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Submission date: 20-Mar-2023 09:39AM (UTC+0700)

Submission ID: 2041178144

File name: oceeding_2020_Numerical_calculation_based_on_mass_and_energy.pdf (711.66K)

Word count: 2408

Character count: 11590

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To cite this article: A Khuriati *et al* 2020 *J. Phys.: Conf. Ser.* **1524** 012002

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Numerical calculation based on mass and energy balance of waste incineration in the fixed bed reactor

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Abstract. To evaluate the waste process incineration, a mass, and energy balance is employed to investigate the waste incineration process in a fixed bed. Thermodynamics equilibrium is implemented to describe the incineration process. The complete combustion is only products CO₂, H₂O, SO₂, ash, and excess O₂ considered. The mass balance calculates the total mass flow in and out incinerator. Energy balance includes input heat, evaporating heat, chemical heat, radiation, and convection. The input heat is calculated by considering the heat capacity, temperature, heating value, and total mass flow. Evaporation heat is calculated based on the water content, mass flow of each aqueous, and evaporation hot water flow. The result shows that efficiency energy of waste incinerator up to 79,33%. It means the incinerator is included in the good category.

1. Introduction

In Indonesia, in 2017-2018, the generation of waste reached 77 million tons, the province of Central Java reached 5.57 million tons, and the city of Semarang produces around 1,270 tons every day with the assumption per person producing 0.8 kg of waste [1]. The total population of Semarang was 1,595,187 peoples, according to the 2015 census [2]. Sources of waste are households, industrial by-products, mining, cities, agriculture, and other activities. With the increase in the amount of waste generated and low-budget cities for developing countries such as Indonesia, 43% of the waste generated is disposed of in open dumping landfills [3]. Open dumping landfill not only impacts human life on health and sanitation issues but also contaminates groundwater sources, emits greenhouse gases, and loses recycling of nutrients and reusable materials [4]. NMOC concentrations are usually <1% while CH₄ and CO₂ concentrations vary between 40% and 60% and are the main constituents of LFG. Over 100 years, the potential for global warming caused by CH₄ is around 25 times CO₂ and has a residence time in the atmosphere of 12 ± three years [5]. The methane gas from the waste sector in Indonesia in 2015 was



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calculated to be very large at around 504 Gg per year [6] were at that time there were 47% of landfills operating in open dumping, estimated to increase to almost 1,065 Gg per year in 2025. The high potential of methane gas is caused by solid waste in landfills consisting of 57.68% organic waste [1] and humid due to climate.

One alternative method to dispose of waste is incineration. Incineration or combustion is a method of conversion that is found in the world [7]. Incineration has controlled the burning of waste at high temperatures which is the most widely used method in thermal conversion technology [8] - [10]. Incineration is one of the most common waste disposal techniques developed in developed countries such as Japan, the United Kingdom, and the United States because it is related to strict regulations on waste disposal using the final landfill [3]. The United States Environmental Protection Agency (US) EPA declared waste incineration as a cleaner energy source [4]. Incineration is the most common waste treatment technique where waste mass and volume can be 70% and 90%, respectively [5][6][7][8]. At the same time, heat and electricity can also be produced [9]. The paper aims to evaluate the waste process incineration using a mass and energy balance for the waste incineration process in a fixed bed reactor.

2. Material and method

2.1. Characteristics of feedstock

The characteristics of the waste used by the feedstock are given in table 1. The waste used is waste that has no beneficial value.

Table 1. Proximate and ultimate analysis data of feedstock used in testing on a dry basis

Proximate analysis (wt%)				Ultimate analysis (wt%)				
FC	VM	Ash	HHV kJ/kg	C	H	N	S	O
16,96	74,04	9	9722	42,77	6,33	0,63	0,13	41,14

2.2. Equipment information

The equipment used for the experiment is given in Figure 1. The incinerator unit includes the combustion chamber, afterburner, temperature control, water scrubber, two burners, stack, water pliers + pump1, pump2 + Erlenmeyer pumpkins. Waste is incinerated in the combustion chamber at 650°C. Flue gas flows into the afterburner and is burned, after passing through the scrubber, smoke flows into the chimney. The smoke is then pumped and fed to the Erlenmeyer Pumpkins. Each exhaust gas constituent parameters are measured for one hour. The measurement is carried by the Centre for Industrial Pollution Prevention Technology (BBTPPI)

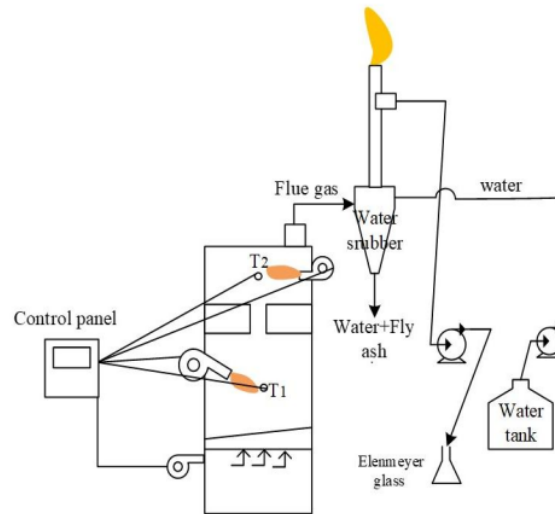


Figure 1. The equipment for the experiment

2.3. Mass and energy balance equations

The law of conservation of mass states that mass is neither destroyed nor created. According to the law, the mass entering the system equal the accumulated mass plus the mass that comes out within a certain time. The energy balance is calculated based on the first law of thermodynamics, namely the principle of conservation of energy, which states that energy is neither created nor destroyed, it can only transform from one to another form. The mass rate balance equations:

$$\dot{m}_{in} = \dot{m}_{out}$$

$$\dot{m}_w + \dot{m}_{air} + \dot{m}_{LPG} = \dot{m}_{FG} + \dot{m}_{BA}$$

\dot{m}_{in} and \dot{m}_{out} are in mass rate and out mass to/from incinerator respectively.

\dot{m}_w , \dot{m}_{air} , \dot{m}_{LPG} , \dot{m}_{FG} , and \dot{m}_{BA} are the mass rate of water from waste, air, LPG, flue gas, and bottom ash respectively. The energy rate balance equations:

$$\dot{Q}_{in} = \dot{Q}_{out}$$

$$\dot{Q}_w + \dot{Q}_{LPG} + \dot{Q}_{air} = \dot{Q}_{FG} - \dot{Q}_L$$

$$\dot{m}_w HHV_w + \dot{m}_{LPG} HHV_{LPG} + \dot{m}_{air} HHV_{air} = \sum \dot{m}_{gases} \dot{c}_{p(gases)} \Delta T - \dot{Q}_L$$

\dot{Q}_{in} and \dot{Q}_{out} are in energy rate and out mass to/from incinerator respectively. \dot{Q}_{FG} is the heat released by flue gas. \dot{Q}_{in} is the heat needed for the waste drying process, pyrolysis, gasification, and oxidation. \dot{Q}_L is the loss of energy.

The thermal efficiency of incineration:

$$\eta = \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

3. Result and discussion

3.1. The mass balance calculation

The mass balance is based on simple stoichiometric calculations [10]. The mass that enters the incinerator consists of the mass of garbage, the mass of LPG, the mass of air and the mass of material

that does not react and the mass that comes out is the mass feedstock enter to the incinerator = 11.25 kg/h and produce residual ash = 1.69 kg/h. Burned mass converts to exhaust gas = 9.56 kg/hour. Dry mass and water content of feedstock are 5.08 kg/h and 46.9% respectively. LPG mass flow rate = 3.92 kg/h. Two blowers supply the air with mass $= \dot{m}_{u(1,2)} = A \times (V_{b1} + V_{b2}) \times \rho_u = \pi(3.2 \times 10^{-2})^2 \times (10,6 + 8,3) \times 1.15 = 0.07 \frac{\text{kg}}{\text{s}} = 247.3 \text{ kg/h}$. The relative humidity is are 74% at 30°C. From the Psychrometric chart, the steam pressure and the partial steam pressure are 3156.21 Pa and 3140 Pa respectively. Then, the specific humidity 0,019605 kg(water)/kg(air), the total mass water content is 4,85 kg(water)/kg(air). From feedstock proximate analyse, the ash mass = 9% x 11,25 kg/h = 1,01 kg/h. From experiment, ash rate = 1,69 kg/h. So, the mass of material that does not react = 0,58 kg/h. Table 1 shows total mass input rate to the incinerator.

Table 2. mass input rate to the incinerator

Input mass	Kg/h
Air mass for combustion	178,7
Air mass for burner	68,53
LPG	3,92
Dry waste	5,08
Water in waste	4,48
Water in air	4,85
Mass doesn't react	0,58
Water for <i>sprayer</i>	32,40
Total	298,61

Flue gas flow rate measured is 12,74 m³/m = 764 m³/h. The diameter stack is 10 cm (section area = 0,00785 m²). Using the principle of mass balance, the density of the flue gas (ρ) is $\rho \cong 298,61/764 \text{ kg/m}^3 = 0,39 \text{ kg/m}^3$

3.2. The Energy Balance Calculations

(a) Energy input

Energy input is the energy generated by LPG and dry feedstock. Regardless of the energy produced by the air, the input energy includes the energy produced by LPG and the burned feed material. LPG contains 30% propane and 70% butane; heat combustion of LPG is 50158,92 kJ/kg. LPG mass flow rate is 3,92 kg/h, the LPG heat input = 3,92 kg/h \times 50158,92 kJ/kg = 196623 kJ/h. Total feedstock heat input = 5,08 kg/h \times 9722 kJ/kg = 60954,82 kJ/h. Total Energi in = (196623+ 49387,76) kJ/h = 246010,76 kJ/h

(b) Energy Output

The energy released from the combustion system equals the energy released by the flue gases plus the energy lost due to radiation. The total flue gas flow rate measurement is 173,4 m³/h. H₂O_{fg}, H₂O_g, H₂O_{sh} are the heat needed to dry the waste, to evaporate water, to heat up until the desired temperature.

Table 3. Energy released by flue gas

Type of gases	Cp (kJ/kg°C)	ΔT (°C)	Mass rate (kg/h)	Energy in kJ/h
CO2	0,844	350	28,75	8492,75
O2	0,919	770	27,23	19268,76
N2	1,04	770	178,77	143159,02
SO2	0,64	350	0,00	0,00

H ₂ O _{fg}	4,184	70	9,33	2732,57
H ₂ O _f	Evaporation Enthalpy = 2460 (kJ/kg)		9,33	22951,80
H ₂ O _{sh}	1,185	700	9,33	7739,24
			Total	204344,10

The rate of energy lost due to radiation \dot{Q}_R is set 5% [11], so $\dot{Q}_R = 5\% \times 257577,82 \text{ kJ/h} = 12878,891 \text{ kJ/h}$. The rate of energy lost due to chemical formation reaction of CO₂ dan H₂O.

Formation reaction of CO₂.

$$\Delta H^\circ = -393,5 \times \left(\frac{28,75}{44}\right) = -394,15 \text{ kJ/h}$$

Formation reaction of H₂O

$$\Delta H^\circ = 241,8 \times \left(\frac{24,09}{18}\right) = 323,47 \text{ kJ/h}$$

The energy released for the formation reaction = -70.68 kJ / hour. Energy balance is the equilibrium of incoming and outgoing energy given in Table 4.

Table 4. The Energy rate balance

Material	Energy rate in (kJ/h)	Material	Energy balance out (kJ/h)
Feedstock	60954,82	Flue gas	204344,10
LPG	196623,00	The heat lost due to radiation	-12878,89
		The energy released for the formation reaction	-70,68
Total	257577,82	Total	191394,53

Based on the calculation, the heat produced during combustion is 191394,53 kJ/h and the losses heat is 66183,29 kJ/kg. The efficiency energy of incineration is 74,3%. Generally, energy efficient after combustion is 70 to 80% of the heat incineration recovered [12].

4. Conclusion.

The efficiency energy of incineration is up to 74,3%. The combustion process can be categorized as an efficient incinerator.

Acknowledgment

This research was supported by the Faculty of Science and Mathematics, Diponegoro University and Ministry of Research, Technology and Higher Education of the Republic of Indonesia.

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