Combined Heat and Power Generation from Mechanically Dewatered Sewage Sludge: Numerical Modelling

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In the present study, a system for Combined Heat and Power (CHP) generation from mechanically dewatered Sewage Sludge (SS) is numerically analyzed through Aspen Plus software. The proposed system is composed of three consecutive processes: drying, gasification, and energy generation through an internal combustion engine. The gasification model is calibrated by applying a restricted chemical equilibrium approach and validated for four experimental outcomes available in the literature. Optimum gasification temperature (900 °C) is identified at an ideal equivalence ratio which is the ratio between actual air fed to the reactor to the stoichiometric air required for complete combustion of 0.2 predicted in a previous study through a sensitivity analysis. The CHP generation potentiality is assessed, finding 0.89 kWh/kg SS as Dry Solid (DS) of electrical and 1.67 kWh/kg of SS as DS of thermal energy. This allows supplying around 50 % of electrical energy required to run the wastewater treatment plant and is sufficient to complete the thermal drying of mechanically dewatered SS.

1. Introduction

Energy recovery from mechanically dewatered Sewage Sludge (SS) as Combined Heat and Power (CHP) through gasification integrated with an Internal Combustion Engine (ICE) offers a high recovery efficiency, reduces the greenhouse gas emission, and increases renewable energy production (Zhang *et al.*, 2019). Generated electrical energy can be used to run WasteWater Treatment Plants (WWTPs) and thermal energy to reduce the moisture content of mechanically dewatered SS from around 70 to less than 10 % as required for the gasification treatment (Di Fraia *et al.*, 2016; Abdelrahim *et al.*, 2020).

The thermal drying process of mechanically dewatered SS is energy-intensive, with a demand of around 0.85 kWh/kg of evaporated water (Bennamoun et al., 2013). Huang et al. (2016) evaluated the average surface heat and mass transfer coefficients by varying the operating condition of air temperature (100–160 °C) and speed (0.6–2.0 m/s) for SS drying in a convective dryer. Bennamoun et al. (2016) identified optimum operating conditions (air temperature = 140 °C, velocity = 2 m/s, and air humidity = 0.05 $kg_{water}/kg_{Dry\ air}$) for drying of mechanically dewatered SS in a convective dryer, estimating an exergy efficiency of 90 %.

The product generated through the gasification is syngas, a mixture of CO, H_2, CO_2, CH_4, moisture, tar, and other lighter hydrocarbons that may be used for CHP production, district heating, and chemical synthesis (Abdelrahim *et al.*, 2020). The composition of syngas generated through air-gasification of SS depends on the characteristics of SS and the operating conditions of temperature and Equivalence Ratio (ER) (Di Fraia *et al.*, 2021).

de Andres et al. (2011) performed 19 tests to recognize optimum temperature (850 °C) and ER (0.2) during syngas generation from SS in a bubbling Fluidized Bed Reactor (FBR). Jeong et al. (2019) completed 7 experiments during syngas generation from SS through co-gasification with coal by using air in a two-stage FBR to detect optimum temperature (811 °C) and ER (0.3).

Identification of optimum operating parameters for gasification through an experimental campaign is time-consuming and costly. Numerical modelling based on experimental data, i.e. through the simulation software Aspen Plus, to identify the optimum operating parameters for SS gasification can save time and cost significantly (Abdelrahim *et al.*, 2020; Di Fraia *et al.*, 2021).

Model development on Aspen Plus for operating parameters optimization during air-gasification of SS is limited (Abdelrahim *et al.*, 2020; Migliaccio *et al.*, 2021). Abdelrahim et al. (2020) predicted as optimum operating parameters a temperature of 780 °C and an ER of 0.3 whereas Migliaccio et al. (2021) estimated identical ideal temperatures (850 °C) and ER (0.25) for syngas generation from two different SS.

There are limited research articles available in the literature on Aspen Plus model development related to CHP generation from biomass (François *et al.*, 2012; Villarini et al., 2019) and only two from SS through gasification integrated with an ICE system (Di Fraia *et al.*, 2021; Brachi *et al.*, 2022). Francois et al. (2012) assessed electrical (23 %), thermal (40 %) and cogeneration (67 %) efficiencies for CHP generation from wood. di Fraia et al. (2021) estimated electrical (29.20 %), thermal (45.92 %), and cogeneration (53.10 %) efficiencies during CHP generation from SS whereas Brachi et al. (2022) predicted electrical (19.3 %) and thermal (48.7 %) efficiencies.

In the present study, a simulation model is developed to analyse the conversion of mechanically dewatered SS to CHP through three consecutive processes of thermal drying, gasification, and energy generation through an ICE. A convective belt dryer is considered due to its flexibility to manipulate and control (Di Fraia *et al.*, 2016; Huang et al., 2016). The gasification model, based on a restricted chemical equilibrium approach (Abdelrahim *et al.*, 2020; Di Fraia *et al.*, 2021; Migliaccio *et al.*, 2021), is calibrated and validated through the experimental data on syngas generation from SS in a fixed bed gasifier (Werle, 2014). Optimum operating temperature is identified through a sensitivity analysis. Finally, the CHP generation potentiality of SS is evaluated to identify the possible use for wastewater and sludge treatment.

2. Numerical Simulation: CHP from mechanically dewatered SS

2.1 Process flowsheet development

The scheme for the proposed plant by connecting the processing unit of the dryer, gasifier, and ICE to generate CHP from mechanically dewatered SS is presented in Figure 1.
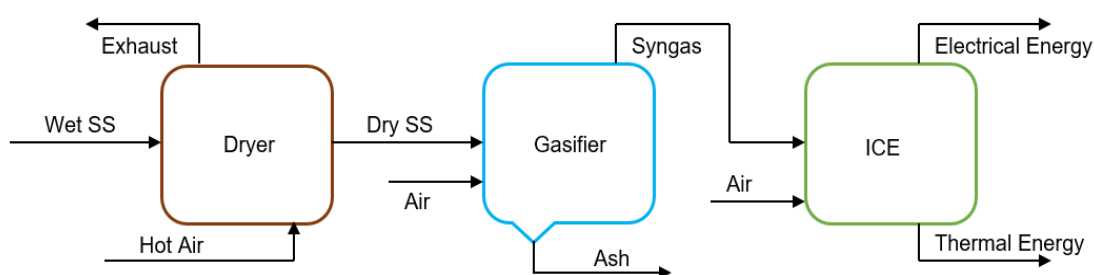

Figure 1: Flow diagram of the proposed plant for CHP generation from mechanically dewatered SS.

A detailed description of simulation related to CHP generation from mechanically dewatered SS through thermal drying, gasification integrated with an ICE is available in the literature (Di Fraia *et al.*, 2016, 2021). ICE system is simulated considering the thermodynamic steps of compression, combustion, and expansion (Villarini, et al., 2019; Di Fraia *et al.*, 2021). The description of the functional activities of each block used from the Aspen Plus library in the proposed plant is depicted in Table 1.

2.2 Model development

Thermal Drying: The drying process is simulated to reduce the moisture content of mechanically dewatered SS from 48.72 to 5.53 % based on the following parameters of dryer length 20 m, drying time 3.45 h, heat transfer coefficient of 20.89 $Wm^{-2}K^{-1}$, critical, and equilibrium moisture content of 0.14 and 0.000984, respectively. Normalized drying rates against normalized moisture content for thermal drying of mechanically dewatered SS at 110 °C are collected from the literature (Huang et al., 2016).

Gasification: The gasification process is simulated based on the following simplifying assumptions (Di Fraia *et al.*, 2021): the developed model is kinetic free and zero-dimensional; gasification is completed in steady-state and isothermal condition; volatile products (H_2, CO, CO_2, CH_4, and H_2O) are formed through instantaneous pyrolysis of SS; all gases behave ideally; char is full of carbon and tar formation is neglected as it is ignored on available literature for SS gasification process (Abdelrahim *et al.*, 2020; Di Fraia *et al.*, 2021; Migliaccio *et al.*, 2021). Indeed, tar formation ignorance does not have any impact on the evaluation of the energy recovery potentiality of SS.

Gasification model is calibrated to reduce the deviation which is created due to the difference between the syngas composition and LHV (Lower Heating Value) predicted through the developed model and experimental data. It is suggested that the deviation of syngas composition from experimental outcomes should be lower than

±20% to claim the developed model has good agreement with the experimental campaign. This can be achieved by restricting individual gasification reactions to a specific temperature according to equation (1) (Abdelrahim *et al.*, 2020; Di Fraia *et al.*, 2021):

$$T_{Eqlm} = T_{Gasf} + \Delta T_{Appr} \tag{1}$$

where, T_{Eqlm} is the equilibrium temperature, T_{Gasf} is the gasification temperature and ΔT_{Appr} is the limit of gasifier temperature where the reaction is restricted.

Characteristics of SS are presented in Table 2. The reactions considered to complete the gasification process simulation are presented in Table 3.

The composition of generated syngas at five distinct operating conditions is presented in Table 4 (Werle, 2014). Operating parameters and syngas properties at condition III is used for model calibration by applying a restricted chemical equilibrium approach whereas the remaining four conditions are for validation. During model calibration, ΔT_{Appr} is predicted through regression tools available in Aspen Plus by setting a 5% standard deviation (95 % confidence level) from the experimental outcomes and the results are illustrated in Table 5 with a fraction of carbon participating in the gasification process.

Table 1. Functional description of unit operation block used in Aspen Plus flowsheet.

Process	Block Name	Function
Drying	Heater	It increases the temperature (110 °C) of incoming air to dry WETSS stream.
	Convective Dryer	It reduces the moisture content of mechanically dewatered SS from 48.72 to 5.53 wt% at 110 °C (Huang et al., 2016).
Gasification	RYield	It completes the decomposition of SS (at 400 °C specifics for pyrolysis) to conventional (C, H_2, N_2, S, Cl_2, F_2) and non-conventional (ash) components based on ultimate analysis (Di Fraia *et al.*, 2021).
	Separator	It separates the decomposed product into three streams: GASFEED (fraction of C, H_2, N_2, S, Cl_2, and F_2), CHAR (fraction of carbon), and C-ASH (ash).
	RGibbs	It completes the combustion of char to supply heat to the gasifier.
	Heater	It increases incoming air temperature to complete the gasification process.
	RGibbs	It completes the gasification reaction by minimizing Gibb's free energy.
	Heater	It increases the ash temperature to equalize with gasification products.
	Mixer	It mixes the gasification products and ash.
Cleaning & Cooling	SSplit	It completes the separation of solid particles from syngas.
	Heater	It reduces the syngas temperature to ambient value (30 °C) through cooling.
ICE system	Compressor	It increases the potential energy of incoming air through pressure raising.
	RGibbs	It completes the combustion of the syngas to generate thermal energy.
	Turbine	It generates mechanical energy from the thermal energy of CMBST stream to produce electricity.
	Heater	It generates thermal energy from the exhaust stream of block TURB.

2.3 Process performance evaluation: Gasification and cogeneration system

Gasification process performances are evaluated through the prediction of syngas LHV, Cold Gas Efficiency (CGE), Carbon Conversion Efficiency (CCE), and net power (P_{net}) available from the gasification products. Syngas LHV depends on composition and corresponds to equation (2) (Zheng *et al.*, 2019). CGE is the ratio of energy content between the gasification products and input and CCE is the ratio of carbon present in the syngas to the reactant, (Jeong *et al.*, 2019). P_{net} is the difference between the power gain from products and the investment to complete the gasification process.

$$LHV_{syngas}(MJ/Nm^3) = 0.108y_{H_2} + 0.126y_{CO} + 0.358y_{CH_4} \tag{2}$$

where, $y_{H_2}, y_{CO},$ and y_{CH_4} denote the volume fraction of H_2, CO, and CH_4 present in syngas, respectively.

Cogeneration process performances are characterized by evaluating electrical and thermal efficiencies of the engine as well as the efficiency of the system (η_{sys}). For the sake of completeness:

$$\eta_{sys}(\%) = \frac{N_{TURB} + Q_{EXCH} + Q_{EX}}{LHV_{SS} \cdot \dot{m}_{SS} + \dot{Q}_{INPUT}} \cdot 100 \tag{3}$$

where, N_{TURB} denotes effective power obtained from the model of the ICE, Q_{EXCH} is the heat available during the cooling of syngas before entering the ICE, Q_{EX} denotes the available thermal power generated from the cooling of turbine exhausts to usable temperature (80 °C) (Di Fraia *et al.*, 2021) and $\dot{Q}_{INPUT}$ is the rate of power supplied associated with the RGibbs reactor including air preheating.

2.4 Operating parameters for cogeneration process simulation

The operating conditions required to complete the cogeneration process simulation are collected from literature and are presented in Table 6 (Di Fraia *et al.*, 2021).

Table 2. Characteristics of thermally dried SS (Werle, 2014).

Proximate analysis (wt%)		Ultimate analysis (wt%)	
Moisture	5.30	C	31.79
		H_2	4.36
Volatile matter	51.00	N_2	4.88
		S	1.67
Fixed carbon	7.20	F_2	0.013
		Cl_2	0.22
Ash	36.50	O_2	20.57
LHV (MJ/kg, d.b)	12.96		

*d.b = Dry basis

Table 3. List of reactions considered in the gasification model.

Rxn	Reaction	Name of Rxn
R1	$C + H_2O \rightarrow H_2 + CO$	Water-gas
R2	$C + O_2 \rightarrow CO_2$	Carbon combustion
R3	$C + 2H_2 \rightarrow CH_4$	Methanation
R4	$CO + H_2O \rightarrow H_2 + CO_2$	Water Gas Shift
R5	$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$	Ethene combustion
R6	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	Propane combustion
R7	$H_2 + 0.5O_2 \rightarrow H_2O$	Hydrogen combustion

*Rxn = Reaction

Table 4. Overview of gasification conditions and corresponding syngas compositions (Werle, 2014).

Test condition	I	II	III	IV	V
Operating Parameters					
Temperature (°C)	900	920	940	960	980
ER (-)			0.23		
SS fed rate (kg/h)			1.0		
Air fed rate (kg/h)			1.01		
Syngas composition (vol%), (Dry & N_2 free basis)					
H_2	12.63	12.95	13.00	13.05	13.00
CO	56.95	57.18	57.40	58.13	58.97
CO_2	28.47	27.90	27.61	26.69	25.80
CH_4	1.95	1.97	1.99	2.14	2.23

Table 5. Predicted ΔT_{Appr} for each reaction and fraction of carbon participate in the gasification process.

Reaction No.	ΔT_{Appr} (°C)
R1	-313.2
R2	-500.0
R3	-485.1
R4	500.0
R5	-500.0
R6	-456.8
R7	-482.0
Fraction of C participating in gasification reaction	0.932

Table 6. Operating parameters for the simulation of the cogeneration system (Di Fraia et al., 2021).

Operating conditions	Value	Operating conditions	Value
Temperature (incoming syngas to the ICE, °C)	30.0	Isentropic expansion and compression coefficient (%)	90.0
Temperature (incoming air to the compressor, °C)	20.0		
Stoichiometric air ratio (-)	3.0	Pressure (fume exit from turbine, bar)	1.0
The pressure of air exit from compressor and combustion chamber (bar)	20.0	Utilization temperature of exhaust fume (°C)	80.0

3. Results and Discussion

Thermal Drying: the thermal energy required to complete the drying process is estimated to be 0.83 kWh/kg.
Gasification: comparison between the results predicted through the developed model and the experimental campaign available in the literature (Werle, 2014) during calibration and validation is presented in Figure 2.
The developed model has a good agreement with the experimental campaign as the deviation of individual components <±15 % with an average value in the range of 6.0 - 11.32 % during model calibration and validation.

3.1 Sensitivity analysis

Variation of syngas composition, CCE, CGE, LHV of syngas and P_{net} with gasification temperature in the range of 700 to 1000 °C at a fixed ER of 0.2 estimated as an optimum value in a previous study carried out by the authors (Di Fraia *et al.*, 2021) is presented in Figure 3. The concentration of H_2 and CO raises continuously with temperature whereas that of CO_2 and C_2H_6 decreases and a slower increase for CH_4 due to the forward movement of endothermic (water-gas and water gas shift) reactions. Combustion reactions present the opposite trend and the concentration of CO_2 and C_2H_6 decreases. H_2 and CO are the major contributor components to syngas LHV (Jeong *et al.*, 2019; Zheng *et al.*, 2019). Consequently, LHV, CGE and P_{net} increase with

temperature. The decrease of carbon content through CO_2 concentration is lower than increment by CO. As a result, CCE increases continuously with temperature. P_{net} rises with temperature up to 900 °C and afterward decreases due to the increase of required thermal power to complete the gasification process. The increase of available power from 900 to 950 °C is lower compared to the demand and consequently, P_{net} decreases.
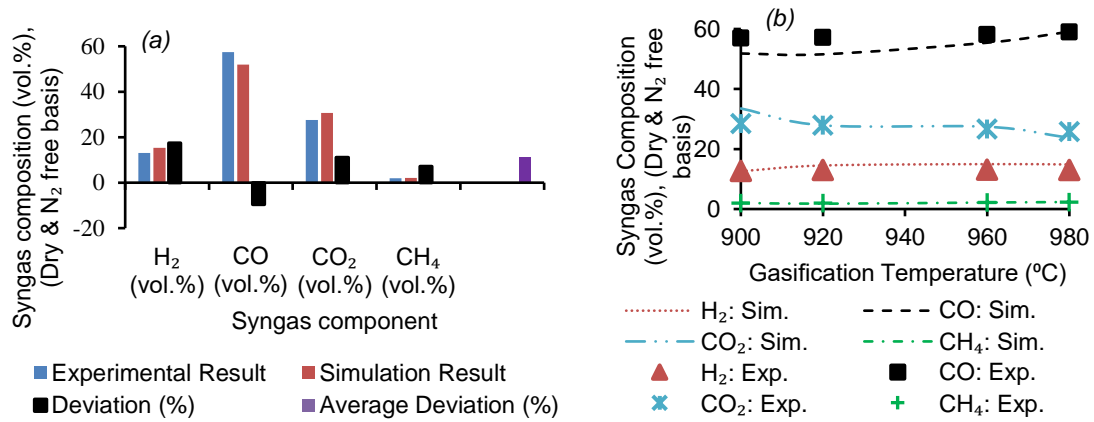

Figure 2: Comparison of syngas composition predicted through the developed model with the experimental campaign during (a) Model calibration and (b) Model validation.
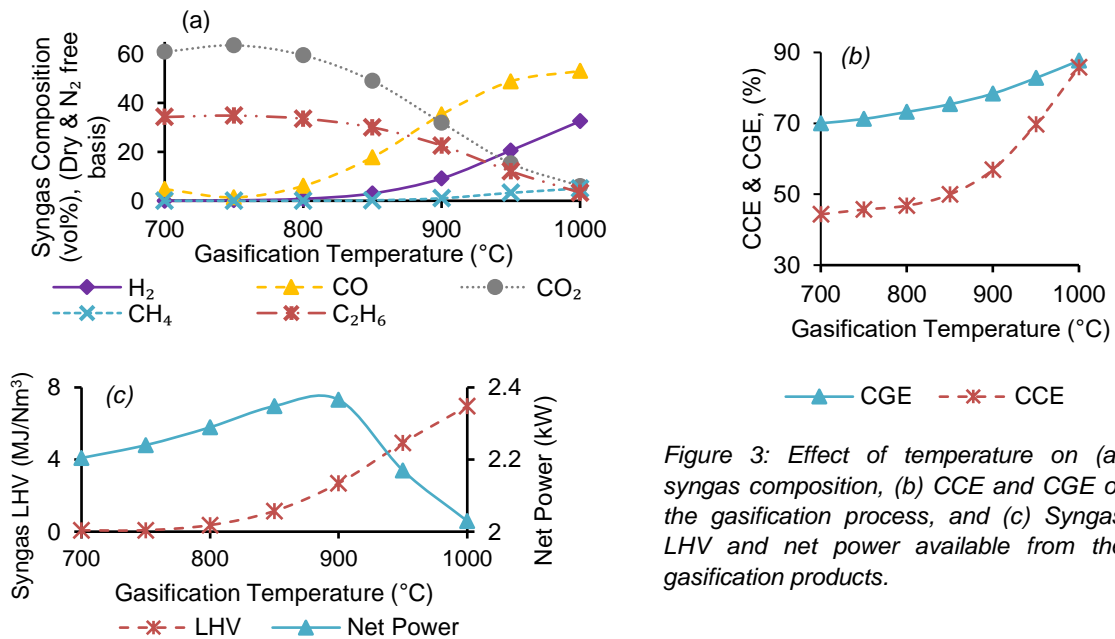

Figure 3: Effect of temperature on (a) syngas composition, (b) CCE and CGE of the gasification process, and (c) Syngas LHV and net power available from the gasification products.

Based on the current simulation results, 900 °C is the optimum temperature for gasification of SS and afterward is not profitable in terms of net power obtained from the products. The effect of temperature on syngas composition, CCE, CGE, and LHV obtained in the present study is in accordance with the available literature on SS gasification (Abdelrahim *et al.*, 2020; Di Fraia *et al.*, 2021; Migliaccio *et al.*, 2021).

3.2 Cogeneration process performances

The potentiality of electrical and thermal power generation from SS is found to be 0.89 kWh/kg SS as DS and 1.67 kWh/kg SS as DS, respectively. The predicted value of CGE, η_{sys}, electrical and thermal efficiencies result to be 72.3 %, 67.4 %, 24.8 %, and 46.3 % respectively which are in agreement with those found in the pertinent literature (Di Fraia *et al.*, 2021).

Based on the current simulation results it can be said that the generated electrical energy can support around 50 % of the demand specified to run a WWTP considering the energy demand evaluated by the German Ministry of Environment (Capodaglio and Olsson, 2020) and thermal power is sufficient to reduce the moisture content of mechanically dewatered SS from 48.72 to 5.53 % by thermal drying.

4. Conclusion

A simulation on Aspen Plus is carried out to analyze the combined heat and power generation potentiality of mechanically dewatered SS. The proposed layout is composed of three consecutive processes: drying followed by gasification and an internal combustion engine. Optimum operating temperature for the gasification of SS is predicted by considering its impact on syngas composition, LHV, CCE, CGE and P_{net}. Temperature rising improves the syngas LHV and gasification process performances.

The evaluated combined heat and power generation potentiality from SS obtained in the present analysis highlights that

- Around 50 % of electrical energy needed for wastewater treatment
- The entire thermal energy required to complete the drying of mechanically dewatered SS as needed for gasification treatment

can be produced through the proposed system.

Simulation on co-gasification of SS with biomass or wood will be carried out as future research to improve the cogeneration efficiencies predicted in the current study.

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