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Performance Investigation and Optimization of Municipal Solid Waste Incineration: Enhancing Energy Efficiency and Reducing Emissions Via Aspen Plus simulation, Study Case in Soreang, Indonesia

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A B S T R A C T

Indonesia faces a critical waste management challenge, generating over 38 million tons of waste annually, with nearly 40% remaining unmanaged. Waste-to-Energy (WtE) technologies, such as incineration, offer a sustainable solution by reducing waste volume while recovering energy. However, emissions of NOx, CO, and other pollutants from incinerators remain a major concern. This study investigates the performance of a municipal solid waste (MSW) incinerator in Soreang, Indonesia, using Aspen Plus simulations to analyze the impact of superheated steam injection on emission reduction and energy efficiency. Key variables included steam mass flow rates (60–120 kg/h) and flue gas integration for waste drying. Results demonstrated that superheated steam injection significantly reduced emissions, with CO decreasing by 0.63 ppm (139.935 to 139.303 ppm) and NO_2 declining by 0.038 ppm (7.877 to 7.839 ppm) across the tested range. The simulation model exhibited high predictive accuracy (RMSE = 0.196) when validated against field data. Furthermore, an optimized intermittent furnace design reduced energy consumption by 3.94–4.16% compared to the existing system, highlighting improved combustion efficiency. The integration of steam and flue gas for MSW drying also achieved a 36.91% moisture reduction, enhancing combustion stability. This study confirms that superheated steam injection is a viable strategy for mitigating emissions in MSW incineration, while the proposed design improvements advance energy recovery. The findings provide actionable insights for policymakers and engineers seeking to align WtE systems with circular economy principles in developing regions.

Keywords: Municipal Solid Waste (MSW), Superheated Steam Incinerator, Emission Reduction, Energy Efficiency, Flue Gas Integration.

1. Introduction

The waste problem in Indonesia has become one of the most pressing environmental issues. Based on data from the Ministry of Environment and Forestry of the Republic of Indonesia in 2023, Indonesia produced more than 38.3 million tons of waste (SIPSN, 2024). Managed waste was 61.75% or 23.6 million tons of the total, while the remaining 14.6 million tons was unmanaged. Most of the waste is in landfills or pollutes the environment, such as rivers, seas, and residential areas (Supriatna, Aminuddin, et al., 2024). This problem harms the environment, public health, and the nation's economy. Various efforts have been made to address the waste problem in Indonesia, ranging from integrated waste management approaches, increasing public awareness, to implementing policies such as reducing single-use plastics and improving recycling facilities (Bachtiar et al., 2022). In addition to waste management efforts, the potential of waste as a renewable energy source is increasingly becoming a concern. For example, Waste-to-Energy (WtE) technology allows waste conversion into heat and/or electricity through various methods, such as incineration, pyrolysis, and gasification (Dafiqurrohman et al., 2022; Supriatna, Zuldian, et al., 2024). This utilization can help reduce the burden on landfills while providing a more environmentally friendly energy alternative.

Incineration can reduce the volume of waste by up to 90%, which helps reduce the space requirement for landfills (Falconi et al., 2020). The incineration process not only burns municipal solid waste (MSW) but also generates thermal energy or electricity that can be used to meet energy needs. The residual ash (clinker) from the incineration process can be used in the road building and construction industry, which gives added value to the remaining waste. Broadly speaking, incineration is still the leading method that is harmless and effective in energy recovery from MSW (Khan et al., 2022). Despite its benefits, incineration poses the environmental challenge of air pollution. Controlling the emission of toxic substances such as nitrogen oxides (NOx) and carbon monoxide (CO) at incinerators remains a significant challenge.

To optimize emissions control in waste incineration, multiple strategies have been explored. Löschau (Löschau, 2018) proposed lower combustion temperatures (800–850 °C) for sewage sludge to minimize NOx emissions, while advanced control systems like RHONN (Recurrent High Order Neural Networks) (Carrasco et al., 2014b, 2014a) and secondary air injection (Choi et al., 2016) improve gas mixing and regulate CO/NOx levels through oxygen and airflow adjustments. However, air-fuel ratio tuning (Maria et al., 2023) faces trade-offs between NOx reduction and combustion efficiency, requiring precise management to avoid process instability. Alternatively, pollution control devices such as cyclones and scrubbers can significantly reduce emissions (up to 53% NOx and 96% CO) (Khair et al., 2023), though hybrid systems like ozone-assisted wet scrubbers (Vattanapuripakorn et al., 2021) risk generating secondary pollutants and entail high operational costs. Each method presents distinct challenges in balancing effectiveness, safety, and economic feasibility.

The injection of superheated steam into incinerator combustion significantly reduces NOx and CO emissions. Superheated steam lowers the peak combustion temperature, an important factor in NOx formation. The lower temperature reduces the thermal NOx generated during combustion. Furthermore, steam modifies reaction pathways, participating in chemical processes that actively inhibit NOx production (Banerjee et al., 2023; Iancu et al., 2017). The effectiveness of steam in reducing NOx emissions is higher when injected into the primary combustion zone as it directly affects the early stages of combustion where NOx formation is most significant (Banerjee et al., 2023). Liu et al. (J. Liu et al., 2020) experimentally demonstrated that superheated steam simultaneously enhances combustion efficiency by reducing moisture content in the combustion chamber. The resulting drier combustion environment and improved burnout characteristics lead to corresponding reductions in CO emissions in the flue gas.

The moisture content of MSW critically impacts incinerator performance, with studies showing combustion efficiency peaks below 30% moisture but declines sharply above 35% (Li et al., 2008; Wang et al., 2025; Yang et al., 2007). While conventional hot flue gas drying enhances combustion efficiency (40.69% at 26.53% moisture) (D. Chen et al., 2004), its effectiveness depends on the flue gas properties (X. Chen et al., 2024; Xing et al., 2021; Zhu et al., 2022). Superheated steam drying emerges as a superior alternative, achieving rapid moisture reduction (from 50% to 20% in 40 minutes) and higher calorific value (Xiao et al., 2011), with hybrid systems (including combined hydrothermal, flue gas integration) enabling 60% thermal self-sufficiency, 40-50% energy savings, and up to 6% power plant efficiency gains (Bai et al., 2021; Guo et al., 2006, 2007; Shuqing & Xiangyuan, 2009).

The combined use of boiler-generated superheated steam and combustion flue gas as co-drying media in incineration systems remains underexplored in the literature. This study examines an operational incinerator in Soreang, Bandung Regency, West Java, that utilizes an integrated water tank to produce superheated steam from waste heat. The steam is injected into both the furnace and rotary dryer, mixing with flue gas for waste drying. Using Aspen Plus simulations, we evaluated: (1) system performance through flue gas emissions, drying kinetics, and MSW moisture reduction; (2) steam injection effects on combustion characteristics; and (3) the combined impact of flue gas and steam on MSW drying. Additionally, this study proposes an optimized system design and assesses its performance through analysis of flue gas emissions and energy consumption.

2. Material and method

2.1 Study area

Soreang is a district in Bandung Regency, West Java Province, one of the major provinces in Indonesia. The population of Soreang is 119.46 thousand people out of the total population of Bandung regency of 3.72 million (BPS, 2023). Although Soreang has a small population compared to other sub-districts, daily waste transportation to Soreang landfill is carried out from 8 sub-districts, namely Rancabali, Ciwidey, Pasirjambu, Soreang, Kutawaringin, Katapang, Margahayu and Margaasih. The total tonnage of waste transportation per year to Soreang Landfill operation in 2023 reached 63.35 tons per year (DLH, 2024). Fig. 1 shows the Soreang landfill and incinerator, managed by the Bandung Regency Environmental Agency in cooperation with PT Bumiresik Nusantara Raya, using RDF and incineration methods for waste disposal.

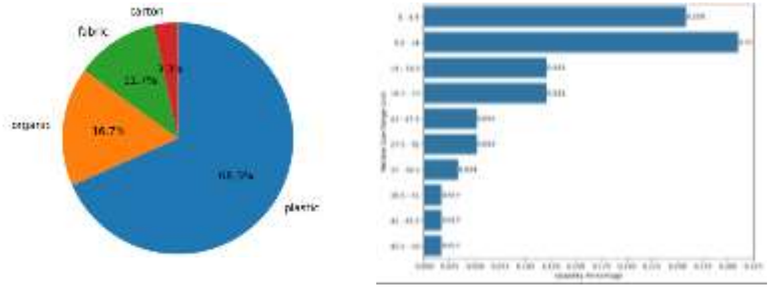
(a)

(b)

Fig. 1 - (a) Soreang landfill; (b) Incinerator owned by PT Bumiresik Nusantara Raya.

2.2 MSW composition

Waste originates from households, markets, commercial areas, and roads. Trucks carrying waste are sent to the landfill, and the waste is unloaded onto the ground. The waste in the container was weighed using a digital electronic weighing floor scale which was then recorded in the log book. In this study, MSW samples were taken with a waste type distribution of 63.3% plastic, 16.7% organic, 11.7% cloth, 3.3% cardboard as shown in Fig. 2a. Particle size distribution measurements were also taken to simulate a more accurate nonconventional solid (MSW) which can be seen in Fig. 2b.



(a) (b)

Fig. 2 - (a) MSW Type Distribution; (b) Particle Size Distribution of MSW.

2.3 Physical and chemical properties of MSW samples

The MSW physical properties were characterized through proximate analysis using a Nabertherm GmbH muffle furnace (Table 1) and bomb calorimetry (LECO AC 500). Moisture content was calculated via Equation 1 (ASTM, 2011), while fixed carbon content was determined by difference (Equation 2) (ASTM, 2021) as the residual mass after accounting for moisture, ash, and volatile matter percentages. For calorimetry, shredded samples (<15 mm) were analyzed in quintuplicate (5 grams per sample) following CEN/TS 14918 (Amulen et al., 2022; CEN, 2006; Codignole Luz et al., 2023), with Higher Heating Values (HHV) calculated using Equation 3, accounting for temperature rise ($\mathbf{T_{rise}}$), calorimeter heat capacity (ε), fuse correction (f), and sample weight (w).

$$Moisture\ content\ (\%) = \frac{w_{wet} - w_{dry}}{w_{wet}} \times 100 \quad (1)$$

Where w_{wet} is the weight of the sample before heating in the muffle furnace while w_{dry} is the weight after heating.

$$Fixed\ carbon\ (\%) = 100 - [moisture\ (\%) + ash\ (\%) + volatile\ matter\ (\%)] \quad (2)$$

$$Higher\ Heating\ Value\ (J/g) = \frac{((T_{rise} \times \varepsilon) - f)}{w} \quad (3)$$

Here, T_{rise} represents the observed temperature rise (°C), ε expresses the effective heat capacity of the calorimeter, f denotes the fuse wire factor, and w indicates the sample weight (g).

Chemical composition was determined using LECO CHN628 and S632 analyzers. Carbon, hydrogen, and nitrogen were quantified through complete combustion in O_2, with combustion products analyzed by IR/TCD detectors. Sulfur content was measured via infrared absorption of SO_2 after combustion at 1350°C (CDFA, 2021; LECO, 2010). Oxygen content was calculated by difference (Equation 4) (ASTM, 2015), subtracting measured ash, C, H, N, and S percentages from 100%.

$$Oxygen\ (\%) = 100 - [ash\ (\%) + C\ (\%) + H\ (\%) + N\ (\%) + S\ (\%)] \quad (4)$$

Table 1 - Proximate analysis and ultimate analysis of MSW.

Component	**Value**
Proximate Analysis (wt%)	
Fixed Carbon	7.64
Moisture Content	22.39
Ash	21.21
Volatile Matter	48.75

Ultimate Analysis (wt%)	
Carbon	27.7
Hydrogen	6.35
Nitrogen	1.09
Oxygen	64.73
Sulfur	0.13
Higher Heating Value (kJ/kg)	13271.94

2.4 Rotary dryer characterization

Rotary dryer performance is evaluated by measuring the MSW's moisture content change before and after drying. Small portions of MSW are collected and weighed individually using a digital floor scale with an accuracy of at least 0.01g. The moisture content of each sample is then measured with a moisture meter, and both the weight and moisture content are recorded. The MSW samples are then placed back on the conveyor to enter the rotary dryer. This process is repeated 29 times, resulting in a total sample weight of 18.39 kg. In parallel, measurements are taken for MSW samples that have been dried for 3 minutes; the weight and moisture content are recorded, and then the samples are returned to the conveyor for further processing in the furnace. Details of this measurement process are illustrated in Fig. 3. During testing, it was observed that changes in the moisture content of the MSW also influenced its weight. As shown in Table 2, the average weight reduction of the waste is 25.81%, and the average moisture reduction is 36.91%, indicating that the dryer is operating efficiently.

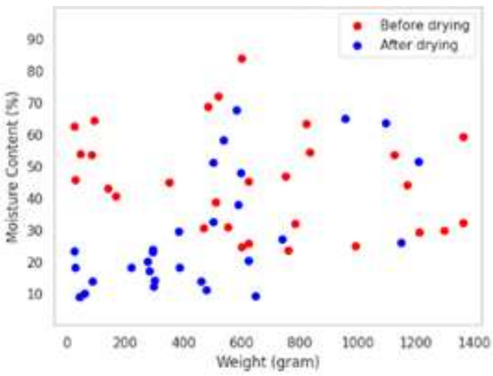


Fig. 3 - MSW's moisture content changes before drying versus after drying.

Table 2 - Weight and moisture content changes before drying versus after drying.

Parameter	**Before Drying**	**After Drying**
Weight change (g)		
Total	18390	13642
Average	634	470.41
Maximum	1362	1209
Minimum	25	23
Deviation	419.7	325.95
Moisture change (wt%)		
Average	45.65	28.8
Maximum	84	67.7
Minimum	23.7	9
Deviation	16.12	18.39

2.5 Flue gas emission characteristics

The combustion gas emissions from MSW were characterized to quantify specific pollutants (SO_2, NO_2, HCl, Hg, CO, HF), which can be seen in Table 3. SO_2, NO_2, and CO concentrations were measured in real-time using an MRU NOVA Emission Analyzer (Model 947010-04), with flue gas sampled via a probe connected to a Tedlar bag (SNI, 2005c). HCl was absorbed in a sorbent solution and quantified spectrophotometrically (HACH DR1900, 460 nm) through a mercury(II) thiocyanate complexation reaction (JIS, 2012b; SNI, 2005a). HF was determined via the lanthanum alizarin complexone method (620 nm) (JIS, 2012a; SNI, 2005b). For Hg analysis, isokinetically collected samples were processed using Cold Vapor Atomic Absorption Spectroscopy (CVAAS) after particulate filtration and solution absorption (Kardono, 2007; SNI, 2009).

Table 3 - Flue gas emissions measurement.

Parameter	Measurement (ppm)
Sulfur Dioxide (SO_2)	25.664
Nitrogen Dioxide (NO_2)	15.488
Hydrogen Chloride (HCl)	2.515
Carbon Monoxide (CO)	278.568
Hydrogen Fluoride (HF)	0.093

3. Model and simulation

3.1 Process detail

The entire MSW incinerator system is shown in Fig. 4. First, the selected dry waste is fed into the furnace for initial combustion. Once the fire reaches a sufficient size and the temperature rises, wet waste is lifted by a conveyor and fed into the rotary dryer. Metal is also removed while waste is on the conveyor to prevent slow burning in the furnace, as the metal has a high heat capacity and absorbs heat needed for combustible materials (Dreizin, 2000; Nzihou & Stanmore, 2013). In addition, the water in the water tank within the furnace is heated until it becomes superheated steam with furnace heat reaching 600-650°C. The superheated steam is pressurized to 5-10 bar and injected into the furnace through a vacuum blower. Flue gas generated from the combustion process in the furnace is used to dry MSW in the rotary dryer. Flue gas detected by the thermocouple is 550-600°C in the ducting before the rotary dryer. Superheated steam is also injected into the rotary dryer to maximize drying. The drying air passing through the rotary dryer enters the dry cyclone and wet cyclone before exiting through the stack. Before going through the stack, the flue gas is filtered from fly ash remaining from the previous filtration process in the cyclone by a wet scrubber. However, current investigations on the existing system found deficiencies in the furnace where thick black smoke and overheating still occur, resulting in fluctuating operation. In this case, an intermittent furnace is required for future product development and optimization.

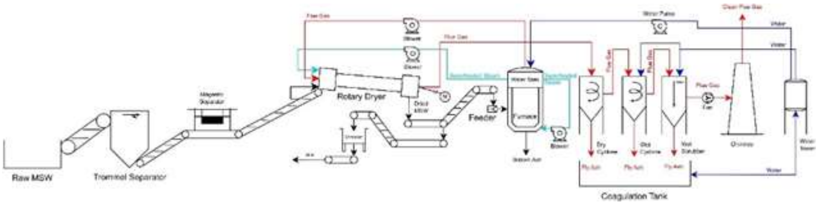


Fig. 4 - Process flow diagram of existing incinerator.

3.2 Model assumption

The incineration system simulation is built using Aspen Plus v12 software, which accurately models chemical processes. Aspen Plus employs thermodynamic models and complex calculations to predict the physical and chemical properties of various components. MSW incineration is a mixed process of gas phase and heterogeneous combustion which can be well modelled by Aspen Plus (Amulen et al., 2022; Shoaib Ahmed Khan et al., 2022; Youcai & Youcai, 2017). Several assumptions were applied in simulating the incinerator model:

1. Processes involving components being mixed, reacted, heated, cooled, and separated are operated in varied steady-state processes (Ong'iro et al., 1996; Pala et al., 2017; Rahman et al., 2014).
2. Heat losses are neglected during the analysis (Ishaq & Dincer, 2020).
3. The model calculates phase equilibrium for solid solutions and vapor-liquid-solid systems that reach chemical equilibrium based on minimizing Gibbs free energy (Hantoko et al., 2019; Jiang et al., 2009).

4. The C, H, N, O, and S contents in MSW are completely reacted into product gas. The remaining C elements that do not react into gas will be converted into ash, which is then removed (Deng et al., 2019).
5. Ash is considered a non-conventional solid and is excluded from the reaction (Pitrez et al., 2023).
6. All gaseous elements included in the reaction follow the ideal gas law (Zaman & Ghosh, 2021).
7. The Peng-Robinson equation of state was applied to determine thermodynamic properties and to explain the non-ideal behavior of the compounds (Hantoko et al., 2019; Tang & Kitagawa, 2005).

3.3Drying model

In the MSW drying process, Rotary Dryer from Solids module was used to simulate the process with flue gas and wet MSW as feed. Wet MSW is supplied with a mass flow rate of 1000 kg/h, a temperature of 25°C, and a pressure of 1 bar. The moisture content variation of wet MSW was varied to 84% and 45.65%. In addition to determining non-conventional solid parameters, the simulation includes particle size distribution (PSD) measurements for the wet MSW. The flue gas input parameters are later introduced when the flue gas (FG4 stream) is formed, along with superheated steam (SSTEAM2 stream), which is then mixed with the flue gas emission characteristics (FLUEGS stream). The mass flow rate of water converted to superheated is 100 kg/hour at a temperature of 25 C, and a pressure of 1 bar. The drying simulation uses a convective dryer model that calculates based on drying rates. The convective dryer model in Aspen Plus takes the Van Meel model approach (van Meel, 1958).

Drying variations are conducted by adjusting the mass flow rate of EMISSION, along with the inlet temperature (550°C and 600°C) and pressure of 1 bar. The value is also determined by a volumetric flow rate of 4500 m³/h generated by the blower. The mass flow rate of EMISSION is calculated based on measurements of temperature, pressure, and volumetric flow rate, generally following this Equation:

$$\dot{m} = \frac{\dot{V}}{R \times \Delta T} \quad (5)$$

Where $\dot{m}$, $\dot{V}$, R, and ΔT are mass flow rate (kg/h), volumetric flow rate (m^3/h), specific gas constant for dry air (287.05 J/kg-K), and temperature difference (K), respectively. Based on the calculations from the formula, a variation of input parameters for the Rotary Dryer simulation was obtained, as shown in Table 4.

Table 4 - Variation of input parameters for the drying process.

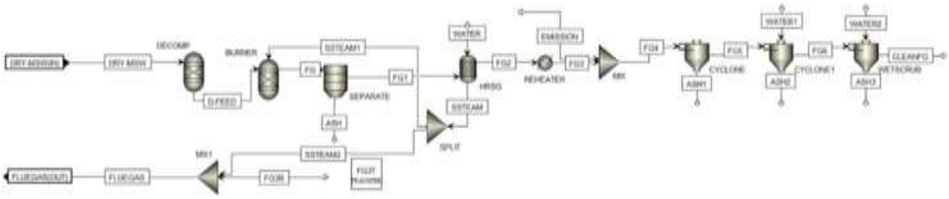
Pressure (bar)	Temperature (°C)	Mass Flow Rate (kg/h)
1	550	1904.48
1	600	1795.42

During the drying process, some of the evaporated water is carried away by the exhaust flue gas, reducing the moisture content of MSW and preparing it for combustion (Begum et al., 2014). The dried MSW (DRY-MSW stream) is then processed by the DECOMP block (RYield). DECOMP decomposes the non-conventional solids and converts them into several conventional components, such as N_2, O_2, H_2, C, and H_2O.

3.4 Existing incinerator model

In the Aspen Plus simulation, the incinerator furnace is modelled by using RGibbs reactor. The BURNER reactor (RGibbs) calculates the combustion process parameters and chemical equilibrium by minimizing Gibbs free energy (Hantoko et al., 2019; Jiang et al., 2009; Okolie & Rogachuk, 2024; Schefflan, 2016). The SEPARATE block separates solids from the flue gas, with the solids settling as bottom ash. The HRSG block (HeatX) is a heat recovery steam generator that produces superheated steam. The superheated steam is then split by the SPLIT block (FSplit) into two streams: 80% flows into the SSTEAM1 stream, which is injected into the BURNER, and 20% flows into the SSTEAM2 stream, which is mixed with the flue gas and injected into the Rotary Dryer. The temperature of the flue gas exiting the HRSG is lower than expected, so a REHEATER block (Heater) is used to raise the flue gas temperature back up. The flue gas is mixed (by using Mixer module) with its emission characteristics to determine the emission reduction due to the effects of superheated steam and emission cleaning systems (cyclone and scrubber). A Transfer block from the Manipulators module is used to copy the entire parameters of the FG4 stream which is a mixture of emission and conventional flue gas. Finally, the flue gas is cleaned using a dry cyclone, wet cyclone, and wet scrubber to reduce its emissions.

(a)



(b)

Fig. 5 - Aspen Plus Process simulation of existing (a) rotary dryer; (b) incinerator.

The energy analysis of the existing incinerator is calculated using FORTRAN block, which considers the conditions in the D-FEED stream and FG3 stream.

$$\dot{Q} = (\dot{m}_{D-FEED} \times h_{D-FEED}) - (\dot{m}_{FG3} \times h_{FG3}) \quad (6)$$

This analysis determines the heat required for the combustion process, the generation of superheated steam, and the hot flue gas entering the dryer.

3.4 Improved incinerator model

The improvement simulation focuses on combustion efficiency, specifically heat loss, chemical equilibrium, increased waste processing capacity, and reduced emissions. The proposed system features an intermittent furnace design, where the boiler is constructed separately from the furnace. This design aims to facilitate superheated steam generation in a separate boiler, which can reduce the heat load, increase the capacity for waste combustion, improve chemical equilibrium, and yield cleaner emissions. The proposed simulation diagram is almost like the existing system, with the primary difference being the replacement of the HRSG and REHEATER blocks with a standalone BOILER block, separate from the furnace system, as shown in Fig. 6.

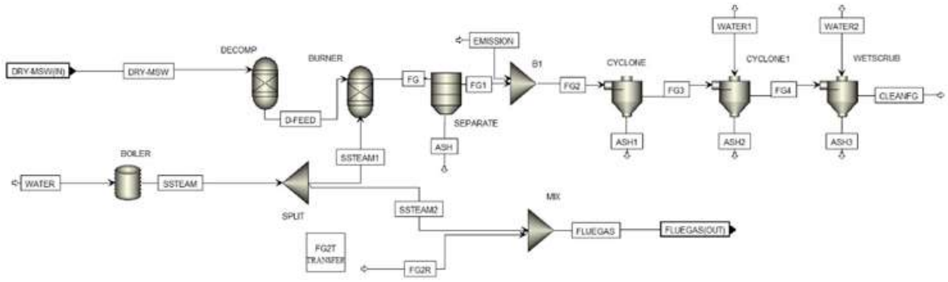


Fig. 6 - Aspen Plus Process simulation of proposed incinerator.

Energy analysis calculations on the proposed incinerator are also carried out to compare the heat required by the proposed system to the existing system.

$$\dot{Q} = (\dot{m}_{D-FEED} \times h_{D-FEED}) - (\dot{m}_{FG1} \times h_{FG1}) \quad (7)$$

3.5 Simulation parameter

In the Aspen Plus simulation, several key parameters are employed in the drying process, combustion process, and superheated steam generation. MSW and ash are classified as non-conventional components. Their thermophysical properties are determined using the HCOALGEN enthalpy and DCOALIGT density model, based on the proximate and ultimate analysis in Table 2. On the other hand, water, nitrogen, oxygen, hydrogen, carbon, nitrogen dioxide, nitrogen oxide, carbon monoxide, carbon dioxide, sulfur dioxide, hydrogen chloride, mercury, and hydrogen fluoride are defined as conventional components. The parameters used in the simulation of the existing and proposed incinerator process are listed in Table 5.

Table 5 - Parameters used in Aspen Plus simulation.

Component	Value
MSW Specifications	
Temperature	25°C
Pressure	1 bar
Feed Rate	1000 kg/h
Moisture Content	45.65 and 84 wt%
Dryer Specifications	

Dryer Type	Convective
Gas Flow Direction	Co-current
Length	11 meter
Residence Time	3 min
Furnace Specifications	
Temperature	600 and 650°C
Pressure	1 bar
Water Supply Specifications	
Temperature	25°C
Pressure	1 bar
Feed Rate	100 kg/h
Heater Specifications	
Temperature	575 and 625°C
Pressure	5 and 10 bar

4. Results and discussion

4.1 Model performance

The performance of the incinerator model simulation was evaluated by comparing simulated flue gas emissions with field test results as described in Table 2. The model performance was analyzed using the Root Mean Square Error (RMSE), calculated with the following basic equation (Sharma et al., 2022):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Modeli - Actuali)^2}{N}} \quad (7)$$

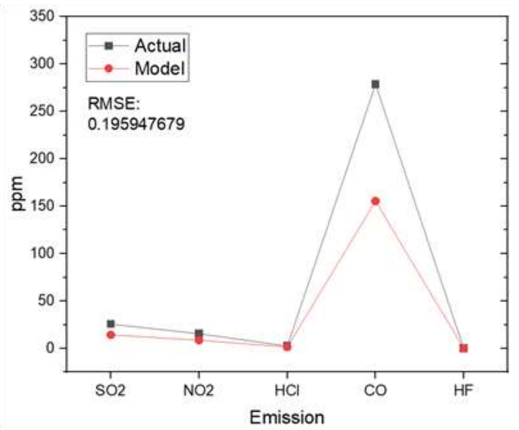


Fig. 7 - Actual measurements versus model simulation.

Fig. 7 compares actual emission measurements with model predictions for five flue gas components (SO_2, NO_2, HCl, CO, and HF). The model demonstrates strong agreement with experimental data, as evidenced by a low Root Mean Square Error (RMSE) of 0.196. This high predictive accuracy (deviation <0.2) suggests the model reliably reproduces emission measurements.

4.2 Effect of superheated steam on flue gas emissions

Superheated steam injection significantly reduces emission gas components, including NO_2, CO, SO_2, HCl, Hg, and HF. Simulations were performed at dryer conditions, inlet pressures of 5 bar and inlet temperatures of 550°C with different superheated steam mass flow rates (60, 80, 100, and 120 kg/h).

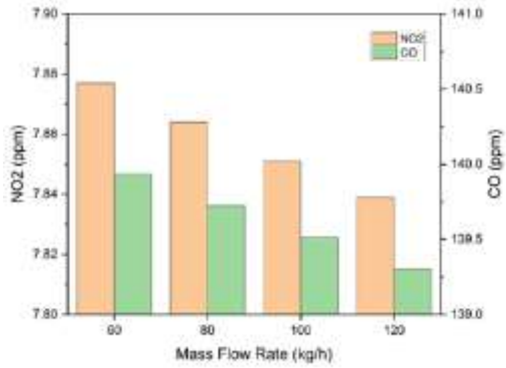
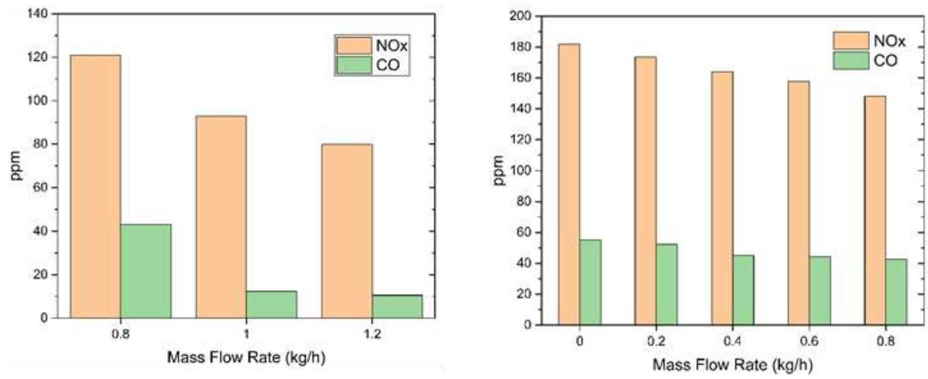


Fig. 8 - Characteristics of model flue gas emissions at superheated steam mass flow rate of 60, 80, 100, and 120 kg/h.

As shown in Fig. 8, a reduction in flue gas emissions (NO_2 and CO) was observed. An increase in the mass flow rate of superheated steam leads to an overall reduction in NO_2 and CO emissions. As the steam flow rate increases by 20 kg/h increments, NO_2 concentrations exhibit a marginal but steady decline from 7.877 ppm to 7.839 ppm, while CO levels decrease more noticeably from 139.935 ppm to 139.303 ppm. This trend suggests that higher steam flow rates enhance combustion efficiency or promote oxidation reactions, albeit with diminishing returns. These findings align with the studies by Anufriev & Kopyev (Anufriev & Kopyev, 2019) and Sadkin, et al. (Sadkin et al., 2023) confirming that superheated steam injection can significantly reduce flue gas emissions.



a) b)

Fig. 9 - Validations of flue gas emission reduction (a) (Anufriev & Kopyev, 2019); (b) (Sadkin et al., 2023).

Another experimental study by Anufriev et al. (Anufriev et al., 2021) revealed that superheated steam injection in the combustion zone can reduce carbon monoxide (CO) emissions by 25% and nitrogen oxide (NOx) emissions by 30% compared to air. This reduction is attributed to the steam gasification of incomplete combustion products and the reduction in thermal NOx formation. Kopyev et al. (Kopyev et al., 2022) observed a reduction of up to 70% in NOx and 95% in CO emissions by injecting superheated steam into the combustion zone of a laboratory burner. All these findings show that this method makes the incinerator process more environmentally friendly.

4.3 Comparative energy analysis

A comparative energy analysis is necessary to determine which incineration system requires the least energy for efficient combustion. The energy analysis of the existing and proposed incinerator systems is based on Equations 6 and 7. The analysis was conducted under identical MSW and water supply conditions for both the existing and proposed incinerators. As shown in Table 6, the proposed system consistently requires less energy under various pressure and temperature conditions than the existing system.

Table 6 - Energy analysis of existing system versus proposed system.

	Energy Required (kJ/s)	
	600°C	**650°C**
Current system	2511.918	2344.760
Proposed system	1204.862	1139.380

At a pressure of 5 bar and a temperature of 600°C, the existing system required energy reaches 620,622 kJ/s, while the proposed system requires only 594,851 kJ/s — a significant reduction of 4.15%. Similarly, at a pressure of 5 bar and a temperature of 550°C, the existing system consumes 646,059 kJ/s, compared to 620,626 kJ/s for the proposed system, marking a 3.94% decrease. Under conditions of 10 bar and 600°C, the existing system demands 621,137 kJ/s, whereas the proposed system requires just 595,299 kJ/s, reflecting a 4.16% improvement in efficiency. Finally, at a pressure of 10 bar and a temperature of 550°C, the energy demand of the existing system is 646,651 kJ/s, while the proposed system only requires 621,141 kJ/s — a 3.94% efficiency gain.

These results demonstrate that the proposed system effectively reduces energy losses across all tested conditions. The improved efficiency can be attributed to the optimized combustion system design and the minimization of energy lost during flue gas formation. The results of this study align with the findings of Liu et al. (X. Liu et al., 2024) which demonstrate that appropriate design modifications to the incinerator can improve combustion efficiency, reduce emissions, and enhance thermal efficiency. Zhou et al. (Zhou et al., 2023) also found that an optimized incinerator design can improve temperature uniformity a critical factor for efficient incineration.

5. Conclusion

This study evaluated the performance of a municipal solid waste (MSW) incinerator in Soreang, Indonesia, through Aspen Plus simulations, focusing on the effects of superheated steam injection on emission reduction and energy efficiency. The key findings demonstrate that increasing the mass flow rate of superheated steam (60–120 kg/h) significantly reduces flue gas emissions, with CO decreasing from 139.935 ppm to 139.303 ppm and NO_2 declining marginally from 7.877 ppm to 7.839 ppm. The model validation yielded a low RMSE (0.196), confirming its accuracy in predicting emission trends. Furthermore, the proposed intermittent furnace design reduced energy consumption by 3.94 – 4.16% compared to the existing system, highlighting improved combustion efficiency and lower heat losses.

The integration of superheated steam and flue gas for MSW drying proved effective, achieving a 36.91% moisture reduction and enhancing combustion stability. These results align with prior studies (Anufriev & Kopyev, 2019; Sadkin et al., 2023), validating steam injection as a viable method for NOx and CO abatement. However, the marginal reduction in NO_2 suggests the need for complementary techniques (e.g., selective non-catalytic reduction) to meet stringent emission standards.

Declaration of Competing Interest

The authors declare no conflict of interest

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