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Performance evaluation of a biomedical waste incinerator on the basis of Mass and energy balance, fuel consumption and cycle time (A case study of the biomedical waste incinerator Etmadpur, Agra, India)

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ABSTRACT

In the present paper the performance evaluation of a biomedical waste incinerator on the basis of mass and energy balance, fuel consumption and the cycle time, is presented. Mass and energy balances are based on the principle of the conservation of mass and the conservation of energy. The conservation of mass means that if there is no accumulation inside the reaction chamber, what goes into the process, must come out. In the same way the energy balance means that whatever the energy goes into the process, must come out fully, if there has been no leakage in the pipes or in the incineration chambers. In case of the presence of any leakage, the air may enter and cause the excess consumption of fuel which would prolong the cycle time. For measuring the excess fuel consumption it is necessary to find the accurate amount of fuel which is essential for complete combustion. For determining the accurate amount of the fuel, the calculations have been performed on the basis of the method prescribed by the Ontario, Ministry of Environment, West Toronto, "Ontario, Canada, October 1986". The experimental studies have been conducted on every week-end (Saturday). It was started from 4th Jan. 2019 and was continued up to 30th March 2019. The data of twelve experimental studies showed that the fuel consumption and the cycle time were nearly appropriate except one, in which higher fuel consumption and longer cycle time was found. In all twelve experimental studies it was seen that about 3% of waste remained half-burned which is caused due to the formation of cold pockets or inactive zone in the side corners and top portion corners of both chambers. This is a technical fault in the design which took place at the time of manufacturing the equipment. The operator of the common biomedical waste treatment facility (CBWTF) was advised to install the new plant with latest improved design in which the corners are rounded from inside.

Key words: *Biomedical waste, Incinerator, Primary fuel, Ash, Flue gas etc.*

Introduction

The mass and energy balance, fuel consumption and cycle time are the most important parameters for performance evaluation of incinerators. The mass and energy balance are based on the principle of conservation of mass and the conservation of energy which states that the mass and energy going into a system of processing (unit operation), must balance with the mass and the energy coming out of the system. If mass is not balanced properly, it shows that some amount of mass is stored inside the system and if the energy is not balanced, it shows that come amount of energy has leaked out from the system. In both the cases it is concluded that the system is not efficient. Fuel consumption is the next parameter on the basis of which, the efficiency can be judged. The proper amount of fuel can be determined by the calculation of Mass and Energy balance. If the amount of fuel consumed, is more than the proper amount, determined as per calculations, it will show that some deficiency is there in the system. Cycle time is the third important parameter which exhibits the efficiency of the incinerator. The cycle time can be defined as the time taken from the start of the incineration process to the end of the combustion (up to the time when the chamber is cooled to about 250 °C – 300 °C). The cycle time does not include the delays caused by carelessness of the operator. Only the legitimate time required for the operation of the equipment is taken into consideration (Manyele, and. Kagonji (2012). There are possibilities of several types of defects that may be detected in the equipment, such as, leakages in the piping's or other fittings or the doors might have become warped due to overheating which might allow the air to enter. In such cases if the excess air enters the primary chamber, the volatile gases would be partially burned in the primary chamber and will not be available to heat the secondary chamber. Such abnormal functions may lead to higher fuel consumption. The higher moisture percentage in the medical waste also causes higher consumption of fuel (LPG). The poor skill of the operator is also a major cause of higher fuel consumption. The operator may not be well trained and he may not properly operate the temperature control system. The required temperature of 11000C may not have been achieved which lead to the continuous fuel flow into the burner causing higher fuel consumption as well as the longer cycle time.

Literature Review

Many researchers have carried researches on the performance evaluation of waste incinerators. Civil Engineering Civil Engineering Manyele and *Kagonji (2012)* have presented many graphic models on the variations in the Diesel oil consumption and also on variations in the incineration cycle time during the waste incineration. Lee and Huffman (2007) have observed that the mass and heat balance play the most important role in evaluation of the performance of the incinerators. (*Omari et al.,* 2015) have presented their study of the performance of a fixed bed incinerator and have concluded that the material and energy balance is the most important factor for performance evaluation of the incinerator. *Ganguli et al.* (2017) have concluded that the heat and mass balance plays the most important role in evaluation of the performance of the incinerators. Civil Engineering Civil Engineering. *Bujak* (2010) has investigated the heat and mass balance of the incinerator and had found that during the combustion process, the fuel (wastes) undergo significant changes due to which the velocity of the combustion also change which causes the variations in the temperature and pressure which effects the fuel consumption.

Methodology of the Experimental Study

A programme was prepared to conduct an experimental study for evaluating the performance of the biomedical waste incinerator, Etmadpur, Agra. In order to obtain the permission to conduct the experimental study, the Director, Hindustan College of Science and Technology issued a letter to the Regional Officer, Uttar Pradesh Pollution Control Board, Agra, requesting him to provide assistance and advise the operator of the common biomedical waste treatment facility, Etmadpur to Collaborate and support and instruct the waste handling staff including the operator of the incinerator to cooperate accordingly.

Due to the load of academic works from Monday to Saturday, the authors could manage time for the experimental observations only on Saturdays. The experimental works continued for three months which means twelve Saturdays. The mathematical calculations for determining the accurate amount of LPG (Liquefied Petroleum Gas), required for complete combustion of the medical waste, was performed through the method prescribed by the "Ontario, Ministry of the environment, 135 St. Clair Avenue, West Toronto, Ontario Canada". The objective of the study was to find out the accurate data of fuel consumption and the duration of cycle time for incinerating 200kg of medical waste. With this objective, the operator was instructed to take all skillful precautions during the operation. The data obtained would be treated as the basic data for further comparative study of the fuel (LPG) consumption for incineration of higher amounts of the waste. The operator of the incinerator was also instructed that before the start of the incinerator the amount of waste would be weighed and noted in the presence of authors and at end of the cycle time the half burned materials as well as the ash would also be weighed and noted. All the further observations of the amount of the auxiliary fuel required, as determined by energy balance calculations, actually consumed amount of fuel (LPG), cycle time, amount of ash and the amount of half burned waste would be compared with the basic data. The comparisons will reveal the efficiency of performance.

The Calculation Mass and Energy Balance

For calculation of mass and energy balance of the incinerators, some basic information are required, such as chemical/empirical formula of the components of the biomedical waste, their molecular weight and higher heating value which are as follows:

Chemical Characteristics of the Components

For calculation of mass and energy balance some other essential information's were also collected which are as follows:

(i) The temperature of the air was measured and found to be 160C.
(ii) Moisture of air was measured and found to be 0.0132 Kg at the humidity of 60%.
(iii) For vaporization of water at the temperature of 160C was worked out and found to be 2460.3 kJ/kg.

After collecting all the aforesaid data the calculation was started step-by-step for convenience, because all further steps are interconnected with their previous steps.

Step-1: Determining the amount of Stoichiometric Oxygen

The amount of Stoichiometric Oxygen and all other required data are presented in the following Chemical Equilibrium Equations.

Components	Empirical Formula	Molecular Weight	Higher Heating Value (kJ/kg)	Input Kg/h	Total Higher Heating Value (kJ/h)
Tissue	$C_5H_{10}O_3$	118.1	20,471	60	12,28,260
Cellulose, swabs	$C_6H_{10}O_5$	162.1	18,568	61	11,32,648
Plastics-Poly –Ethylene 96%	$(C_2H_4)x$	28.1	46,304	8	3,70,432
PVC4%	$(C_2H_3Cl)x$	62.5	22,630	6	1,35,780
Moisture	H_2O			48	
Ash				17	
			Total :	**200**	**28,67,120**

1.	$C_5H_{10}O_3$	+	$6O_2$	=	$5CO_2$	+	$5H_2O$		
	118.1		6(32)		5(44)		5(18)		
	1.0		1.63		1.86		0.76		
Tissue (as fired)	60		97.80		111.60		45.60		
2.	(C_2H_4)	+	3O2	=	2CO2	+	2H2O		
	28.1		3(32)		2(44)		2(18)		
	1.0		3.43		3.14		1.29		
Poly Ethylene (asfired)	8		27.44		25.12		10.32		
3.	$2(C_2H_3Cl)$	+	5O2	=	4CO2	+	2H2O	+	2Hcl
	2(62.5)		5(32)		4(44)		2(18)		2(36.5)
	1.0		1.28		1.41		0.29		0.58
PVC (as fired)	6		7.68		8.46		1.74		3.48
4.	$C_6H_{10}O5$	+	6O2	=	6CO2	+	5H2O		
	162.1		6(32)		6(44)		5(18)		
	1.0		1.19		1.63		0.56		
Cellulose (as fired)	**84**		**99.96**		**136.92**		**47.04**		

The aforesaid equations show that the components of biomedical waste which are combustible are 135 kg/h (sum of 60+8+6+61) and the stoichiometric oxygen is 205.51 kg/h (sum of 97.80+27.44+7.68+72.59).

Step-2. Calculation of Air, based on 150% Excess

(i) Stoichiometric oxygen (from step-1) = 205.51 kg/h
(ii) Calculation for finding stoichiometric air – 205.51 x 100/23 = 893.52 kg/h
(iii) The air needed for waste (at 150% excess)(893.52 x 1.5) + 893.52 = 2233.8 kg/h

Step-3: Calculation of Mass Balance

(i) Mass of Total Waste = 200 kg/h
(ii) Mass of Dry Air (from Step-2) = 2233.8 kg/h
(iii) Water contents in air = 2233.8 × 0.0132 = 29.49 kg/h
Total Mass Input :(sum of 200+2233.8+29.49) = 2463.29 kg/h

Observing the actual fuel (LPG) consumption in presence of the authors and the operator of the incinerator it was found that the fuel consumed was 18.75 Kg. On the comparison of both the amounts of fuel it was found that the fuel actually consumed was only 0.23 Kg in excess. Since the difference in amount of 0.23 Kg in excess is a negligible amount, it can be concluded that the incinerator is efficient on the parameters of fuel consumption. The time taken to complete the incineration process was 60 minutes, so it shows that the performance is efficient even on the parameter of cycle time.

Further Experimental Studies

Such further experimental studies were conducted continuously on every subsequent Saturdays. For determining the amount of required fuel for complete combustion of a particular amount of biomedical waste, the same procedure of calculation of mass and energy balance has been performed but all calculations are not needed to be reproduced hear. The relevant data are presented. The amount of the required fuel that was determined by calculations has been compared with the amount of the fuel (LPG), actually consumed up to the end of the cycle time. The ash and the half- burned materials were also weighed separately. In all experimental observa-

Step-4: Total Mass Output

(A)	Dry Products from Waste	
	(1) Amount of Air Supplied for Waste (from Step-3) = **2233.8**	
	(2) Less Stoichiometric air	= **893.52**
	(3) Total Excess Air (2233.8-893.52)	1339.48 kg/h
	(4) Adding Nitrogen from Stoichiometric Air (0.77 x 893.52)	688.01 kg/h
	Sub Total :	2027.49 kg/h
	CO_2 from Combustion	
	CO_2 formed from $C_5H_{10}O3$	111.60 kg/h
	CO_2 formed from C_2H_4	25.12 kg/h
	CO_2 formed from C_2H_3Cl	8.46 kg/h
	CO_2 formed from $C_6H_{10}O5$	99.43 kg/h
	Sub Total :	**244.61** kg/h
	Total of (A) (2027.49+244.61)	2272.10 kg/h
(B)	Water Contents in Waste :	
	(1) H_2O in Waste (Kg)	48.00 kg/h
	(2) H_2O from combustion reaction =Sum of 45.60+10.32+1.74+34.16	91.52 kg/h
	(3) H_2O in Combustion Air (from Step-3)	29.49 kg/h
	Sub Total (48+91.52+29.41)	169.01 kg/h
(c)	Ash Output	17.00 kg/h
(D)	HCl formed from (C2H3Cl)x	3.48 kg/h
	Total Mass Out : A+B+C+D= 2272.10 + 169.01 + 17.00 + 3.48	2461.59 kg/h
	The difference in input and output 2463.29 – 2461.59	
	The difference is only 1.7 because in calculation of fractions havebeen done only up to 2 decimal point.	1.7 kg/h

Step-5: Energy Balance:

(A)	Total energy in the combustible medical waste =Q-1 = 28,67,408 kJ/h		
(B)	Total Heat output (to be calculated on the basis of equilibriumtemperature of 11000C Process of Calculation of Energy Output		
	(i)	Loss due to radiation = 5 percent of the total available energy= (0.05 x 2867408)	143370.40kJ/h
	(ii)	Energy absorbed by Ash : The formula = M CP dtWhereas M stands for Ash = 17 KgCP stands for average of energy capacity of Ash = 0.831 kJ/h dt stands for the difference in temperature(1100-16 = 1084) Calculation 17 x 0.831 x 1084	**= 15313.67 kJ/h**
	(iii)	Energy absorbed by dry combustion products - The formula = M CP dt Whereas M stands for Weight of combustion products = 2272 kJ/hCP stands for energy capacity of Dry Products = 1.086 dtstands for difference in temperature = 1100-16=1084 Calculation – (2272.9 x 1.086 x 1084) =	2675712.43kJ/h
	(iv)	Energy absorption of moisture Formula – M CP dt + MHV M stands for weight of water = 169.01 kJ/kgCP stands for energy capacity of water = 2.347 kJ/kg dt stands for difference in temperature = 1100-16= 1084 HV Latent Heat for vaporization = 2460.3 kJ/kg Calculation (169.01x2.347x1084) +(169.01x2460.3= 429986.45 + 415815.30 =	845801.75kJ/h
		Total energy out = 1+2+3+4 =143370.40 + 15313.67 + 2675712.43 + 845801.75	3680198.25kJ/h
		Total energy out - total heat in = 3680198.25-2867408 =Deficiency =	812790.25kJ/h

Step-6. The requirement of auxiliary fuel

Calculating the total required auxiliary fuel Adding 5% radiation loss	
Calculation : 812790.25 x 0.05 = 40639.50812790.25 + 40639.50 = 853429.75	853429.75 kJ/h
Converting the heating value into Kg.	
Higher heating value of LPG is 46100 kJ/kg= Thus 853429.76 ÷ 46100 = 18.512= Rounded figure 18.52 kg	
Thus for incineration of 200 kg of waste the Required auxiliary fuel LPGwould be	18.52 kg

tions the measurements were performed in the presence of the operator of the incinerator and the authors. The data are presented as follows :

Results and Discussion

Mass Balance

In the Mass balance calculations it was found that the mass input was 2463.29 and mass output was 2461.59. The difference is only 1.7, which was caused by calculation of fractions only up to 2 decimal points.

The aforesaid calculation of mass balance has been performed assuming that complete combustion would take place but practically it was found that, although 97% of the total bio-medical wastes have been completely combusted yet the remaining 3% of wastes are incompletely combusted and found to be in half-burned condition which might have emitted carbon mono oxide which is a poisonous gas.

Energy Balance

In the 1st experimental observations it was found that for incineration of 200 kg of waste the requirement of the fuel (LPG),as per energy balance calculations, was 18.25 Kg but the fuel consumed was noted and found to be 18.75 Kg. The difference is only of 0.23 kg which is negligible. The cycle time was 60 minutes. The ash was 17 kg and the half -burned materials were found to be 6 Kg. The performance of the incinerator can be said to be satisfactory.

In the 2nd experimental observations it was found that for incineration of 210 kg. of waste, the fuel requirement, determined through the calculation of energy balance was 19.45 kg but the actual consumption was found to be 19.75 kg. The difference is negligible. The ash was 17.85 kg and the half

Experiments	Quantity of Biomedical Waste in Kg/h	Amount of Fuel LPG required as per Energy Balance Calculations.	Amount of fuel (LPG) actual consumed during the cycle time.	Difference between the both (the consumed amount and the required amount)	Cycle Time	Remarks	Quantity of Ash (kg)	Quantity of half burned materials
1st Experimental Observation. 5th January	200kg/h	18.52 kg	18.75kg	0.23 kg	60 minutes	Difference is negligible	17	6
2nd Experimental Observation. 12th January	210kg/h	19.45 kg	19.75kg	0.30 kg	60 minutes	Difference is negligible	17.85	6.3
3rd Experimental Observation. 19th January	245 kg/h	22.69 kg	23.00 kg	0.31 kg	60 minutes	Difference is negligible	20.82	7.35
4th Experimental Observation. 2nd February	235 kg/h	21.76 kg	22.00 kg	0.24 kg	60 minutes	Difference is negligible	19.97	7.05
5th Experimental Observation. 9th February	205 kg/h	18.98 kg	22.14 kg	3.16 kg	70 minutes	Cycle time increased by 10 minutes more due to moisture which caused excess fuel consumption.	17.42	6.15
6th Experimental Observation. 16th February	240 kg/h	22.22 kg	22.60 kg	0.38 kg	60 minutes	Difference is negligible	20.4	7.2
7th Experimental Observation. 23rd February	230 kg/h	21.30 kg	21.60 kg	0.30 kg	60 minutes	Difference is negligible	19.55	6.9
8th Experimental Observation. 2nd March	225kg/h	20.84 kg	21.30kg	0.34 kg	60 minutes	Difference is negligible	19.12	6.75
9th Experimental Observation. 3rd March	215 kg/h	19.91 kg	20.30 kg	0.39 kg	60 minutes	Difference is negligible	18.27	6.45
10th Experimental Observation. 9th March	220kg/h	20.37 kg	20.75kg	0.38 kg	60 minutes	Difference is negligible	18.7	6.6
11th Experimental Observation. 16th March	248kg/h	22.96 kg	23.30kg	0.34 kg	60 minutes	Difference is negligible	21.08	7.44
12th Experimental Observation. 23 March	242kg/h	22.40 kg	22.75kg	0.35 kg	60 minutes	Difference is negligible	20.57	7.26

burned materials were found to be 6.3 Kg. The performance of the incinerator can be said to be satisfactory.

In the 3rd experimental observation it was found that for the incineration of 245 kg of waste, the required amount of fuel, as per energy balance calculations, was 22.69 kg but the actual fuel consumption was 23 kg. The difference was only 0.31 kg. The difference in amount is negligible. The cycle time was 60 minutes. The ash was 22.82 kg and the half -burned materials were found to be 7.35 Kg. The performance of the incinerator can be said to be satisfactory.

In the 4th experimental observation it was found that for the incineration of 235 kg of waste, the fuel required, as per energy balance calculations, was 21.76 kg while the actual fuel consumption was 22 kg. The difference was found to be 0.24 kg, which is negligible. The cycle time was 60 minutes. The ash was 19.97 kg and the half -burned materials were found to be 7.05 Kg. The performance of the incinerator can be said to be satisfactory.

In the 5th experimental observation it was found that for incineration of 205 kg of waste, the fuel required as per energy balance calculations, was 18.98 kg while the actual consumption of fuel was found to be 22.14 kg. This shows that an excess amount of 3.16 kg was consumed. The cycle time was 70 minutes. The difference was caused by the higher percentage of moisture contents in the fuel. The ash was 17.42 kg and the half -burned materials were found to be 6.15 Kg. The performance of the incinerator can be said to be satisfactory.

In the 6th experimental observation it was found that for incineration of 240 kg of waste, the required fuel, as per calculation of energy balance, was 22.22 kg while the actual consumption was 22.60 kg. It shows that an excess amount of 0.38 kg was consumed. The difference was negligible. The ash and the half- burned waste were also weighed separately. The ash was 20.4 kg and the half- burned materials were found to be 7.2 Kg. The performance of the incinerator can be said to be satisfactory.

In the 7th experimental observations it was found that for incineration of 230 kg of waste, the required auxiliary fuel, as per calculations of energy balance, was 21.30 kg while the actual fuel (LPG) consumption was found to be 21.60 kg. The difference is 0.30 kg which is negligible amount. The ash and the half burned materials were also weighed separately. The ash was 19.55 Kg. and the half burned materials were 6.9 kg. The cycle time was 60 minutes. The performance of incinerator can be categorized as satisfactory.

In the 8th experimental observations it was found that for incineration of 225 kg. of waste, the required amount of auxiliary fuel as per energy balance calculations, was 20.84 kg while the actual amount of fuel consumption was found to be 21.30 kg. The difference is 0.36 kg. which is negligible. The cycle time was 60 minutes. The ash and the half- burned materials were also weighed. The ash was 19.12 kg and the half- burned material was 6.75 kg. The performance of the incinerator can be said to be satisfactory.

In the 9th experimental observations it was found that for incineration of 215 kg of waste, the required amount of auxiliary fuel, as per energy balance calculations, was 19.91 kg, while the actual fuel consumption was 20.30 kg. There is a difference of 0.39 kg. The difference is negligible. The cycle time was 60 minutes. The ash and the half -burned materials were also weighed separately. The ash was found to be 18.27 kg and the half - burned materials were 6.45 kg. Thus the performance can be said to be satisfactory.

In the 10th experimental observations it was found that for the incineration of 220 kg of waste, the required amount of auxiliary fuel, as per energy balance calculations was 20.37 kg while the actual fuel consumption was 20.75 kg. There is a difference of 0.38 kg, which is negligible amount. The cycle time is 60 minutes. The ash and the half -burned materials were weighed. The ash was found to be 18.7 kg and the half- burned material was 6.6 kg. The performance of the incinerator is satisfactory.

In the 11th experimental observations it was found that for incineration of 248 kg of waste, the required amount of auxiliary fuel, as per energy balance calculations, was 22.96 kg, while the actual fuel consumption was 23.30 kg. There is a difference of 0.34 kg which is negligible amount. The cycle time was 60 minutes. The ash and the half- burned materials were weighed. The ash was 21.08 kg and the half- burned materials were 7.44 kg. Thus the performance of the incinerator is satisfactory.

In the 12th experimental observations it was found that for incineration of 242 kg of waste, the required amount of auxiliary fuel, as per energy balance calculations was 22.40 kg while the actual consumption of the fuel was 22.75 kg. The difference is 0.35 kg which is a negligible amount. The cycle time was 60 minutes. The ash and the half-burned materials were weighed. The ash was 20.57 kg and the half- burned material was 7.26 kg. On the whole, the performance of the incinerator has been satisfactory.

Findings

On the assessment of the data obtained from the twelve experimental observations it has been found that in only one experimental study (the 5th Study) the performance was unsatisfactory on the other hand, in all other eleven experiments the data obtained, indicated that the performance was satisfactory.

It has been found that about 3% of the waste has remained half-burned. Such situations are caused due to the cold pockets or inactive zones which are created in the side corners and the top-most corners inside the chamber. It can be removed by modifying the design of the chambers. The chambers should be rounded from the inside so that such cold pockets or inactive zones may not be created.

Conclusion

The conclusions are as follows-

1. There is no leakage in any of the pipes.
2. The doors are not warped due to heat and the air from outside have not been able to enter in the chamber.
3. The operator is also well trained and controls the 3Ts (Turbulence, Temperature and time) inside the combustion chamber efficiently.

Recommendations

The operator of the common biomedical waste treatment facility (CBWTF) Etmadpur, Agra has been advised to install new incineration equipment's with the improved design so that the generation of half-burned waste that cause emissions of carbon mono oxide and other carbon particles, may be avoided. The central pollution control board has already issued guide lines for installing incinerators of improved designs as per the notifications dated 28th April 2017.

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