Two-Dimensional Modeling of Fixed-Bed Gasification of Sewage Sludge and Other Municipal Byproducts for Clean Energy Generation

E. Dahlquist*, H. Chen*, J. Yahya *, Lara Carvalho*, H. Li*, E. Thorin*, G. Legnettino**, Luigi Iannitti** and Luciano Di Felice **

* Future Energy Center, Mälardalen University, PO Box 883, SE- 721 23 Västerås, Sweden.
(E-mail: *erik.dahlquist@mdu.se*; *hao.chen@mdu.se; yahya.jani@mdu.se;lara.carvalho@mdu.se; hailong.li@mdu.se; eva.thorin@mdu.se)*
** RESET-ENERGY, Via Maestri del Lavoro, 15/17, 02100 Rieti, Italy.
(E-mail: *giuseppe.legnettino@reset-energy.com; luigi.iannitti@reset-energy.com; luciano.difelice@reset-energy.com*)

Abstract
Sewage sludge, a byproduct of wastewater treatment processes, possesses a complex physicochemical composition, making it valuable yet challenging to manage. This study explores its conversion into renewable energy through modular syngas production systems, which can offer decentralized, cost-effective solutions for electricity, heat, and cooling. To accommodate diverse compositions and varying working conditions, a simplified two-dimensional model is developed to support design optimization of the gasifier. By combining data-driven (the partial least square method) and kinetic-based approaches, the proposed two-dimensional model captures local phenomena and their distribution inside the gasifier without introducing large computational costs.

Keywords
Biomass, optimization, pyrolysis, 2-D model

INTRODUCTION

Sewage sludge, a complex waste stream of wastewater treatment plants that comprises organic and inorganic residues that can pose environmental challenges if not properly handled, needs efficient management strategies. The high content of organic materials makes it a good candidate for the recovery of energy through for example incineration, anaerobic digestion and gasification. Gasification is a thermochemical treatment of biomass at a temperature of up to 900 ^{o}C with the presence of gasification agent (usually steam or air) to produce syngas (a mixture of combustible gases H_2, CH_4, CO and CO_2). The composition of the syngas depends on the characterization of the raw materials as well as the process parameters, like residence time, temperature, pressure and the used catalyst in the reforming process. Therefore, designing the gasifier is a key step to produce high-quality syngas that can be used for electricity and heat generation or be converted into liquid fuels like ethanol, gasoline and diesel (Al-Zuhairi et al., 2024).

The SUPREMAS Horizon EU project focuses on developing innovative, compact, modular, and transportable syngas production units, designed to recover bioenergy from diverse waste feedstocks like sewage sludge. The project focuses on systems treating 60 kg/h to 200 kg/h of feedstock, adaptable to small communities or plants managing residual biomass and organic wastes, utilizing the produced syngas for combined heat and power generation, for decentralized energy supply. The unit will be demonstrated at wastewater treatment plants and to model and optimize the gasifier is important to enhance its flexibility under different operating conditions to reach optimal production yields.

Due to variation in the feedstock composition, designing the gasifier is a challenge, especially for waste materials like sewage sludge. In addition, laboratory and pilot-scale experiments to assess the impact on syngas production are often time-intensive and costly. Modeling and simulation are therefore valuable tools for investigating the effects of variables, such as particle size distribution,

organic and moisture contents, metals content, and calorific value as well as the choice of gasifying agent, equivalence ratio, reactor pressure, and temperature. They provide flexibility to test different operation conditions and to optimize the gasification process reducing the need for intensive laboratory experiments.

Models in literature includes thermodynamic equilibrium, chemical kinetics based, computational fluid dynamic (CFD) as well as AI models (Baruah et al., 2017, Chen et al., 2020, Kartal et al., 2022, Sezer et al., 2022). Thermodynamic equilibrium models often fail to provide insights into the complex mechanisms occurring within the gasifier. In contrast, CFD models can provide those insights but are computationally intensive. There is a need for an alternative method and therefore, the objective of this study is to build a two-dimensional (2D) simplified model based on chemical kinetics in combination with partial least square (PLS) method for gasifier design optimization.

MATERIALS AND METHODS

RESET has developed a fixed bed gasification system combined with an internal combustion engine modified for low calorific value fuel, used to produce electric power from the syngas. To optimize the gasifier, a 2-D simulator has been developed, where different strategies for feed of air can be tested, and different fuels be evaluated.

The 2-D model describes the gasifier from above the air feed to the bed-bottom with several cells, distributed from the wall to the center (axi-symetric bed), as illustrated in Figure 1. Input to the model is the amount of oxygen in relation to what is needed for full combustion of the fuel (Relox), initial temperature in each cell, and cell configuration. Calculation of heat release related to the gas composition and how much of the original mass that has been converted during each time step is calculated with Equation 1-5 in Table 1, with heat release per mol of component generated as shown in Table 2. The temperature increase is calculated using Equation 6, the new temperature in the cell using Equation 7 and the heat transferred between cells with different temperatures using Equation 8. The gas composition as a function of Relox and temperature is calculated from a polynomial built from gasification process simulations at different operating conditions in Aspen Plus, followed by PLS regression using Aspen Unscrambler.

RESULTS AND DISCUSSION

From the results of the Aspen Plus simulations (Table 3) the PLS-models (Table 4) were formed. Figure 2 give an example of results of the 2D-model, to illustrate the principles. Temperature in cells towards the center increase, for the cells closer to the wall it first increases and then decreases and cells highest up in the reactor show a smaller change. It is mainly the heat transfer between the cells, except the impact of the air at the inlet, that influences the cell temperatures in this example.

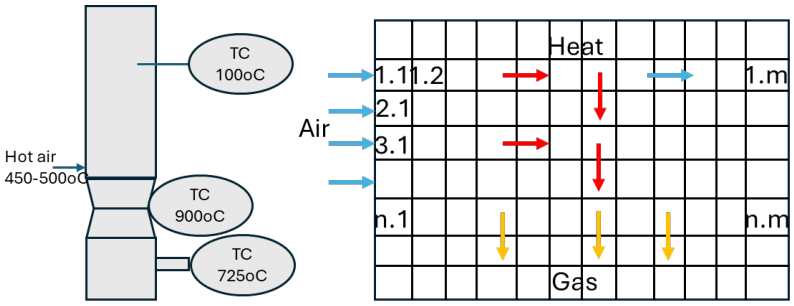

Figure 1. Representation of the fixed bed gasifier to the right and gasifier configuration to the left.

Table 1. Equations used in the 2D-model

Eq. no	Equation	Parameter description
1	$dH = n_{CO} \cdot dH_{CO} + n_{H2} \cdot dH_{H2} + n_{CO2} \cdot dH_{CO2} + n_{CH4} \cdot dH_{CH4}$	n=mole of component, dH= kJ/mole
2	$dH_{c,t} = \frac{dH \cdot reacted_{c,t+1}}{n_{CH2O}}$	*reacted* =mole of fuel converted
3	$reacted = n_{CH2O} \cdot k$	
4	$k = A \cdot e^{-\frac{E_a}{R \cdot T}}$	A=10^6, E_a=-200000 J/mole, R=8.3 J/K, mole, T = temperature (K)
5	$n_{CH2O,t+1} = n_{CH2O,t} - n_{CH2O,t} \cdot k$	t=timestep
6	$dT_t = \frac{dH}{Cp \cdot m}$	m=mass, C_p= heat capacity kJ/kg,K
7	$T_{t+1} = T_t + dT_{t+1}$	
8	$Q = U \cdot A \cdot (T_i - T_{i+1})$	U=heat transfer coefficient (W/m^2, K), A=heat transfer area (m^2), i= cell, i+1=neighbour cell

Table 2: Heat release values (Salman et al., 2019; Tomas-Aparicio E. 2020; Saxena et al 2021).

Component	CO_2(dH_{CO2})	H_2(dH_{H2})	CO(dH_{CO})	CH_4(dH_{CH4})
kJ/mol	393.5	242	110	74.8

Table 3: Data for PLS model development. n is given in mole and n_{CH2O} is set to 30 mole.

Relox, %	Temperature, °C	n_{O2}	n_{N2}	n_{CH2O}	n_{CO}	n_{H2}	n_{CH4}	n_{CO2}	n_{H2O}
7	850	2.1	7.9	30	27.8	27.6	0.1	2.1	2.2
14	850	4.2	15.8	30	25.9	25.5	0.3	4.1	4.4
14	1100	4.2	15.8	30	27.1	24.5	0	2.9	5.5
7	1100	2.1	7.9	30	28.6	27.2	0	1.4	2.8
35	750	10.5	39.5	30	18.5	20.4	0	11.4	9.6
7	750	2.1	7.9	30	26.1	25.8	2.0	2.9	2.2
35	1100	10.5	39.5	30	21.9	17.1	0	8.1	12.9
33	1100	10	0	30	22.4	17.6	0	7.6	12.4
33	750	10	0	30	18.9	20.7	0.1	11.0	9.1
17	750	5	0	30	23.7	24.5	0.4	5.8	4.6
17	450	5	0	30	1.7	3.3	11.3	17.0	4.2
33	450	10	0	30	1.4	4.5	8.5	20.1	8.5
35	450	10.5	39.5	30	1.9	6.1	7.8	20.3	8.4
49	450	14.7	55.3	30	1.8	7.2	5.4	22.8	12.0
70	450	21	79	30	1.5	7.7	2.2	26.3	17.9
35	450	10.5	39.5	30	0.2	2.0	9.2	20.6	9.6
33	350	10	0	30	0.1	1.4	9.6	20.2	9.4
100	350	31.5	118.5	30	0	0	0	30.0	30.0

Table 4: Polynomials of the developed PLS model.

$n_{co} = -8.762 - 0.1655 \cdot \text{Relox} + 0.0380 \cdot \text{temp}$ $R^2 = 0.85$

$n_{H2} = -6.738 - 0.0002 \cdot \text{Relox} + 0.0307 \cdot \text{temp}$ $R^2 = 0.73$

$n_{CH4} = 8.765 + 0.0658 \cdot \text{Relox} - 0.0104 \cdot \text{temp}$ $R^2 = 0.725$ (without R11)

$n_{CO2} = 16.85 + 0.3037 \cdot \text{Relox} - 0.0183 \cdot \text{temp}$ $R^2 = 0.942$ (without R15)

$n_{H2O} = -3.4839 + 0.3003 \cdot \text{Relox} + 0.045 \cdot \text{temp}$ $R^2 = 0.958$ (without R15)

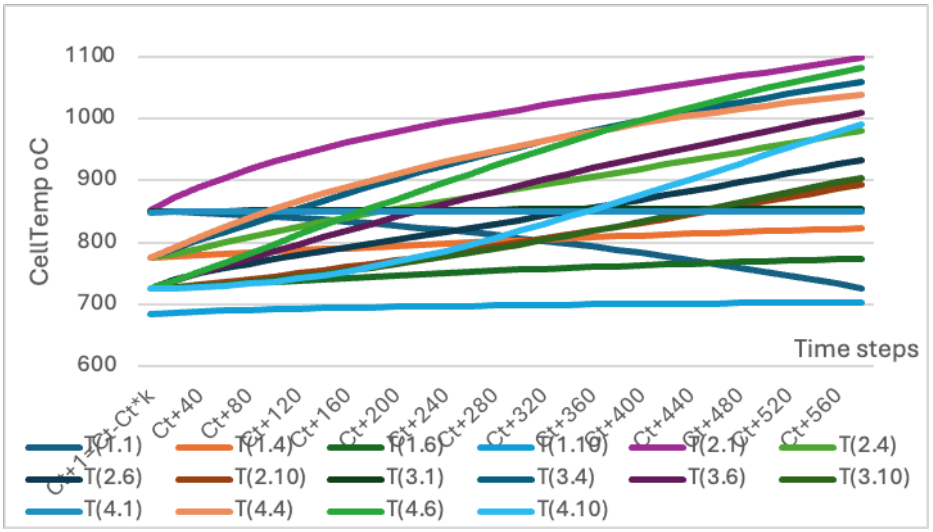

Figure 2. Temperature development in the cells during 580 timesteps, with 10 columns and 4 rows.

This is the first step to develop a dynamic model for the gasification process. The initial results look promising and the next stage is to validate the model with experimental data.

ACKNOWLEDGEMENT AND DISCLAMER

The study is part of The SUPREMAS project funded by the European Union, under the Horizon Europe programme, with grant agreement number 101160713. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

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