



e-ISSN: 2319-8753 | p-ISSN: 2320-6710

IJIRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH


IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 9, Issue 11, November 2020

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 7.512

 9940 572 462

 6381 907 438

 ijirset@gmail.com

 www.ijirset.com

Design of an Incinerator to Treat Biomedical Solid Wastes in Lae City, Papua New Guinea

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ABSTRACT: Healthcare waste or biomedical waste is all the waste generated by healthcare facilities, medical laboratories and biomedical research facilities. In Papua New Guinea, the health and environmental risks from poor management of health care wastes are very high and need immediate attention. The main objective of this research is to design an incinerator to treatment biomedical wastes for the three major hospitals in Lae city, Papua New Guinea. The estimated waste generated is about 200 kg/day and incinerator has been designed with an operating capacity of 100kg/hr. The dimensions of the primary chamber of the incinerator were 2.05 * 1.17 * 2.5m. For complete combustion, giving a deficient heat requirement of 472121.5 kJ/h was required to be supplied by auxiliary fuel to maintain the temperature of 1100°C. The required flow rate of natural gas was 31.36 m³/h and the designed volume of secondary chamber is found to be 3.09 m³ to maintain the retention time of one second.

KEYWORDS: Biomedical waste, Healthcare waste, Incineration technology, Heat input, Lae city.

I. INTRODUCTION

Healthcare waste is all the waste generated by healthcare facilities, medical laboratories and biomedical research facilities, as well as waste from minor or scattered sources. According to World Health Organization (WHO), among total amount of healthcare waste, 85% is non-hazardous waste and only 15% is considered hazardous material that may be infectious, toxic or radioactive. High-income countries generate on average up to 0.5 kg of hazardous waste per hospital bed per day; while low-income countries generate on average 0.2 kg (WHO, 2018). Health-care waste contains potentially harmful microorganisms that can infect hospital patients, health workers and the general public.

In Papua New Guinea (PNG), the health and environmental risks from the poor management of health-care wastes are very high. The common challenges related to management of health care wastes that PNG faced was lack of financial sources, unclear policies, unclear organisational structure, nonexistence of guidelines, poor management practices, and shortage of trained human resources (Sprep, 2020). Proper handling of wastes includes collection, segregation, storing, treating and safe disposing of all health care wastes. Most biomedical solid wastes from the hospitals are organic in nature and few contains toxic chemicals and hazardous materials include chemotherapy and antineoplastic chemicals, formaldehyde, photographic materials, radio nuclides, solvents, mercury, waste anesthetic gases, other toxic, corrosive and chemicals (John and Swamy, 2011). Because of their nature, incineration is considered the best option in detoxification and safe disposal of biomedical wastes.

A medical waste incineration involves the burning of wastes produced by hospitals, veterinary facilities and other medical facilities under very high heat of about 800°C to 1600°C under controlled condition. The high temperature is required to be maintained in the incinerator chamber to ensure complete combustion of toxic and pathogens and elimination of odours. These wastes include both infectious and non-infectious medical wastes and general wastes. It then produces carbon dioxide gas, water and ash residuals as end products. In general, there are basically three types of incinerator including multiple chamber (retort and in-line), controlled Air and the rotary kiln. Landfill will always be considered for the residue, which usually amounts to about one-third of the initial mass of waste. However, incineration also produce potential pollutants contained in the emissions.

The main objective of this research is to design an incinerator to treatment biomedical wastes for the three major hospitals in Lae city, Papua New Guinea.



II. SITE LOCATION

Lae is the capital of Morobe Province in the Momase Region and the second largest city in Papua New Guinea. It is located at the coordinates 6°44'S 147°0'E, with a latest population of 100, 677 as per 2012 census (Subramanyam, 2021). Angau Memorial General Hospital is 2nd largest hospital in the country located in the Lae city central next to old Lae Airfield. It is the main Government referral hospital for the Morobe province area, as well as the other provinces connected by road link. It is serving over 675, 000 residents of Morobe and a referral hospital for 1.9 million people of Momase region (Angau, 2020). This hospital offers radiotherapy, chemotherapy and palliative care services to the population of entire PNG and thus serves as the main referral centre for cancer patients (National cancer centre, 2008). The Lae international hospital (LIH) is of good developing private hospital located at Marsina Street, Lae. It is a 20 bed facility hospital including one emergency bed. The LIH staffed by 6 doctors including two obstetricians and each one general practitioner, surgeon, anaesthesiologist and radiologist (LIH, 2019). One more well-known private hospital is GM Flores hospital located at Top Town, Lae. This hospital consists of 7 specialized doctors with facilities of Ultrasound, X-ray, ECG and laboratory tests (GM Flores, 2020).

III. MATERIALS AND METHODS

The following sub-sections describe the methodology carried out for complete design of the incinerator.

A. Quantification of Waste

The total quantity of waste generated in Angau, Lae International and GM Flores private hospitals on a monthly and daily basis was quantified to obtain a sample size of waste to be used for designing purpose. Table 1 illustrates the total wastes generated per day from three hospitals is 167.33kg/day and hence the design waste is assumed to be 200kg/day. The characterization of biomedical waste was considered from John and Swamy (2011) and Rajiv et al. (2017).

Table 1: Waste generation from three major hospitals of Lae city used for incinerator design.

S.No.	Hospital	Quantity of waste generated/ month	Quantity of waste generated/ day
1	Angau	2100 kg/ month	70 kg/day
2	Lae international hospital	1420 kg/ month	47.33 kg/day
3	GM Flores Private	1500 kg/ month	50 kg/day
Total waste generated		5020 kg/ month	167.33 kg/day

B. Design of an incinerator

The following steps were used to design the incinerator. Each step is discussed in detail including the assumptions involved in the design process.

C. Design of Primary Chamber

For designing of primary chamber of multiple chamber incinerator under controlled air conditions, initially volume of primary chamber is to be determined. In order to find out the volume, 200 kg of waste is dumped as a heap and the volume of the heap is considered.

Volume of heap (for 200 kg of waste) = 6m³

Assuming a suitable depth of 2.5m, find out the area of chamber.

Area = Volume /depth

= 6/2.5 = 2.4m²

Assume the ratio of length and breadth as 1.75:1

Therefore, $L/B = 1.75/1$

$$L = 1.75B$$

$$\text{Dimensions of Primary Chamber} = L * B * H$$

$$\text{Area} = L * B$$

$$2.4 = 1.75 B * B$$

$$2.4 = 1.75 B^2$$

$$B = 1.17 \text{ m}, L = 1.75B = 1.75 * 1.17 = 2.05 \text{ m}, H = 2.5 \text{ m}$$

Hence, the dimensions of the primary chamber are 2.05 m x 1.17 m x 2.5 m

D. Heat and Material Balance Sample Calculations

The essential part of designing an incinerator is the heat and material balance. It is mainly mathematical evaluation of input and output condition of the incinerator. This determines the required combustion air and auxiliary fuel for incinerating a given waste.

The general assumption is that an incinerator is to be designed to incinerate a mixture of 30% red bags and 70% yellow bags (with a PVC contented 3%) of the biomedical waste (USEPA, 1990). In general, the waste input rate is 100 kg/h. The auxiliary fuel used in the incinerator is natural gas, and when ignited, the secondary burner is modulated.

Design requirements are summarized as follows:

1. Temperature to be maintained in the secondary chamber: 1100°C
2. The flue gas residence time for this temperature: 1 second
3. The residual oxygen content in flue gas: 6% minimum

Step 1. Assumptions in the design

The following shows the first step of the design process which includes the major assumptions.

- The design involves number of assumptions, the chemical empirical formula, the molecular weight and higher heating values of the components have been taken from specific tables given in design books of Incinerator.
- Input Temperature of the waste, fuel and air is assumed as 15.5°C.
- Air in general contains approximately 23 % oxygen (O₂) and 77 % Nitrogen (N₂) by weight.
- Air contains 0.0132 kg H₂O/kg dry air at 60% relative humidity and 26.7°C dry bulb temperatures.
- For any ideal gas 1kg/mole is equal to 22.4 m³ at 0 °C and 101.3 KPa.
- Latent heat of vaporization of water at 15.5°C is 2460.3 kJ/kg.

Step 2. Calculation of material input

Sound decision should be worked out when making use of this data from John and Swamy (2011) to assign the component weight percent required performing heat and material balance calculations.

The red bag waste is typically composed of mainly human tissue as indicated by John and Swamy (2011). Based on an input of 30% of 100 kg/h (i.e., 30 kg/h), the red bag was assumed to have the following composition as shown in Table 2.

In a similar way, the yellow bag waste input is 70% of 100 kg/h (i.e. 70 kg/h) and the different constituents were summarized as shown in Table 3.



Table 2: Waste generation from red bags considering three major hospitals in Lae city used for incinerator design.

Components	Empirical formula	Fraction assumed	Generation (kg/h)
Tissue (dry)	$C_5H_{10}O_3$	0.15	$0.15 * 30 = 4.5$
Water	H_2O	0.10	$0.10 * 30 = 3.0$
Ash	-	0.05	$0.05 * 30 = 1.5$
Cellulose, swabs, bedding	$C_6H_{10}O_5$	0.15	$0.15 * 30 = 4.5$
Plastics-Poly-Ethylene 96%	$(C_2H_4)_x$	0.55	$0.55 * 30 = 16.5$
Total Red bag		1.00	30

Table 3: Waste generation from yellow bags considering three major hospitals in Lae city used for incinerator design.

Components	Empirical formula	Fraction assumed	Generation (kg/h)
Tissue (organs)	$C_5H_{10}O_3$	0.25	$0.25 * 70 = 17.5$
Polyethylene	$(C_2H_4)_x$	0.20	$0.20 * 70 = 14.0$
PVC	$(C_2H_3 Cl)_x$	0.1	$0.10 * 70 = 07.0$
Cellulose, swabs, bedding	$C_6H_{10}O_5$	0.45	$0.45 * 70 = 31.5$
Total yellow bag		1.00	70

Step 3. Calculation of heat input of waste

The heat generated from the waste (input value) considering the red and yellow bags is the product of the calorific value of the specific waste type by the total amount of waste generated. The total heat generation from the waste input has been summarized and presented in Table 4. The method adopted is similar to as described in John and Swamy (2011) and Rajiv et al. (2017).

Table 4: Summary of total heat generation from waste input (considering both red and yellow bag)

Components	Empirical formula	Calorific Value (kJ/kg)	Total Input (kg/h)	Total Heat (kJ/h)
Tissue	$C_5H_{10}O_3$	20,741	$4.5 + 17.5 = 22$	4,50,362
Water	H_2O	0	$0 + 3 = 3$	0
Ash	-	0	$0 + 1.5 = 1.5$	0
Cellulose, swabs, bedding	$C_6H_{10}O_5$	18,568	$4.5 + 31.5 = 36$	6,68,448
Plastics-Poly-Ethylene 96%	$(C_2H_4)_x$	46,304	$16.5 + 14 = 30.5$	14,12,272
PVC	$(C_2H_3 Cl)_x$	22,630	$0 + 7 = 7$	1,58,410
Total heat generated			100	26,89,492

Step 4. Determination of stoichiometric oxygen for wastes

The total stoichiometric requirement of oxygen has been determined from chemical reactions for each of the individual components of the biomedical waste and has been represented in each of the following reactions shown below.

- Tissue

$$C_5H_{10}O_3 + 6O_2 = 5CO_2 + 5H_2O$$

118.1	6(32)	5(44)	5(18)
1.0	1.63	1.86	0.76

 Tissue 22 35.77 40.98 16.77
 (as fired)
- Polyethylene

$$(C_2H_4)_x + 3O_2 = 2CO_2 + 2H_2O$$



28 3(32) 2(44) 2(18)
 1.0 3.43 3.14 1.29
 Polyethylene **30.5 104.57** 95.86 39.21
 (as fired)

3. PVC
 $2(C_2H_3Cl) x + 5O_2 = 4CO_2 + 2H_2O + 2HCl$ 2(62.5)
 5(32) 4(44) 2(18) 2(36.5) 1.0
 1.28 1.41 0.29 0.56

PVC **7 8.96** 9.86 2.02 4.09
 (as fired)

4. Cellulose
 $C_6H_{10}O_5 + 6O_2 = 6CO_2 + 5H_2O$ 162.1
 6(32) 6(44) 5(18) 1.0 1.18 1.63
 0.56

Cellulose **36 42.64** 58.63 19.99
 (as fired)

To summarize,

The total combustible components of biomedical waste generated per hour = 22+30.5+7+36 = **95.5kg/h**

Total amount of stoichiometric oxygen required to burn the combustible components of biomedical waste generated per hour = 35.77 + 104.57 + 8.96 + 42.64 = **191.88 kg/h**

Therefore, total stoichiometric oxygen required = 191.88kg/h for burning combustible components of the biomedical waste 95.5kg/h.

Step 5. Determination of air for waste based on 150% excess

It is observed that the total stoichiometric oxygen requirement is 191.88kg/h. and from the assumption of air consists of 23% oxygen, therefore, 191.88 * (100/23) = 834.26 kg/h and since the Air determination is based of 150 excess, the total Air requirement for the 150 % excess = 1.5 x 834.26) + 834.26 = **2085.65 kg/h**

Step 6. Material balance

Mass balance of the different products of the biomedical waste has been given below:

Total Mass Input

Waste Input Rate = 100kg/h

Dry Air = 2085.65 kg/h

Moisture in Air = (0.0132kg * 2085.65 = 27.53kg/h

Therefore, total mass input = **2113.18kg/h**

Total mass output (assuming complete combustion of waste).

(A) Dry products from waste.

Air requirement for waste = 2085.65 kg/h

Subtracting stoichiometric air requirement (step5) = 834.26kg/h

Therefore, total excess air = 2085.65 – 834.26 = 1251.39 kg/h

But the stoichiometric air also consists of Nitrogen gas which 77% (step1), therefore add nitrogen to the stoichiometric air which is $0.77 * 834.26 = 642.38$ kg/h

Hence the total production = 1251.39 + 642.38 kg/h = 1893.77 kg/h

In addition, the combustion of these products will also generate CO₂ (step 4).

CO₂ formed from C₅H₁₀O₃ = 40.98kg/h

CO₂ formed from C₂H₄ = 95.86

CO₂ formed from C₂H₃CL = 9.86kg/h

CO₂ formed from C₆H₁₀O₅ = 58.63kg/h

Total CO₂ generated = 40.98+95.86+9.86+58.63 = 205.33kg/h

Hence, the total waste dry products = 1893.77 + 205.33 = **2099.07 kg/h**

(B) Moisture

Total moisture i.e., H₂O generated from waste = 3kg/h

Moisture generated from combustion reactions = 16.77+39.21+ 4.09 +19.99 = 80.06kg/h

Moisture in combustion air = 27.53kg/h (step6)

Total Moisture = 3+ 80.06 +27.53 =**110.59kg/h**

(C) Ash

Total ash output = **1.5kg/h**

(D) HCl formed from waste

HCl formed from (C₂H₃Cl) x = 4.09kg/h

Total Mass Output = \sum (A, B, C, D) = 2099.07 +110.59+1.5+4.09 = **2,215.25 kg/h**

Step 7. Heat balance

- I. Total heat input generated from the waste (Step 3) (table 5). = Qi = **26,89,492kj/h**
- II. The total heat output is based on the Equilibrium Temperature of 1100°C and consists of different components as given below:

- a) Radiation Loss generally assumed to be 5% of the total heat available= $0.05 * 26, 89,492 =$
1,34,474.6 kj/h

- b) Heat to Ash is calculated using the formula

$$Q = mCpdT$$

Where, m = mass of ash (1.5kg/h); Cp = mean heat capacity of ash = 0.831kj/kg°C (assumed average value); dT = Temperature difference = (1100 – 15.5)°C) = 1084.5°C

Therefore, using the given formula $Q = mCpdT= 1.5 * 0.831 * 1084.5 =$ **1,351.83kj/h**

- c) Heat to Dry Combustion Products is computed using the expression $Q = mCpdT$

Where, m = weight of combustion products = 2099.07kg/h;

Cp = mean heat capacity of dry products = 1.086 kj/kg°C (assumed average value); dT = Temperature difference = (1100 – 15.5) °C = 1084.5 °C

Substituting these values, $Q = 2099.07 * 1.086 * 1084.5 = 24,72,215.38 \text{ kJ/h}$

d) Heat to moisture is calculated using the equation $Q = mC_p dT + mH_v$

Where, $m =$ weight of water $= 110.59 \text{ kg/h}$; $C_p =$ mean heat capacity of water $= 2.347 \text{ kJ/kg}^\circ\text{C}$, $dT =$ temperature difference $= 1100 - 15.5 = 1084.5^\circ\text{C}$ and $H_v =$ Latent heat of vaporization of water $= 2460.3 \text{ kJ/kg}$, hence

$$Q = (110.59 * 2.347 * 1084.5) + (110.59 * 2460.3) \\ = 281,487.11 + 272,084.58 = 553,571.69 \text{ kJ/h}$$

Therefore, Total heat output $= Q_o = \sum (a, b, c, d) = 31,61,613.5 \text{ kJ/h}$

Now the net heat balance $= Q_i - Q_o = 26,89,492 \text{ kJ/h} - 31,61,613.5 \text{ kJ/h} = -4,72,121.5 \text{ kJ/h}$ (Heat insufficient)

Therefore, auxiliary fuel must be supplied to achieve the Design temperature of 1100°C .

Step 8. Required auxiliary fuel to achieve 1100°C

- (i) Total heat required from fuel $= 4,72,121.5 + 5\%$ radiation loss $= 4,72,121.5 + (0.05 * 4,72,121.5) = 495,727.58 \text{ kJ/h}$
- (ii) The available net heat from natural gas at 1100°C and 20% excess air $= 15,805.2 \text{ kJ/m}^3$ (assumed value)

Therefore, the required Natural Gas $= 495,727.58 / 15805.2 = 31.36 \text{ m}^3/\text{h}$

Step 9. Products of combustion from auxiliary fuel

- i. Dry Products from fuel at 20% excess air $= 16 \text{ kg} * 31.36 \text{ m}^3/\text{h} = 501.76 \text{ kg/h}$
- ii. Moisture from fuel $= (1.59 \text{ kg/m}^3) * 31.36 = 49.86 \text{ kg/h}$

Step 10. Secondary chamber volume required to achieve one second residence time at 1100°C

- i. Total Dry Products (waste and fuel) $= 2099.07 + 501.76 = 2600.83 \text{ kg/h}$ assuming, the dry products have the properties of air and using the ideal gas law, the volumetric flow rate of dry products (V_p) at 1100°C can be calculated as shown: $V_p = 2600.83 \text{ kg/h} * (22.4/29) * (1373/273) * (1/3600) = 2.81 \text{ m}^3/\text{s}$
- ii. Total Moisture (waste and fuel) $= 110.59 + 49.86 = 160.45 \text{ kg/h}$ and using the same ideal gas law, the volumetric flow rate of Moisture at 1100°C (V_m) can be calculated as shown, $V_m = 160.45 * (22.4/18) * (1373/273) * (1/3600) = 0.28 \text{ m}^3/\text{s}$
Total volumetric flow rate $= \sum (V_p \text{ and } V_m) = 2.81 + 0.28 = 3.09 \text{ m}^3/\text{s}$

Now it can be seen from the design that a volume of 3.09 m^3 with one second retention time is sufficient for the active chamber, but there will be some dead spaces where there will be no flow or flow will be negligible which are not accounted for in the design calculation of retention volume. The length of chamber should be calculated from the flame front to the location of the temperature sensing device to maintain the one second time.

Step 11. Residual oxygen in the flue gas

The residual oxygen in the flue gas can be calculated using the formula given below

$$\text{Excess Air} = \% \text{ Residual O}_2 / (23\% - \% \text{ Residual O}_2)$$

From the assumption, assumed that the excess air is 150% and air contains 23% oxygen

$$\text{Residual Oxygen} = \text{RO}_2$$

$$\text{Substituting values into the equation: } 150/100 = \text{RO}_2 / (0.23 - \text{RO}_2) = 1.5 = (0.345 - 1.5\text{RO}_2) = \text{RO}_2 \text{ in flue gas} = 0.345/2.5 = 0.138 = 13.8\%$$

IV. RESULTS AND DISCUSSIONS

The above section shows the design of an incinerator for a waste of 200kg/day generated from the three Major hospitals in Lae City. Similar designs regarding the assumptions and design considerations for the design of biomedical waste incinerator, especially the calculations are not easily available, therefore sometimes making the comparisons of such designs difficult (Rajiv et al., 2017).

Furthermore, similar context of such designs were reported for few hospitals in India. John and Swamy (2011) designed an incinerator to treat biomedical waste with a capacity of 100 kg/h for a total of 11 hospitals and nursing homes, and 27 private clinics and laboratories. Rajiv et al. (2017) designed an incinerator with a capacity of 500 kg/d for four major hospitals. In the present study, the wastes generated from three major hospitals in Lae city, which is 200 kg/day and is less to that of the four major hospitals in district of Chandigarh and Shimla city of India but more for that of Chikmagalur city in India. The additional heat requirement for this case was observed to be slightly higher (4,72,121.5 kJ/h) than the studies of the two cities of India which was 4,12,802.1kJ/h for Chikmagalur and 4,44,423.5kJ/h for Chandigarh and Shimla city. Further observations has led to finding the volume of primary and secondary chamber for the incinerator for this study was 6m³ and 3.09m³ respectively and comparing it with Chandigarh and Shimla city which was 8m³ and 3.07m³ accordingly.

V. CONCLUSIONS

To conclude, the following were drawn from the design of the incinerator system.

- 1) The waste generated is about 200 kg/day for the three major hospitals in Lae city.
- 2) An incinerator has been designed with an operating capacity of 100kg/hr for the treatment of biomedical waste which is being generated in Lae city.
- 3) The dimensions of the primary chamber of the incinerator were 2.05 * 1.17 * 2.5m
- 4) For the material balance assuming complete combustion, the total mass input was 2113.18kg/h which is almost equal to the total mass output was 2215.25kg/h.
- 5) From the heat balance analysis, the total heat input is found to be 2689492kJ/h and the total heat output is found to be 3161613.5 kJ/h for complete combustion, giving a deficient heat requirement of 472121.5 kJ/h was required to be supplied by auxiliary fuel to maintain the temperature of 1100°C.
- 6) From the analysis the required flow rate of natural gas determined was 31.36m³/h to cover up for the deficiency of heat and maintain the designed temperature of 1100°C.
- 7) And the designed volume of secondary chamber is found to be 3.09m³ to maintain the retention time of one second.

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