beta O_\gamma N_\delta$ and air at equivalence ratio φ react, and the products get to equilibrium at a pressure and temperature.

$$X_{12}\left[C_\alpha H_\beta O_\gamma N_\delta + \frac{\alpha+\frac{\beta}{4}-\frac{\gamma}{2}}{\varphi}\left(O_2 + Q_{N_2}N_2 + Q_{CO_2}CO_2 + Q_{H_2O}H_20\right)\right] \longrightarrow X_1H + X_2O + X_3H_2 + X_4OH + X_5CO + X_6NO + X_7O_2 + X_8H_2O + X_9CO_2 + X_{10}N_2 + X_{11}N \quad (40)$$

where x1 to x11 are mole fractions of the product species, the number x12 shows the moles of fuel that will present one mole of products.

$$r_0 = \frac{\alpha+\frac{\beta}{4}-\frac{\gamma}{2}}{\varphi} \quad (41)$$

$$r = r_0\left(1 + Q_{CO_2} + \frac{Q_{H_2O}}{2}\right) + \frac{\gamma}{2} \quad (42)$$

$$r_1 = r_0 Q_{N_2} + \frac{\delta}{2} \quad (43)$$

$$r_2 = r_0\, Q_{CO2} + \alpha \quad (44)$$

$$r_3 = r_0\, Q_{H2O} + \beta \quad (45)$$

The atom balances for the several elements present:

C: $x_5 + x_9\, r_2 = x_{12}\, r_2$ (46)

H: $x_1 + 2x_3 + x_4 + 2x_8 = x_{12}\, r_3$ (47)

O: $x_2 + x_4 + x_5 + x_6 + 2x_7 + x_8 + 2x_9 = 2x_{12}\, r$ (48)

N: $x_6 + 2x_{10} + x_{11} = 2x_{12}\, r_1$ (49)

The constraint that the mole fraction of all the products count up to entity wants that:

$$\sum_{i=1}^{11} X_i = 1 \quad (50)$$

As was explained previously, to decipher the 12 unknowns, we require seven more equations that are supplied by the criteria of equilibrium in the middle of the products, indicated by the following seven theoretical reactions:

$$\frac{1}{2}H_2 \Leftrightarrow H \qquad K_1 = \frac{X_1 P^{0.5}}{X_4^{0.5}} \quad (51)$$

$$\frac{1}{2}O_2 \Leftrightarrow O \qquad K_2 = \frac{X_2 P^{0.5}}{X_8^{0.5}} \quad (52)$$

$$\frac{1}{2}N_2 \Leftrightarrow N \qquad K_3 = \frac{X_a P^{0.5}}{X_{11}^{0.5}} \quad (53)$$

$$\frac{1}{2}H_2 + \frac{1}{2}O_2 \Leftrightarrow OH \qquad K_5 = \frac{X_5}{X4^{0.5} X_8^{0.5}} \quad (54)$$

$$\frac{1}{2}N_2 + \frac{1}{2}O_2 \Leftrightarrow NO \qquad K_7 = \frac{X_7}{X_8^{0.5} X_{11}^{0.5}} \quad (55)$$

$$H_2 + \frac{1}{2}O_2 \Leftrightarrow H_2O \qquad K_9 = \frac{X_9}{X_4 X_8^{0.5} P^{0.5}} \quad (56)$$

$$CO + \frac{1}{2}O_2 \Leftrightarrow CO_2 \qquad K_{10} = \frac{X_{10}}{X_6 X_8^{0.5} P^{0.5}} \quad (57)$$

Newton-Raphson method is then applied to solve the above equations.

The specific emission

The environmental impact has been calculated by computing CO, HC and NOx specific emissions. For specific emissions dedication depended on electrical power, Eq. (1) was applied by [20]:

$$e_{com} = \frac{CC \times M_f \times [com] \times MW_{com} \times 106}{P_{shaft} \times ([CO] + [CO_2])} \quad (58)$$

where e_{com} is the "com" exhaust gas component specific emission (for example, NO or CO) in g/kWh, *CC* is the fuel carbon content in kmol of carbon/kg of fuel; M_f is the fuel mass flowrate in kg/s; *[com]* is the "com" exhaust gas molar fraction (NO or CO); M_{com} is the "com" exhaust gas component atomic mass in kg/kmol; P_{shaft} is the power produced from a system in kW; and *[CO_2]* and *[CO]* are the CO_2 and CO molar fraction in the exhaust. Regarding the NO specific emission, a particular impact from Equivalence Ratio (*ER*) and ignition advance was discovered [20].

The Monte Carlo method

In the analysis for the solid waste use for power generation, the most analytical question is a variety between the traditional power plant and waste gasification with power plant by the conditions of the input fuel. The input fuel to a traditional power plant is determinate; On the other hand, the waste gasification with power plant has a fluctuating fuel composition every hour, day, and season because of the composition fluctuations in the feedstock. Because of the composition uncertainty in the feedstock, using the Monte Carlo method will be suitable.

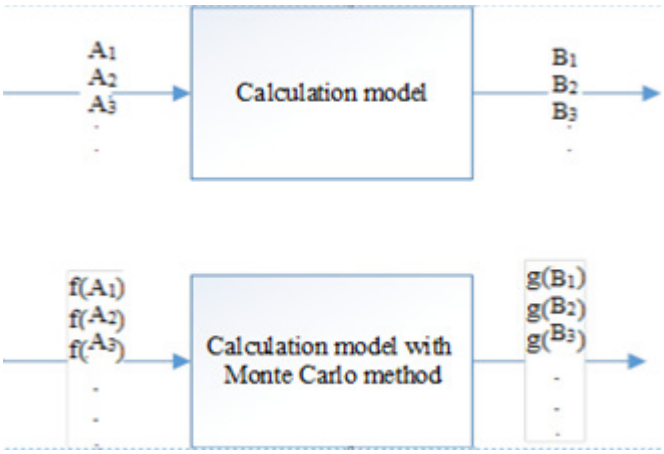
Figure 4 shows a diagram of the Monte Carlo method. In this figure, the parameters *A1, A2, A3, …* can describe an input feedstock to a gasifier and an input syngas to an engine in the modeling. Also, the parameters *B1, B2, B3, …* specified the subsequent items in modeling:

- Combination of pollutants and emissions from the engine
- Composition of output syngas from the gasifier
- The amount of power generation from the engine

Applying the amounts of a mean value achieved from a waste analysis probability distribution will influence the exactness of the appropriate computations. As one of the applications of municipal solid waste is in forming electricity and heat, it is necessary to study the behavior of the waste gasification process and the internal combustion engines. As a result, the

latest plan was obtained for the internal combustion engine model.

Figure 4. Monte Carlo method diagram.

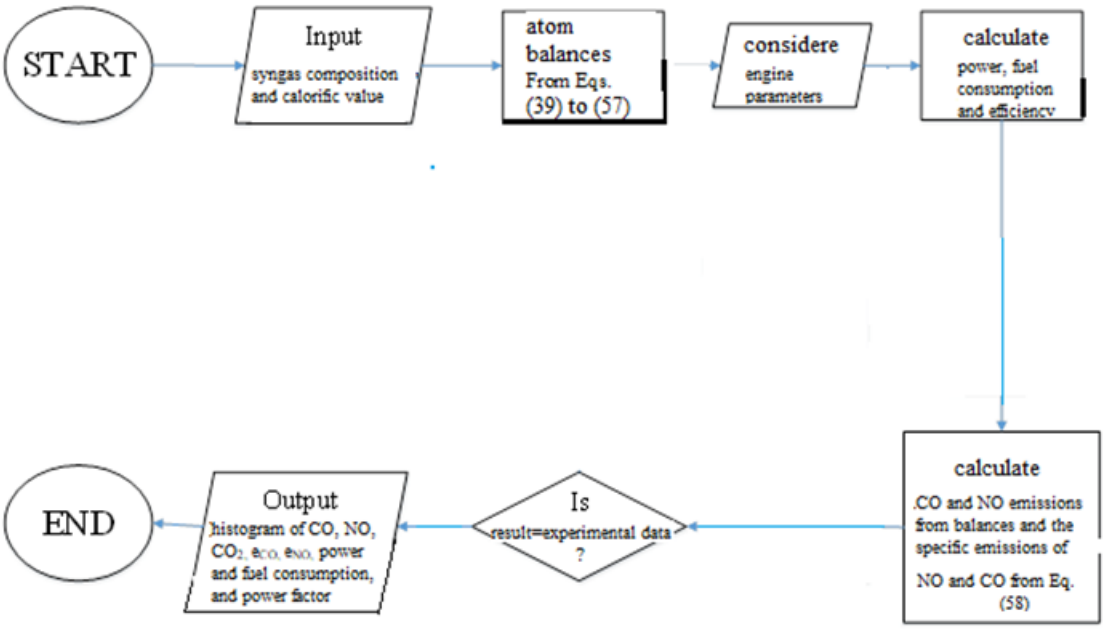


As the input waste has uncertainty, it is essential to attach the Monte Carlo method and the probability density function to a model for obtaining the histogram for the mean values of the fuel consumption, power, emissions, syngas composition, the specific emissions, the syngas flow rate, the ash-flow rate, the waste heat from an exhaust, and the waste heat from the jacket water. After detecting the probabilities and mean values of results such as power, locating the weight of the power in Eq. (32), and assuming a generator efficiency, a power factor of a power plant can be obtained:

$$\text{Power Factor} = \text{PF} = \frac{\text{P}_{mean\ value} \times \eta_g}{\text{no min al power}} \qquad (59)$$

Figure 5 The thermo-equilibrium gasification model flowchartpresents the flowchart of the power and emission model for the engine system. It shows the perfect flowchart for understanding the modeling after obtaining the composition and net calorific value of syngas from the gasification model. The Newton-Raphson method is used to determine variables of emission polutants. Finally, if the results are equal with experimental data, the histogram of emissions, power, and fuel consumption are presented.

Figure 5. Flowchart of the methodology.



To calculate the emissions of NO and CO, the mathematical model for balance of atoms has been used. The relationships related to these balances are equations number 39 to 57. After using these relationships, if the results differ from the experimental results and have a large error, another method related to the Zeldovich mechanism can be used to calculate the amount of NO emission. The equations related to this mechanism are relations number 19 to 28, which gives the amount of NO emission. In order to calculate the amount of CO emission, it can be calculated from relations number 29 and 30, which show the dependence of the rate of reactions on temperature. In the methodology section, equation 31 also shows the consumption of syngas as fuel after entering the engine specifications into the calculations. All these equations are entered in MATLAB software and the results are from this software.

RESULTS AND DISCUSSION

As described in the methodology, it is essential to explain the results in two parts for the stages of calculations.

Validation of modeling

For the model validation, experimental data for 1500 rpm (revolutions per minute) engine is used for contrast. As the exactness of the mathematical model depends on the usage of reasonable data, syngas characterization is collected from experimental studies developed by source [12]. Syngas composition and net calorific values are presented in **Table 1** Net calorific values and composition (% vol.) for syngas fuel. Net calorific values have been computed to consider recognized fuel compositions. Additionally, the syngas includes approximately 50% combustible gases, primarily hydrogen and CO [12]. So the syngas fuel is used as a source feedstock for the power generation system from the downdraft gasification for validating of modeling.

The results are used by the experimental study organized for the 'GE Jenbacher 320', spark-ignited, and multi-cylinder engine. Additionally, experimental results are used to calculate a predictable capability for a presented model. The engine is a turbocharged, four-stroke, water-cooled, fuelled with syngas, and spark-ignited [12].

Total experimental results are obtained the speed of 1500 rpm and four various engine loads according to 40, 65, 85, and 100% of full load. So, applying inputs introduced in **Table 1** and **Table 2**, model validation is done. The experimental engine power output, fuel consumption, efficiency, NO emissions, and CO emissions on the products, are shown in **Table 3** at the engine speed of 1500 rpm from reference [12]. Also, these variables of power, efficiency, fuel consumption, and emissions are calculated at the engine speed of 1500 rpm from modeling with defined syngas fuel composition and detailed in **Table 3**.

The approximation between experimental and computed results of fuel consumption, efficiency, and emissions below different load and power output conditions are shown in **Table 3**. As presented in **Table 3**, in the states that the feedstock flow, and the output power for gasification and engine systems is the same, which correspond with the experiments' results.

Whereas the primary aim is to analyze, on a theoretical result of the category of fuel used in terms of engine performance and pollutant emissions, with the same input values, are additionally used for the theoretical study about engine operation under syngas fuel system. Therefore, it would be probable to secure the actual effect of the fuel used on the combustion and pollutant emission mechanisms despite any differences in the power generation.

Table 1. Net calorific values and composition (% vol.) for syngas fuel.

CO	H2	CO2	N2	CH4	net calorific value (MJ/kg)	net calorific value (MJ/Nm3)
47.1	5.5	45	0.5	9.3	13.9	6.84

Table 2. Values of parameters for modeling [12]

Parameter	Value
Number of cylinders (nc)	20
Displacement (Vc)	48.7
Cylinder bore (lbore)	0.135 m
Cylinder stroke (sc)	0.17 m
Connecting rod length (lc)	0.32 m
Compression ratio (rc)	11:1
Mean piston speed	8.5 m/s
Rated engine speed (Nrev)	1500 rmp (25 rev/s)

Table 3. Comparison of experimental engine power, fuel consumption, efficiency, NO, and CO emissions from source [12] with these calculated variables from modeling.

Experimental data					Computed results
load (%)	40	65	85	100	65
CA b TDC (deg.)	35	30	27	25	30
power (kW)	300	500	700	800	498
fuel consumption (g/kWh)	800	750	720	700	742.0852
efficiency (%)	32.37	34.53	35.97	37	34.9
NO emission (ppm)	200	180	170	160	178
CO emission (ppm)	1400	1500	1650	1700	1596

The effect of the syngas composition entering the engine, in addition to the ppm of emissions such as CO and NO, can also be investigated in terms of the specific emissions of these pollutants. For this reason, to revalidate the model, the input syngas composition of another reference [13] will be used in the input of the model, and the amount of specific emissions of these pollutants will be checked. The composition of the syngas used is given in **Table 4**. So the syngas fuel is used as a source feedstock for the power generation system from the downdraft gasification for revalidating of modeling.

Table 4. Composition of syngas (%, by vol.).

CO	H2	CO2	N2	CH4
25.4	18.3	13.6	40.3	2.4

The specific emissions of CO and NO, and electrical efficiency with the generated power are calculated. The results are shown in **Table 5**.

As seen in **Table 5**, the results denote that with the engine operating by this syngas with the mentioned specification, the emissions were significant, especially in air to fuel equivalence ratio (ER) of 1.5. Therefore, according to the results obtained from this validation, gas modeling and engine modeling are acceptable.

Table 5. Comparison of the specific emissions of CO and NO, and electrical efficiency with the generated power reported by source *[13]* with these calculated variables from modeling

Reported by source										Computed results
CA b TDC (deg.)	10	15	20	25	30	35	40	45	50	23
power (kW)			3.8							5.3
efficiency (%)	27	27.5	29	31	32	32.5	32	31	30	30.08
eNO (g/kWh)	0.8	0.9	1.2	2.2	3.7	4	4.8	6.5	7.7	1.399
eCO (g/kWh)	47	30	26	25	24	22	23	20	20	26.472

Simulation with specified distribution functions and the Monte Carlo method

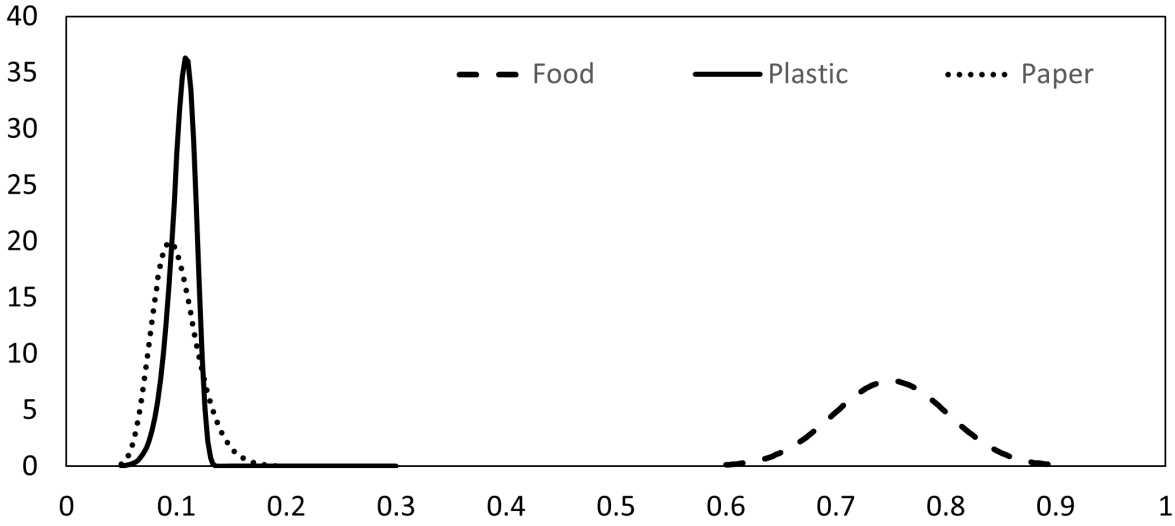
Analysis of municipal solid wastes is wanted to model gasification and engine by the MATLAB R2019a. The present data in this section is based on the physical decomposition in which the mass fraction of food, paper, plastic, and other components is presented. Standard simulators may pretend systems are applying input parameters, such as fuel analysis. 22 samples are gathered from a municipal solid waste hole near the location of the reference power plant at various months [21].

Analysis of samples is used to recognize suitable Probability Distribution Functions (PDFs) [22]. Various distribution functions are tested, and the best distribution functions are chosen, and are shown in **Figure 6**, by their fitting functions and coefficients reported in **Table 6**. The wood and textile in wastes are neglected. The sum of selected random values for food, paper, and plastic mass fractions normalized to 100 percent for each prediction [21].

Table 6. Parameters of PDFs used for MSW Analysis *[21]*.

	Distribution	1st parameter	2nd parameter
Food	Normal	μ=0.75	σ=0.0524
Paper	Log-normal	ω=2.32	sigma=0.208
Plastic	Weibull	a=0.11	b=10.8548

Figure 6. Input distribution functions for MSW analysis [21]

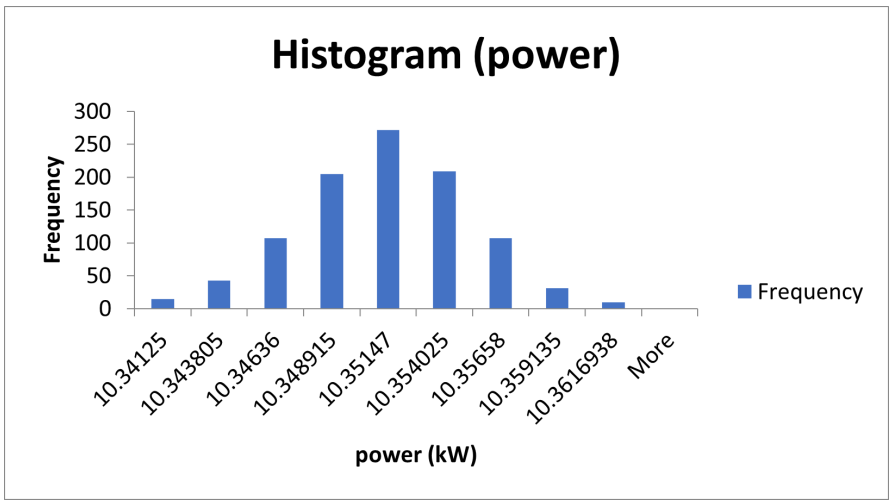


These PDFs are applied to compute the probability distribution and the mean values of the generated power, fuel consumption, emission composition of NO, CO, and CO_2, and specific emission of NO, and CO. The Monte Carlo (MC) is a way for simulation with stochastic inputs investigation, and a simulator verifies the PDF of the output. In this method, input parameters are estimated iteratively based on their PDFs, and results are applied to create outcome PDFs. The results of these variables for 1000 repetitions are presented in **Figure 7,Figure 8,Figure 9,Figure 10,Figure 11,Figure 12, and Figure 13**.

In this section, the Monte Carlo (MC) method is performed to verify that generalizations can be performed for emissions leading to environmental analysis. Inputs assumed are presented in Table 6 Parameters of PDFs used for MSW Analysis [21]. Limited with the high and low values in the table, uncorrelated distributions, and uniform histograms are applied. Uniform histogram distributions are chosen as conventional representations from uncertainty. One hundred achievements from uncertain inputs are produced with the Monte Carlo (MC) method. **Figure 7** shows histograms of CO_2 emissions obtained with one hundred achievements for a Monte Carlo method.

Within **Figure 7,Figure 8,Figure 9,Figure 10,Figure 11,Figure 12, and Figure 13**, the horizontal axis of the diagrams for the described state presents the percentage of each generated emission component. The vertical axis additionally presents the number of available results for each percent of the 1000 output results. The sample size (using randomly selected samples of data from 1000 input compositions of MSW) can influence the appearance of the graph. A histogram operates best when the sample size is more significant. The larger the sample, the more the histogram will be similar to the shape of the generated power, fuel consumption, emission composition and specific emission distribution.

Figure 7. Histogram of generated power (kW) from the Monte Carlo method.



For the generated power, **Figure 7** displays that the results fluctuate between 10.34125 (kW) and 10.36169 (kW). So, the data spread is from about 10.34125 (kW) to 10.36169 (kW) for a gasification process and internal combustion engine in the power plant. In this histogram, the peak of the data happens at about 10.35147 kW. The majority of the data are located in the center

of the graph. This histogram indicates that the data may be normally distributed.

Figure 8. Histogram of the fuel consumption from the Monte Carlo method.

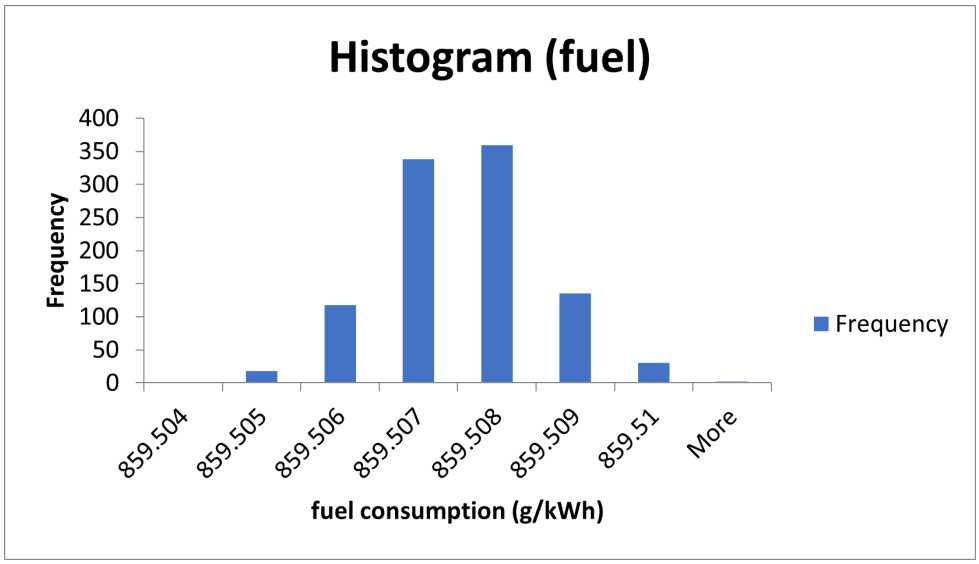
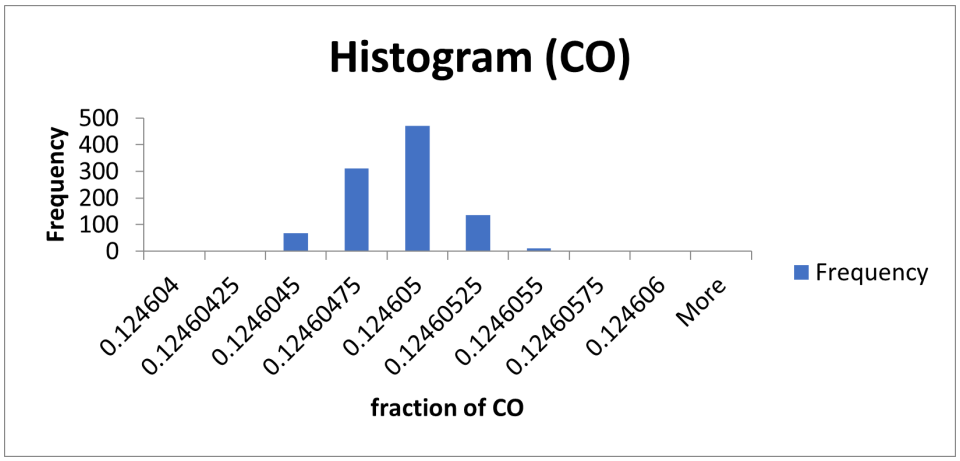


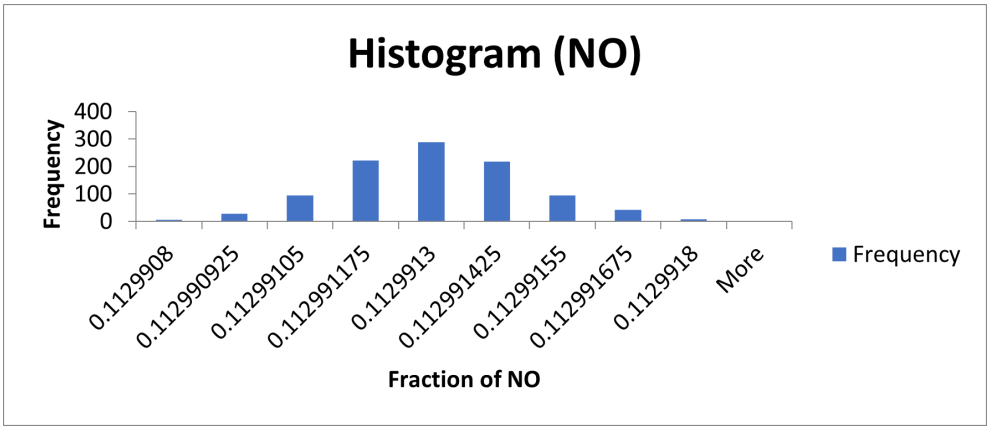
Figure 8 shows that fuel consumption fluctuates between 859.504 g/kWh and 859.511 g/kWh (the data spread is from about 859.504 g/kWh to 859.511 g/kWh). In this histogram, the peak of the data takes place at about 859.508 g/kWh. This histogram almost presents skewed data, and the histogram with left-skewed data displays failure time data. A few items fail directly, and many more items fail later.

Figure 9. Histogram of CO in emissions composition from the Monte Carlo method.



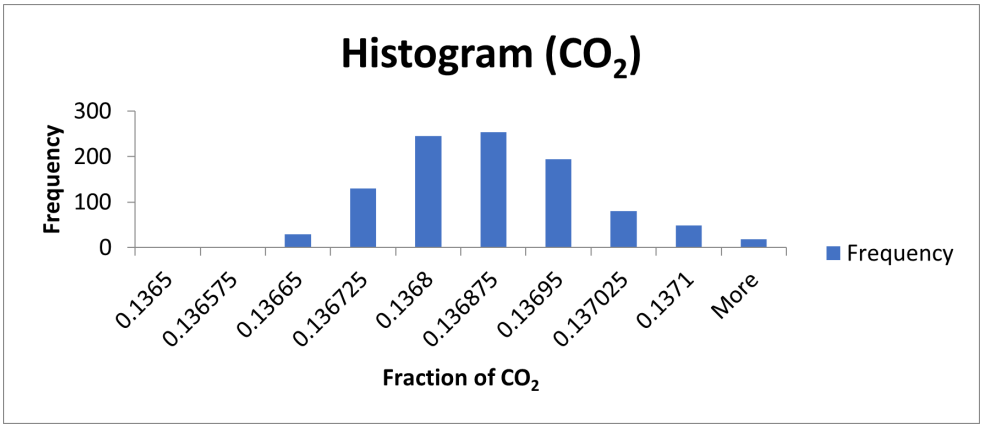
For the percentage of CO in emission composition, **Figure 9** presents that the results fluctuate between 12.4604% and 12.460575% for gasification and engine systems in the power plant. The data spread is from about 12.4604% to 12.460575%. In this histogram, the peak of the data occurs at about 12.4605% of CO. The peaks show the most common values. When data are skewed, the majority of the data is situated on the high or low side of the graph. Skewness displays that the data may not be normally distributed. This histogram indicates the left-skewed data and failure time data.

Figure 10. Histogram of NO in emission composition from the Monte Carlo method.



For the percentage of NO in emission composition, **Figure 10** shows that the results fluctuate between 11.29908% and 11.29918% (the data spread is from about 11.29908% to 11.29918%) for a gasification process and internal combustion engine in the power plant. In this histogram, the peak of the data occurs at about 11.29913% of NO. The greater of the data is situated in the center of the graph. This histogram demonstrates the data may be normally distributed.

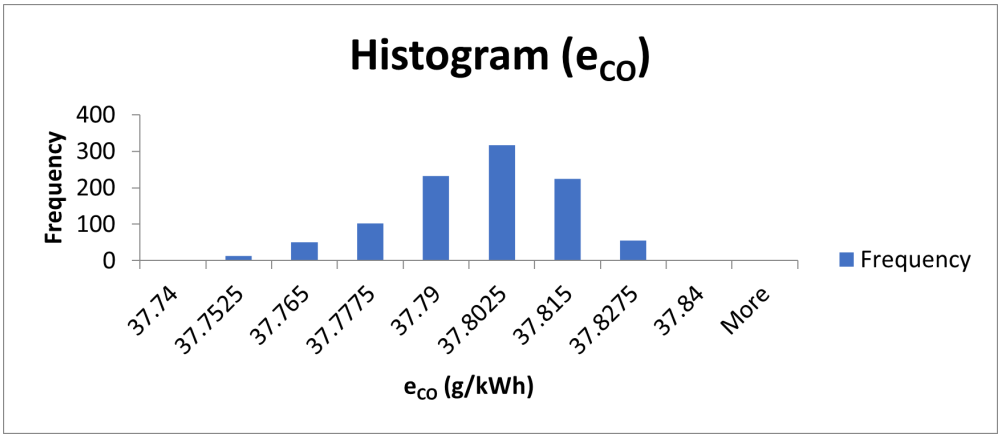
Figure 11. Histogram of CO2 in emission composition from the Monte Carlo method



Also, **Figure 11** shows that the percentage of CO_2 in syngas composition fluctuates between 13.65% and 13.72% (the data spread is from about 13.65% to 13.72%) for a gasification process and engine systems in the power plant. In this histogram, the peak of the data happens at about 13.6875% of CO_2. Skewness shows that the data may not be normally distributed. This histogram displays the right-skewed data and failure time data.

In **Figure 12** and **Figure 13**, the horizontal axis of the diagrams shows the specific emission distribution of CO and NO (g/kWh). The vertical axis also shows the number of available results for each percent of the 1000 output results.

Figure 12. Histogram of the specific emission of CO (eCO) from the Monte Carlo method



Also, **Figure 12** exhibits that the specific emission of CO fluctuates between 37.74 (g/kWh) and 37.84 (g/kWh). So the data spread is from about 37.74 (g/kWh) to 37.84 (g/kWh) in the power plant. This fluctuation is ignored in any analysis based on the constant fuel analysis, which is far from reality. In this histogram, the peak of the data appears at about 37.8025 (g/kWh). The peaks describe the most common values. Skewness shows that the data may not be normally distributed. This histogram approximately displays skewed data (with left-skewed data).

Figure 13. Histogram of the specific emission of NO (eNO) from the Monte Carlo method.

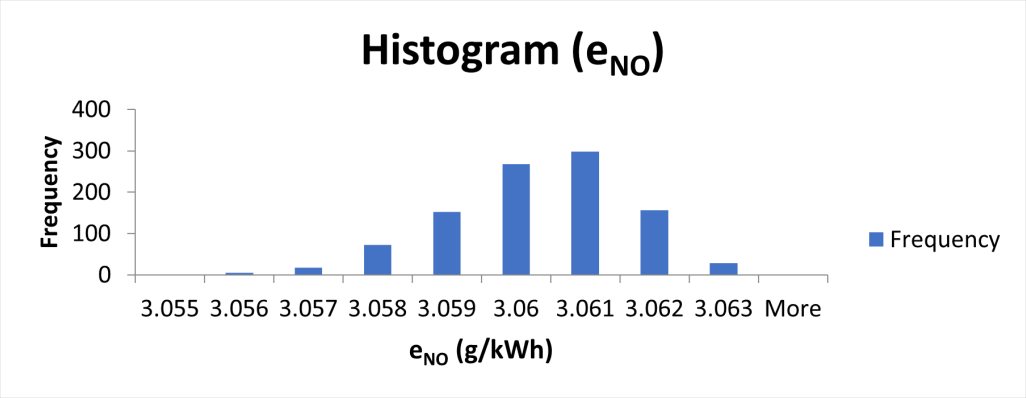


Figure 13 presents that the data spread of the specific emission of NO is from about 0.83465 (kg/h) to 0.83899 (kg/h) in the power plant. In this histogram, the peak of the data occurs at about 0.83682 (kg/h). This histogram almost illustrates skewed data (with left-skewed data).

Finally, after running the model with input data, the mean value and Standard Deviation (Std) of output results are obtained in **Table 7**. Within the Monte Carlo method, independent variables by their specified standard deviations can be randomly chosen of their base amounts throughout the simulation. In a finale from the Monte Carlo method, an appearance probability from every effect characterisation with the satisfied percent is calculated. An effect potentials that can be decreased present larger distribution from probability for appearance, in opposite of limit distributions differently.

Table 7. Mean value and Std. of outputs

Emission composition	Unit of the mean value	Mean value	standard deviation
CO	%	12.46	164.2735
NO	%	11.299	105.6083
CO2	%	13.687	99.46747
eCO	g/kWh	37.8025	117.3877
eNO	g/kWh	3.061	
fuel consumption	g/kWh	859.5	147.1161
generated power	kW	10.35147	97.70869

The Monte Carlo method permits examination for standard deviations from independent procedure variables for forecasting total effect potentials probability distributions. more number from the Monte Carlo method runs confirm that effect potentials probability distributions can be created better and more correct. The Monte Carlo method runs 1000 to achieve powerful effect potentials probability distribution curves.

The standard deviation presents a normalized deviation from the scattered data for their mean value or average. Eq. (60) presents a principle to compute n data points standard deviation, with consideration their average.

$$\sigma = \left(\frac{\sum_{i=1}^{n} \left(X_i - X_{mean\ value} \right)^2}{n} \right)^{0.5} \qquad (60)$$

After determining probabilities and mean values of results such as fuel consumption and power, by putting the amount of generated power in Eq. (32), the power factor of the system can be computed and is equal to 0.88727. So, the produced power ($P_{mean\ value}$) is the generated electricity from the power plant is considered in the $P_{mean\ value}$ computations. The generator efficiency (ηg=90%), which is assumed as the function of the generator fraction load ratio [16],

$$\text{Power Factor} = \text{PF} = \frac{P_{mean\ value} \times \eta_g}{\text{nominal power}} = \frac{10.35147 \times 0.9}{10.5} = 0.88727$$

The power plant overhaul is not assumed in Eq. (34), and the power factor is computed by the constant failure and repair rates. So, this computation presents that the power plant generated power mean value is less than the real nominal power measured in the reference [16] despite the similar technology of the power plant operation and design. The amount of power factor (less than 100%) results the influence of MSW quality on the waste-to-energy power plants performance. It shows the inability of methods based on constant municipal solid waste analysis for the performance analysis.

In addition, technical and economic analysis of the performance of gasification technology, considering the lack of electricity consumption and the production of electricity from syngas produced from solid waste, showed that a gasification unit with a high capacity factor and power factor is the most cost-effective solution [23]. This analysis will be presented in subsequent articles and projects.

CONCLUSION

The performance and emissions from the small-scale downdraft gasification and engine are modeled to convert municipal solid waste to electric power and heat. A mass, equilibrium, and energy equations are formulated for the gasification. The performance and emissions model of a total system, which consideres gasifier and internal combustion engine, is created. Through patterns progressed by this paper, the amount of emission pollutants and power production from the total system can be modeled. Furthermore, this paper presents essential theoretical and functional guidance to design the similar systems.

For the model validation, an experimental data arranged and collected by the 1500 rpm engine was used for contrast. The syngas components compare within the amounts provided by the reference, and according to the results presented from this validation, power modeling and emission modeling are acceptable. The feedstock flow is the similar, the output power for the gasification and engine systems is the same, which corresponds with the experiments' results.

The main limitation of the gasification and the internal combustion engine is the fluctuating gas composition and a syngas flow rate. The gasification and engine analysis will present a fluctuation point from the emission pollutants, efficiency of power, and fuel consumption. A probabilistic methodology is presented to show and calculate the power generation, fuel consumption, NO, CO, and CO_2 emissions, specific emissions of NO and CO, and the power factor of the Waste-to-Energy power plant.

MSW analysis with mass fractions of the food, plastic, and paper, is not constant, and the power generation, fuel consumption, and emission compositions fluctuate continuously. The variability of municipal solid waste is modeled using the Monte Carlo method. Study the peaks and spread of the distribution, and examination of skewed data show that data may be nonnormal. Although a nominal power production is 10.5 kW, a mean value of the power production was calculated at 10.35 kW. Assuming the generator efficiency, the power factor of the power plant is equal to 0.88727.

In future research, air-to-fuel ratio, compression ratio, and operating cylinder pressure ignition timing are some of the parameters that need to be studied and optimally used for better engine performance and reduced emissions.

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Ethical Approval

No aspect of this work involves experimental animals or specific human diseases that requires ethical disclosure and approval.

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